

DEPARTMENT OF
ECOLOGY
State of Washington



**Advancing Organics Management in
Washington State:
The Waste to Fuels Technology Partnership**

February 2016
Publication no. 16-07-008
Contract no. C1400134

Publication and Contact Information

This report is available on the Department of Ecology's website at <https://fortress.wa.gov/ecy/publications/SummaryPages/1607008.html>

For more information contact:

Waste 2 Resources
P.O. Box 47600
Olympia, WA 98504-7600

Phone: 360-407-6900

Washington State Department of Ecology - www.ecy.wa.gov

- Headquarters, Olympia 360-407-6000
- Northwest Regional Office, Bellevue 425-649-7000
- Southwest Regional Office, Olympia 360-407-6300
- Central Regional Office, Yakima 509-575-2490
- Eastern Regional Office, Spokane 509-329-3400

If you need this document in a format for the visually impaired, call the Waste 2 Resources Program at 360-407-6900. Persons with hearing loss can call 711 for Washington Relay Service. Persons with a speech disability can call 877-833-6341.

Advancing Organics Management in Washington State

The Waste to Fuels Technology Partnership

By

*Shulin Chen, Craig Frear, Manuel Garcia-Perez, Jim Jensen, Dave Sjoding,
Chad Kruger, Nehal I. Abu-Lail, Greg Astill, Ian Dallmeyer, Tao Dong, Markus Flury,
Ann-Marie Fortuna, Jesus Garcia-Nunez, Sonia A. Hall, James B. Harsh,
Hamid Iqbal, Nick Kennedy, Jingwei Ma, Shannon Mitchell, Brennan Pecha,
Raul Pelaez-Samaniego, Ayca Seker, Matt Smith, Waled Suliman,
Georgine Yorgey, Liang Yu, and Quanbao Zhao*

Compiled and edited by

Sonia A. Hall

Waste 2 Resources
Washington State Department of Ecology
Olympia, Washington

Table of Contents

List of Figures and Tables.....	iv
List of Abbreviations	x
Acknowledgements.....	xi
Executive Summary.....	xiii
1. Survey of Current Gaps, Priorities and Research Needs for Organics Management	1
1.1 Abstract.....	1
1.2 Background.....	2
1.3 Methods overview.....	3
1.3.1 Survey scope.....	6
1.3.2 Survey participants	6
1.3.3 Objectives	6
1.4 Pre-survey interviews.....	6
1.4.1 Methods	6
1.4.2 Results	6
1.5 Survey and follow-up interviews on current gaps, priorities, and research needs for organics management.....	7
1.5.1 Methods	7
1.5.2 Analysis of survey responses.....	10
1.5.3 Understanding and interpreting survey responses	11
1.5.4 Survey results and discussion.....	13
1.6 Conclusions.....	27
1.7 References.....	28
2. Converting Composting Facilities into Biorefineries	30
2.1 Abstract.....	30
2.2 Background.....	31
2.2.1 Composting.....	32
2.2.2 Biorefinery.....	35
2.3 Objectives	36
2.4 Methods.....	36
2.5 Results and discussion	37
2.5.1 Part 1 – Baseline compost model	37
2.5.2 Part 2 – Emerging technologies to integrate with a compost facility.....	51
2.5.3 Part 3 – Technical analysis of emerging technologies	57
2.6 Conclusions.....	73
2.7 References.....	75
3. Extension and Outreach	82
3.1 Abstract.....	82
3.2 Outreach and extension activities	82
3.2.1 Conference presentations.....	83
3.2.2 Technical support	85
3.2.3 Training of future professionals	86

3.2.4	Extension products	86
3.3	Impacts of outreach and extension activities	87
4.	Improving Understanding of Biochar Physico-Chemical Properties and its Behavior as a Soil Amendment	89
4.1	Abstract	89
4.2	Background	89
4.2.1	Potential value of biochar	89
4.2.2	Factors affecting biochar properties	90
4.2.3	Effect of biochar and co-composted biochar on the retention of nutrients from composting materials	92
4.2.4	Additional applications of biochar in soil amendments	93
4.3	Methods.....	94
4.3.1	Effects of feedstock source and pyrolysis temperature on biochar yield and properties	94
4.3.2	Effects of pyrolysis temperature on biochar oxidability and its resultant properties	94
4.3.3	Effect of biochar and co-composted biochar on the retention of nutrients from composting materials	95
4.3.4	Additional studies on the effects of biochar soil amendments on relevant soil properties	95
4.4	Results and discussion	96
4.4.1	Effects of feedstock source and pyrolysis temperature on biochar yield and properties	96
4.4.2	Effects of pyrolysis temperature on biochar oxidability and its resultant properties	99
4.4.3	Effect of biochar and co-composted biochar on the retention of nutrients from composting materials	103
4.4.4	Additional studies on the effects of biochar soil amendments on relevant soil properties	106
4.5	Conclusions.....	108
4.6	References.....	109
5.	Separating Polyphenolic Compounds from Fruit Pomace for Use as a High Value Food Additive.....	114
5.1	Abstract	114
5.2	Background.....	114
5.2.1	Existing extraction methods	117
5.2.2	Existing purification methods.....	119
5.2.3	Exploring magnetic particles' potential for purification of polyphenols	122
5.3	Methods.....	122
5.3.1	Synthesis of magnetic particles	122
5.3.2	Preparation of the crude polyphenol extract.....	123
5.3.3	Purification of polyphenols with magnetic particles grafted with polyethylene glycol	123
5.3.4	Determination of antioxidant activity.....	125
5.4	Results and discussion	125
5.4.1	Characterization of the magnetic particles	125

5.4.2	Adsorption and desorption performance	126
5.4.3	Antioxidant activity	127
5.5	Conclusions.....	128
5.6	References.....	129
6.	Using Biochar to Remove Hydrogen Sulfide from Biogas	133
6.1	Abstract.....	133
6.2	Background.....	134
6.3	Methods.....	135
6.3.1	Char production and preparation	135
6.3.2	Hydrogen sulfide breakthrough experiment.....	136
6.4	Results and discussion	138
6.5	Conclusions.....	140
6.6	References.....	140
7.	A Pre-market Analysis of Finished Compost Marketing.....	142
7.1	Abstract.....	142
7.2	Background.....	142
7.2.1	Benefits of compost.....	142
7.2.2	The Washington Biomass Inventory needs a market component	144
7.3	Methods.....	145
7.3.1	Understanding the demand for crop nutrients in Washington State.....	145
7.3.2	Identifying challenges and opportunities for marketing finished compost for agricultural use	146
7.4	Results and discussion	146
7.4.1	The demand for crop nutrients in Washington State.....	146
7.4.2	Challenges and opportunities for marketing finished compost for agricultural use.....	150
7.5	Conclusions.....	159
7.6	References.....	160
8.	Appendices.....	164
Appendix A.	Questions for pre-survey interviews	164
Appendix B.	Final Survey, Organics Management in Washington State.....	166
Appendix C.	Demographic analysis of survey respondents	177
Appendix D.	The status of organics management in Washington State: full survey results.....	180
Appendix E.	Comments about barriers to better organics management.....	199
Appendix F.	Research questions that survey respondents would like answered.....	213
Appendix G.	Questions for post-survey follow up interviews	225
Appendix H.	Results from follow-up interviews.....	227
Appendix I.	Comments about gaps in organics management.....	233
Appendix J.	Construction of the baseline compost model.....	249
Appendix K.	Construction of the pyrolysis and pelletization models	271
Appendix L.	Construction of the AD-CNG model.....	288
Appendix M.	Additional resources related to the marketing of finished compost	299

List of Figures and Tables

Figures

Figure 1.1: Number of new responses by date received from the survey, June 18 through July 17, 2014. Initial announcement was sent to Group 1 on June 19, with reminders on June 24, June 30, and July 8. Initial announcement was sent on June 25 to Group 2 and Group 3, with reminders on June 30 and July 8.....	9
Figure 1.2: Hypothetical results showing how big of a benefit two different elements of organics management (X and Y) provide to Washington State. Results with the same letter are statistically similar, as indicated by Fisher’s exact test at $p < 0.05$...	12
Figure 1.3: Hypothetical results showing how big of a benefit two different elements of organics management (W and Z) provide to Washington State. Results with the same letter are statistically similar, as indicated by Fisher’s exact test at $p < 0.05$...	12
Figure 1.4: Extent to which respondents considered each benefit of Washington’s organics management system has been achieved. Elements followed by the same letter are not statistically different at the $p < 0.05$ level, as determined using the chi-squared test (if expected values were all equal to or greater than 5) or Fisher’s exact test (if this condition was not met).....	14
Figure 1.5: Extent to which respondents thought each benefit was a priority for investment of public resources. Elements labeled with the same letter are not statistically different at the $p < 0.05$ level, as determined using the chi-squared test (if expected values were all equal to or greater than 5) or Fisher’s exact test (if this condition was not met).....	16
Figure 1.6: Extent to which respondents considered each issue a barrier preventing better management of organics in Washington. Elements with the same letter are not statistically different at the $p < 0.05$ level, as determined using the chi-squared test (if expected values were all equal to or greater than 5) or Fisher’s exact test (if this condition was not met).....	17
Figure 1.7: Extent to which respondents thought benefits could be gained from resolving challenges. Elements followed by the same letter are not statistically different at the $p < 0.05$ level, as determined using the chi-squared test (if expected values were all equal to or greater than 5) or Fisher’s exact test (if this condition was not met).....	20
Figure 1.8: Extent to which respondents agreed with statements related to the scale and complexity of organics management. Questions labeled with the same letter are not statistically different at the $p < 0.05$ level, as determined using the chi-squared test (if expected values were all equal to or greater than 5) or Fisher’s exact test (if this condition was not met).....	22
Figure 2.1: Disposed waste stream composition in Washington State in 2009 (Ecology, 2010b).....	32
Figure 2.2: Common compost feedstock received by Washington facilities (Ecology, 2013)..	33

Figure 2.3: Composting biorefinery vision.....	36
Figure 2.4: Strategy to evaluate biorefineries processing organics from MSW.....	37
Figure 2.5: Aerial view of the hypothetical 160,000 tons per year composting facility.....	40
Figure 2.6: Detailed composting model flow diagram.	43
Figure 2.7: Summary of model input and output information (Levis and Barlaz, 2013).	44
Figure 2.8: Process diagram of the pyrolysis unit with heat recovery. The material properties for each numbered step are listed in Table 2.20.	57
Figure 2.9: Scheme for a pyrolysis unit with a Rankine cycle for the production of electricity and biochar.....	62
Figure 2.10: Schematic layout of typical biomass pelleting plant (Mani et al., 2006).	65
Figure 2.11: Block flow diagram of anaerobic digestion with food scraps.	70
Figure 2.12: AD-CNG mass flow diagram.	70
Figure 2.13: Effect of plant capacity on AD-CNG profitability.	73
Figure 4.1: Biochar yields as a function of temperature for Pine wood (PW), Pine bark (PB), and Hybrid poplar wood (HP).....	96
Figure 4.2: Bulk composition parameters as a function of pyrolysis temperature for Pine wood (PW), Pine bark (PB), and Hybrid poplar wood (HP): (a) atomic ratios and (b) total oxygen of PW, PB, and HP biochars.	97
Figure 4.3: Percentage of volatile matter as a function of pyrolysis temperature for Pine wood (PW), Pine bark (PB), and Hybrid poplar wood (HP) biochar.	97
Figure 4.4: Influence of pyrolysis temperature and feedstock source on (a) surface area and (b) pore volume of prepared biochars.....	98
Figure 4.5: Variation in surface acidic and total basic functional group as a function of pyrolysis temperature.....	98
Figure 4.6: Mineral content of PW, HP, and PB biochars made at six pyrolysis temperatures.	99
Figure 4.7: Carboxylic (left panels) and total acidic functional groups (right panels) of oxidized (red symbols) and unoxidized (blue symbols) PW (top), HP (middle) and PB biochars (bottom panels), measured via the Boehm analysis.	101
Figure 4.8: pH at which the charge on the surface of oxidized and unoxidized biochars becomes zero (pH_{PZC}), as a function of pyrolysis temperatures for different feedstocks.....	102
Figure 4.9: Nitrogen, phosphorus, and dissolved organic carbon (DOC) leached from pure media and media mixes. Data represent averages of three replicates from composite samples, and error bars are \pm one standard deviation (Figure 5 in Iqbal et al. 2015).	104
Figure 4.10: Nitrogen, phosphorus, and dissolved organic carbon (DOC) loads in the leachate, normalized by the mass of compost used in each treatment. Data represent averages of three replicates from composite samples, and error bars are \pm one standard deviation. Asterisks indicate significant differences ($p=0.05$) compared to pure compost (Figure 6 in Iqbal et al. 2015).....	105

Figure 5.1: Transesterification reaction.	123
Figure 5.2: Comparison of FT-IR spectra in the 4000-1500 cm^{-1} region of magnetic particles grafted with PEG-600 before (A) and after (B) the transesterification reaction....	126
Figure 5.3: Adsorption capacities of magnetic particles grafted with PEG-600 and XAD-4 resin at 25°C.	127
Figure 5.4: Desorption of magnetic particles grafted with PEG-600 and XAD-4 resin with ethanol at 25°C.....	127
Figure 5.5: Antioxidant activity of crude polyphenol extract (Raw), polyphenols purified with XAD-4 resin (XAD) and polyphenols separated with magnetic particles grafted with PEG-600 (M-PEG).	128
Figure 6.1: Schematic of the experimental setup designed to carry out the hydrogen sulfide breakthrough experiments.....	136
Figure 6.2: Actual experimental apparatus set up in the laboratory to carry out the hydrogen sulfide breakthrough experiment.	137
Figure 6.3: Hydrogen sulfide concentration in biogas after it has flowed through columns of materials being tested as H_2S scrubbing agents. The different curves reflect tested materials developed from AD fiber with different thermal treatments. The first number in the treatment name refers to the pyrolysis temperature (e.g., T500 was pyrolyzed at 500°C), and the second number refers to the length of treatment (e.g., 60 was pyrolyzed for 60 minutes). Treatment names with an “I” at the end were additionally impregnated with sodium carbonate before being tested.....	139
Figure 7.1: County-level distribution of cull potatoes from food packing plants (left panel) and manure from dairy farms (right panel) (Washington Biomass Inventory, 2013). .	152

Tables

Table 1.1: Hypothetical results showing how big of a benefit two different elements of organics management (W and Z) provide to Washington State. Results with the same letter are statistically similar, as indicated by Fisher’s exact test at $p < 0.05$...	13
Table 1.2: Percentage of respondents who considered benefits of Washington’s organics management system were being achieved at different levels. Benefits are organized from those considered largest (top row) to smallest (bottom row).	15
Table 1.3: Percentage of respondents who ranked each benefit as a certain priority for investment of public resources. Benefits are organized from those considered highest priority (top row) to lowest priority (bottom row).	16
Table 1.4: Percentage of respondents who considered different issues were barriers preventing better management of organics in Washington. Barriers are organized from those considered biggest (top row) to smallest (bottom row).	18
Table 1.5: Percentage of respondents who considered different levels of benefits could be gained from resolving each challenge. Benefits are organized from those considered biggest (top row) to smallest (bottom row).	21
Table 1.6: Percentage of respondents who agreed to different degrees with statements related to the scale and complexity of organics management. Statements are organized from those for which there was highest agreement (top row) to lowest agreement (bottom row).	23
Table 2.1: Composting facilities in Washington State that received more than 20,000 tons of feedstock per year (Ecology, 2013).	33
Table 2.2: Selected odorous compounds released during handling and decomposition of organic material (IWMB, 2007).	34
Table 2.3: Composition of municipal solid wastes to be processed in the baseline scenario (Komilis et al., 2004; Levis and Barlaz, 2013).	38
Table 2.4: Design and operational parameters of the hypothetical composting facility.	39
Table 2.5: Specifications and assumptions of the hypothetical compost facility, broken down by general unit operation. These specifics were obtained from Levis and Barlaz (2013), Komilis and Ham (2004), US DOE (2003), and Krogmann and Woycechowski (2000).	40
Table 2.6: Calculated material flow during composting.	45
Table 2.7: Estimated emissions from composting.	46
Table 2.8: Diesel and associated emissions (Levis and Barlaz, 2013; Komilis and Ham, 2004).	46
Table 2.9: Estimate of electricity consumed each day (Levis and Barlaz, 2013; Komilis and Ham, 2004; US DOE, 2003).	46
Table 2.10: Land and construction cost estimates (Levis and Barlaz 2013; Komilis and Ham, 2004; Marshall and Swift Indices were 1,558.7 and 1,596 for 2013 and 2015, respectively).	47

Table 2.11: Main equipment cost estimates (Levis and Barlaz, 2013; Komilis and Ham, 2004; Marshall and Swift Indices were 1,558.7 and 1,596 for 2013 and 2015, respectively).....	47
Table 2.12: Total capital cost estimates (Levis and Barlaz, 2013; Seider et al., 2009).....	48
Table 2.13: Cost of diesel, electricity, water, bulking agent, and chemicals (estimated from Zhang and Matsuto, 2011).....	48
Table 2.14: Maintenance cost estimate (estimated from data reported in: Komilis and Ham, 2004).....	49
Table 2.15: Estimation of labor costs (Levis and Barlaz, 2013; Komilis and Ham, 2004).....	49
Table 2.16: Summary of compost facility economic estimates.....	49
Table 2.17: Composting costs for three large facilities (Diaz et al., 1993).....	50
Table 2.18: Annual revenues.....	50
Table 2.19: Summary of gross earnings.....	50
Table 2.20: Properties of main streams.....	58
Table 2.21: Elemental composition of biomass, char, and vapor (Suliman et al., <i>in prep.</i> [a]).....	59
Table 2.22: Equipment cost for the pyrolysis for biochar and heat model (Seider et al., 2009).....	60
Table 2.23: Calculation for the Total Capital Investment (TCI) for the pyrolysis for biochar and heat system to be added to a composting facility (see Peters et al., 2003, p. 251, for a solids processing plant).....	60
Table 2.24: Estimated annual cost for operation and maintenance.....	61
Table 2.25: Summary of factors to calculate the gross earnings.....	61
Table 2.26: Equipment cost.....	63
Table 2.27: Calculation for the Total Capital Investment (Peters et al., 2003).....	63
Table 2.28: Estimated annual cost for operation and maintenance.....	64
Table 2.29: Summary of factors to calculate the gross earnings.....	64
Table 2.30: Equipment needed for woody biomass pretreatment (Quote from: Jinan Biomass Machinery Equipment; http://www.bio-machinery.com/ , retrieved 4/14/2015).....	66
Table 2.31: Equipment needed for woody biomass pellet production (Quote from: Jinan Biomass Machinery Equipment; http://www.bio-machinery.com/ , retrieved 4/14/2015).....	66
Table 2.32: Fixed capital investment (FCI) calculations for pretreatment and pellet production for 5 tons hour ⁻¹ capacity and with a scaling factor of 1.65 (Peters et al., 2003).....	67
Table 2.33: Estimated annual cost for operation and maintenance.....	67
Table 2.34: Summary of factors to calculate the gross earnings.....	68
Table 2.35: Assumed composition of food scraps used in the anaerobic digester.....	69
Table 2.36: Estimation of capital costs.....	71
Table 2.37: Estimation of operation and maintenance costs.....	72
Table 2.38: Estimation of revenue.....	72

Table 2.39: Summary of economic analysis for composting, pyrolysis, pellet production, and AD.....	74
Table 4.1: Composition of soil amendments tested in this study. See full details on the methodology in Iqbal et al. (2015) (see <i>Authors' note</i> on page 93).	95
Table 4.2: Characteristics of microporous structure of unoxidized (UO) and oxidized (AO) PW, PB, and HP biochars as a function of pyrolysis temperature.....	100
Table 4.3: Effect of biochar application to sandy soil on bulk density, pH, electrical conductivity (EC), and soil water contents (θ).	107
Table 5.1: Polyphenolic content of different plant foods and beverages (Kuhnau, 1976).	116
Table 7.1: Summary of soil and plant fertilizer nutrients in Washington State, 2013-2014 (WSDA 2014).	146
Table 7.2: Compost production by registered facilities in Washington State. Facilities processing dairy manure and agricultural, food processing, and municipal solid waste organics (such as yard and garden materials and food scraps) are included (Ecology, 2013).....	148
Table 7.3: Top ten commodities in Washington State in 2012 (Washington Department of Agriculture).....	151

List of Abbreviations

AD	Anaerobic Digestion
C:N	Carbon to Nitrogen Ratio
CH ₄	Methane
CNG	Compressed Natural Gas
CO ₂	Carbon Dioxide
CPE	Crude Polyphenol Extract
CSANR	Center for Sustaining Agriculture and Natural Resources
DOC	Dissolved Organic Carbon
EPA	Environmental Protection Agency
GHG	Greenhouse Gas
H ₂ O	Water
H ₂ S	Hydrogen Sulfide
HWE	Hot Water Extraction
K	Potassium
LCA	Life-Cycle Assessment
MSW	Municipal Solid Waste
N or N ₂	Nitrogen
N ₂ O	Nitrous Oxide
NH ₃	Ammonia
NIMBY	Not In My Back Yard
NR	Nutrient Recovery
NRCS	Natural Resource Conservation Service
O ₂	Oxygen
O&M	Operations and Maintenance
P	Phosphorus
PEG	Polyethylene Glycol
ROI	Return on Investment
SFE	Supercritical Fluid Extraction
TCI	Total Capital Investment
TS	Total Solids
US	United States
USDA	United States Department of Agriculture
VOC	Volatile Organic Compounds
VS	Volatile Solids
WA	Washington State
WSDA	Washington State Department of Agriculture
WSU	Washington State University
WWTP	Wastewater Treatment Plant

Acknowledgements

The authors of this report thank the following people for their contribution to this study:

- Andy Bary, Washington State University
- David Granatstein, Washington State University
- Greg Ovenell, Ovenell Farms
- Thad Shutt, Royal Organics Products
- Ron Reyer, Cascade Agronomics
- Don McMoran, Washington State University – Skagit Extension

The authors also thank Sonia A. Hall for her time, effort, and skill in compiling and editing this report.

Finally and most especially, the authors gratefully acknowledge the many individuals who responded to the organics management survey. They also extend a special thanks to the individuals who agreed to be interviewed before and after the surveys, providing additional thought an insight.

Executive Summary

Introduction

Increasing amounts of organic “waste” materials that were once disposed of in landfills and wastewater treatment plants are instead being used to support new industries and product lines across Washington State. These materials can provide a myriad of benefits, including improved soil quality and structure, reduced demand for landfill space, lower greenhouse gas emissions, increased carbon sequestered in the soil, and the generation of renewable energy. To advance the management of such organic materials in Washington, and thereby increase the benefits provided to Washington’s citizens, Washington State University’s Center for Sustaining Agriculture and Natural Resources has conducted targeted applied research and extension on emerging technologies for managing residual organic matter. This work was funded through a partnership with the Washington Department of Ecology’s Waste 2 Resources Program. Work was carried out in seven complementary research and extension areas, including an assessment of the status of organics management in Washington (Chapter 1), an assessment of biorefinery capabilities (Chapter 2), extension and outreach (Chapter 3), and four seed research projects exploring high value-added products of organics management, such as biochar (Chapters 4 and 6), polyphenols (Chapter 5), and finished compost (Chapter 7). Each of these seven areas is introduced briefly here, and covered comprehensively in the respective chapter.

Status of organics management in Washington State

The Washington Department of Ecology’s *State Solid and Hazardous Waste Plan (Beyond Waste)* articulates a goal of closed-loop recycling and reuse of organic materials. Using this goal as a basis for formulating questions, researchers carried out a survey targeting the organics management sector in Washington State. This survey was designed to help identify critical gaps between current and desired organics management, priority areas for action, and future research needs. Improved information in these areas can aid the implementation of future Waste to Fuels Technology partnership activities. With input from key stakeholders in the organics management sector, researchers developed and fielded the survey, and carried out in-depth follow-up interviews with a cross-section of individuals working in organics management, who reflected on survey results and provided additional detail.

Survey participants included the current organics management industry, new technology developers, government agency personnel, finished product end-users, non-governmental organizations, and community members involved in waste management. A total of 273 responses were received, with a 55% response rate from a set of specific targeted individuals working in organics management. The survey results indicated several benefits from improved organics management were currently being realized: improved soil quality and structure, reduced use of fertilizers and pesticides. Survey respondents felt these benefits were high priorities. Being realized to a lesser extent were other high-priority benefits, such as water conservation and renewable energy production. Important barriers to achieving stated organics management goals in Washington included some well-recognized barriers—opposition to facilities from neighbors,

contamination, odors—as well as less-recognized barriers, such as lack of investor support. Additional barriers mentioned frequently by respondents, which may merit additional study, were lack of public awareness, costs and economics, scale issues and innovation and technology development. In addition to addressing neighbor opposition to facilities, contamination, and odors, survey participants felt that diversifying the products being used, especially by agriculture, would lead to organics management providing significant benefits in Washington.

Respondents had a diverse range of organics management questions that they would like research to answer. Many questions revolved around organic recovery technologies, including anaerobic digestion, pyrolysis, composting, and combinations thereof, as well as technology development for product generation, economics and marketing, contamination, and using recycled organics in agriculture. Other important questions related to the scale and economics of organics processing, with specific questions on transportation and costs for both feedstocks and products.

These survey results highlight a sense of where investment in organics-management related research would be perceived by experts in the sector to more directly help overcome existing challenges and realize potential benefits. Taking these perceptions into consideration in future funding decisions could help identify particularly impactful areas of work, as well as fruitful partnerships and supporters for particular focal areas, as Washington State University continues its contributions to Ecology's Waste 2 Resources Program.

Converting composting facilities into biorefineries

Researchers at Washington State University continued previous investigations of biorefinery concepts by evaluating the potential to integrate emerging technologies—pyrolysis for biochar production, pellet formation, and anaerobic digestion with compressed natural gas production—into a baseline composting facility. This baseline facility is a hypothetical facility used to model realistic scenarios based on real scale inputs. The hypothetical composting facility was representative of a large size composting facility in Washington State processing 160,000 wet tons per year, with an assumed waste stream of 76.9% yard trimmings, 19.2% food scraps, and 3% wood. Material flow and economic calculations were done in Excel, based on mass balance equations with performance indicators obtained from the literature. The economic analysis included capital costs, operation and maintenance costs, and revenue. The total capital investment to build the facility was estimated at \$28 million. Most of the revenue came from tipping fees (87%), with the rest from sales of the composted material (13%). The model indicated that if none of the capital cost was financed, the gross earnings would be \$6.3 million per year, and the net earnings (after taxes) would be \$4.0 million per year. The return on investment was 14%, which is considered competitive with current commercial interest rates.

A literature review was conducted to better understand the benefits and limitations of integrating emerging technologies—anaerobic digestion, pyrolysis, and wood-fuel pellet production—with composting facilities. Anaerobic digestion can effectively integrate with composting for treatment of decaying material, with waste treated either in a slurry or a dry reactor. Slurry digesters can produce large amounts of liquid effluent, which can be used as water inputs to the compost feedstock, compost piles, or nutrient recovery units. Nutrient recovery can be installed,

leading to the recovery of saleable fertilizer and recycled water. Pyrolysis—whose products include biochar, heat, and electricity—and pellet production can effectively integrate with compost for treatment of woody waste. The choice of anaerobic digesters and pyrolysis reactors is important to consider as the industry determines ultimate co-product characteristics and market value. Production of wood-fuel pellets, one of the most successfully traded biomass commodities, is promising: the main advantages of pellets are their high density, low moisture content, and high energy value.

Different scenarios were analyzed to explore potential paths for the evolution of composting facilities into biorefineries, each considering an existing composting unit gradually adding emerging technologies. One set of scenarios compared adding pellet production or slow pyrolysis. Compared to the return on investment of the baseline composting facility (14%), pellet production had a return of 88%. Slow pyrolysis had returns on investment of 46% and 21%, when considered with and without heat recovery. A separate scenario considered adding an anaerobic digestion process capable of processing 120 tons of food scraps to the baseline composting facility. This concept had a return on investment of 34%. However, the capital cost for the anaerobic digestion system (\$14.8 million) was significantly higher than those for pyrolysis and for pellet production (\$2.1 million and \$4.7 million, respectively). These results indicate that a less expensive anaerobic digestion system may be needed to more economically treat putrescible material, to initially stabilize the waste and capture energy prior to composting. However, both suggested paths provide increases in profits, and in addition, would allow existing systems to process more material on a given land area, which may be important in an urban context.

These results suggest that well-designed biorefineries can achieve higher rates of return on investment than a composting facility, though those rates—and the associated capital costs—vary depending on the size of the plant, the feedstock used, and the emerging technologies that are integrated with the composting units.

Extension and outreach

Extension and outreach activities are critical for catalyzing adoption of improved technologies, ensuring that the lessons learned by researchers are adopted and applied. Activities carried out during this biennium included: presenting at multiple national and regional conferences attended by extension, engineering, industry, regulatory, and educational professionals; providing technical support to nine stakeholder groups ranging from federal agencies to non-profit entities; training young professionals transitioning from academia to industry; designing an anaerobic digestion curriculum for training anaerobic digestion technicians; and publishing six formal extension publications. An estimated 12,000 scientists, producers, industry specialists, regulators, policy-makers, and other interested parties across the country were reached. These activities led to increased awareness of biorefinery technologies, tools, resources, and successful experiences. Such awareness and resources are critical to the advancement and adoption of technologies and processes in Washington State that create energy from livestock manure and other organic residues.

Seed research

In addition to the projects described above, the Waste to Fuels Partnership included a number of “seed” research projects. These small projects enabled researchers to carry out exploratory research into promising areas of interest. The initial results obtained through these seed research projects are used to evaluate whether or not additional research building on early results is merited, and also support efforts to seek additional funding in these areas.

Biochar’s physico-chemical properties and its behavior as a soil amendment

Researchers carried out fundamental studies to better understand the relationship between biochar production conditions—pyrolysis temperature and post-pyrolysis oxidation—and the physico-chemical properties of the resultant biochar. The results showed that even at very low pyrolysis temperatures, the surface area of biochar started to develop with the formation of very small pores. However, as the pyrolysis temperatures increased, the surface lost oxygenated functional groups, becoming less negatively charged. During the post-pyrolysis oxidation process, the surface was re-oxidized with oxygen. When used as a soil amendment, the oxidized biochars retained more water, dramatically improving the soil’s water holding capacity. In addition, these studies showed that surface charge was a critical parameter controlling the adsorption of *Escherichia coli*. Unfortunately, both the biochar alone and its mix with compost showed very limited adsorption of nitrogen and phosphorus when added to a sandy soil, suggesting limited potential to reduce nutrient leaching. These results highlighted the importance of surface chemistry in determining the capacity of these chars to adsorb nutrients. As a group, these studies also indicated that the potential exists for developing engineered biochars for specific environmental purposes.

Polyphenols: producing a high-value food additive from fruit pomace

There is a growing interest in using naturally derived, bioactive compounds as food additives to help prevent obesity, coronary heart disease, and cancer. High quality polyphenolic compounds can be extracted from grape pomace, the grape pulp, seeds, and skins that are byproducts of Washington’s wine and grape juice industries. However, cost-effective extraction and purification methods are essential. In this study, a purification method based on magnetic polymeric particles with hydrogen bonding affinity ligands was developed to separate high quantities of polyphenols from grape seeds, the main component of grape pomace. Results indicated that the adsorption capacity of magnetic particles grafted with polyethylene glycol 600 (PEG-600) could reach 38 mg g⁻¹ dry adsorbent, compared to 7 mg g⁻¹ dry adsorbent for commercially available polymeric macroporous resin, XAD-4. In addition, it took 12-fold less time for the magnetic particles to desorb the same amount of adsorbed polyphenols compared to the XAD-4 resins. Moreover, the antioxidant activity of the polyphenols separated using magnetic particles was 1.3- and 1.7-fold higher than those separated with the XAD-4 polymeric resins and those in the crude polyphenol extract, respectively. The experimental results of this study are encouraging, and could be used as a basis for future efforts to improve the separation process and develop high value-added food additives from byproducts of the wine and grape juice industries in Washington and beyond.

Using biochar to remove hydrogen sulfide from biogas

Researchers evaluated anaerobically digested fibrous solids produced at dairy farms as a possible scrubbing medium to remove hydrogen sulfide, a contaminant, from raw biogas. Anaerobically digested fiber was subjected to various thermal conditions to produce a char-like material, which was then used for hydrogen sulfide scrubbing tests with synthetic biogas. Results showed that when pyrolysis temperatures were higher—which led to greater porosity—hydrogen sulfide removal also increased. Hydrogen sulfide scrubbing tests using anaerobic digestion fiber subjected to hot water extraction—an alternative thermal pretreatment process—indicated that the effect of water during the treatment was undesirable. In contrast, impregnating the char produced via pyrolysis with sodium carbonate increased the biochar’s capacity for hydrogen sulfide sorption. It is likely that both physical and chemical sorption happen during hydrogen sulfide scrubbing using thermally treated anaerobic digestion fiber. These results indicate that both the characteristics of the thermal treatment and the post-pyrolysis treatments can be manipulated to enhance the effectiveness of hydrogen sulfide removal with anaerobic digestion fiber.

Opportunities and challenges for marketing finished compost

Composting is used as a strategy to manage organic waste from dairy farms, food processing plants, and municipalities. Opportunities and challenges exist for marketing finished compost in the Pacific Northwest. The Pacific Northwest compost industry is concerned about the quality, value and size of the market for finished compost, questions tackled in this project’s pre-market analysis.

Relevant information on the supply and potential demand of finished compost in Washington State was collected from websites with Washington data, published literature, and interviews with experts in the field. The supply analysis indicated that compost production in Washington State is relatively concentrated, with the top ten facilities (not evenly distributed across the state) producing 80% of finished compost. Marketing of finished compost is likewise concentrated, with just two western Washington companies marketing about half the compost produced in the state. In terms of demand for compost, potatoes were used as a representative crop to evaluate the challenges and opportunities for marketing finished compost for agricultural use. Research in Washington State, Idaho, and other potato producing regions in North America have found that using compost as a soil amendment in potato production can address challenges such as management of water availability, pests, and nutrient management, by increasing soil organic matter and associated microbial activity. Though these benefits may be of particular value to organic potato production, they can also improve the sustainability of conventional potato production systems. Important remaining barriers preventing more widespread use of compost in potato production include the cost of compost relative to its perceived benefits and the challenge of applying compost to potato fields.

Conclusions

Taken together, this diverse body of work increases the likelihood that Washington State's organics recycling industry will be able to successfully and profitably incorporate advanced waste treatment technologies such as pyrolysis and anaerobic digestion, and produce high value added products from organic waste. Over time, these developments could contribute to further reductions in the environmental impact of agriculture and urban communities, while reducing the nuisance and public health impacts associated with current municipal organics recycling programs and certain agricultural production practices.

1. Survey of Current Gaps, Priorities and Research Needs for Organics Management

Georgine Yorgey, Jim Jensen, Chad Kruger, Craig Frear, and Sonia A. Hall

1.1 Abstract

A better understanding of critical gaps between current and desired organics management, priority areas for action, and research needs can help inform future Waste to Fuels Technology Transfer partnership activities, such that investments achieve greater impact and efficiency. Using the Washington Department of Ecology's (Ecology) *State Solid and Hazardous Waste Plan (Beyond Waste)* goal of closed-loop recycling and reuse of organic materials as a basis for formulating questions, researchers carried out a survey of the organics management sector in Washington State. The survey was carried out in three phases:

- Phase I: interviews to solicit input on survey development and goals;
- Phase II: development and fielding of the survey;
- Phase III: in-depth interviews with a cross-section of individuals working in organics management to reflect on survey results and provide additional detail.

Researchers surveyed participants within the current organics industry, including new technology developers, government agency personnel, finished product end-users, non-governmental organizations, academic researchers, and community members involved in waste management. The survey was fielded in a web-based format during the summer of 2014. A total of 273 responses were received, with a 55% response rate from the core set of individuals working within the organics management sector that was considered the target audience.

Results indicated that there are several benefits from organics management that survey respondents feel are high priorities, and that are being realized to a great extent currently; these are primarily improved soil quality and structure, and reduced use of fertilizers and pesticides. When interpreted in light of other survey results and in-depth surveys, it is likely that respondents feel that improved soil quality and structure is being realized when the products are applied, and not in areas where they are not applied. Other high-priority benefits, such as water conservation and renewable energy production, are being realized to a lesser extent.

Important barriers include both well-recognized ones—opposition to facilities from neighbors, contamination, and odors—and less-well recognized barriers—lack of investor support. Large numbers of survey respondents were also unsure how big of a barrier lack of investor support was, indicating that additional investigation may be warranted. Lack of public awareness, costs and economics, scale issues, and innovation and technology development are additional barriers that respondents mentioned frequently, which may also merit additional study.

Not surprisingly, survey respondents felt that addressing neighbors' opposition to facilities, contamination, and odors would likely provide a big benefit to organics management. In

addition, getting more products into use by agriculture is seen as an achievement that would provide a big benefit. There were also several challenges that survey respondents either were highly uncertain or had no opinion about: attracting more private investment, commercializing pyrolysis, and putting an economy-wide price on greenhouse gases. This may indicate a need for additional investigation in these areas.

When asked, respondents articulated a large number of specific questions about organics management that they would like research to answer, covering a diverse range of topics. Among these were many questions relating to the products from various organics recovery technologies, including those touching on contamination, technology development, economics and marketing, and using compost and other recycled organics in agriculture. A second area of interest included questions related to scale and economics for organics processing, and transportation and transportation costs for both feedstocks and products. Third, there were a large number of questions both about specific technologies for processing organics—anaerobic digestion, pyrolysis, composting—and about comparing or combining technologies, with a focus on life-cycle assessments.

1.2 Background

The Washington Department of Ecology has a strong interest in assessing the short-term and long-term needs for research and development concerning diversion and recycling of a wide range of organic materials. Organic materials include such things as food, leaves and grass, and animal manures. They also include all types of wood and paper. In 2009, these materials made up 55% of Washington State's disposed waste stream (Ecology 2010). Within this, the most prevalent material was organics (e.g. food, leaves and grass, animal manures, prunings), which accounted for 27%. Paper products, paper packaging, and wood debris made up 10, 9, and 9%, respectively (Ecology, 2010).

Improving organics management has the potential to provide a range of benefits to Washington's citizens. When added to soils, processed organic materials can improve a range of soil quality measures, including organic matter content, bulk density, and water holding capacity (e.g. MacConnell et al., 1993; Silva et al., 2007; Brown et al., 2011). Recovering or recycling nutrients can help sustain limited sources for some nutrients such as phosphorus (Cordell et al., 2009), and reduce the release of both nitrogen and phosphorus into the environment, where they can contribute to a number of issues (Yorgey et al., 2014). Recovery processes such as composting or anaerobic digestion can reduce the release of climate-change causing greenhouse gases and can also sequester carbon, if the resulting products are applied to soils (Brown et al., 2008; Frear and Yorgey, 2010; Masse et al., 2011). Water conservation, reduced use of pesticides and fertilizers, renewable energy production, economic development, and reducing impacts on limited landfills are other important potential benefits (Ecology, 2009).

Ongoing planning and prioritization for actions to improve management of organics in Washington State has been carried out through Ecology's *Washington State Solid and Hazardous Waste Plan (Beyond Waste)*, among other processes. While this process is informed by data, including the percentages of various organics currently recovered or recycled, it has up to now not been informed by any systematic survey of the thoughts, opinions, and priorities of those

who comprise the organics management sector. A cross-sectoral survey has the potential to provide improved information about critical gaps between current and desired organics management, priority areas for action, and research needs, helping to galvanize action and aid in implementing Ecology's *State Solid and Hazardous Waste Plan (Beyond Waste)* goal of closed-loop recycling and reuse of organic materials. Survey results can also inform future research investments made by the Department of Ecology through the Waste to Fuels Technology Program.

1.3 Methods overview

The survey drew on needs assessment methodology described by Kaufman's Organizational Elements Model, which describes three levels of needs or discrepancies—mega, macro, and micro (Kaufman, 1972, 1988, 1999; Kaufman et al., 1993, 2003, cited in Altschuld, 2004). In the case of organics management in Washington State, the mega—or societal—level was defined to include items such as the creation of robust markets, closed-loop organics management, and societal support for a sustainable organics cycle. Macro elements included regulations, residential and commercial recovery programs, processing technologies, government's role in leading by example, end uses and standards for compost and biosolids, and the various markets for products. The micro level was focused on identifying important issues specifically related to the role of research in furthering organics management in the state.

The survey was developed and implemented in three phases:

- Phase I: Pre-survey interviews, used to validate the approach and solicit feedback on important questions to be answered during the survey phase.
- Phase II: A survey designed to capture the breadth of concerns at the mega, macro, and micro levels across the organics management community.
- Phase III: Follow-up interviews designed to gather in-depth information on key areas of concern identified during the survey phase. Because Phase III was explicitly designed to add relevant detail to the results from Phase II, Phases II and III are presented together in this report.

Ecology's *Beyond Waste Plan* provided critical background to understanding the existing conditions and current status. At the time the survey was designed the *2009 Beyond Waste Plan Update* (Ecology, 2009) was the most current plan, and this was used to directly inform the survey questions. For reference, the text of the relevant initiative concerning organics is provided in Textbox 1. During initial planning, conversations within the research team with Ecology partners were used to further define the scope of the needs assessment, as described below.

Textbox 1: Beyond Waste Plan Update 2009 – Initiative #3 - Increasing Recycling for Organic Materials*

The Organic Materials Initiative will help expand and strengthen the closed-loop reuse and recycling system in Washington for organic materials. This system will convert leftover or excess organic materials into feedstocks for resources and bio-products such as compost, bioenergy, and biofuels, without creating new wastes. The extensive list of “organic materials” includes substances and products of biological origin that we could safely return to the soil or turn into new products. *Organic materials include yard waste, food scraps, manures, crop residues, soiled/low-grade paper, wood, and biosolids.*

Ultimately, a closed-loop system for residual organic materials depends upon processing organics according to the highest and best uses possible. When establishing this hierarchy, we must consider environmental, social, and economic impacts.

Benefits of a closed-loop organics recycling system include:

- Reduced demand for landfill space.
- Reduced release of greenhouse gases.
- Reduced need for added chemicals (such as fertilizers and pesticides) to agricultural lands.
- Improved soil quality and structure.
- Production of renewable fuels.
- Water conservation.
- Creation of new jobs.
- Climate change mitigation actions, such as carbon sequestration.

Today’s Reality

Organic materials make up about 30 percent of the municipal solid waste generated by Washington residences, businesses and institutions. The majority of these organic materials – food waste, yard waste, compostable paper, clean wood, and textiles – are now landfilled or incinerated.

30-Year Goals

Robust markets

There are robust markets for organic-based products in all sectors of the economy. There is demand for high-quality organic products in the marketplace, from soil amendments and recycled consumer goods to green energy sources.

Closed-loop materials management

Organics collection and processing is optimized. A network of businesses thrives on transforming residual organic materials into beneficial products. Changes in industrial processes and on-site management, such as composting, have reduced the quantity of organic waste. Organic materials are transformed into beneficial products according to highest and best use.

Society supports a sustainable organics cycle

Full organics recovery and beneficial use are the norms in Washington State. Businesses and governments incorporate full organics recovery into their decisions. Economic and regulatory incentives are aligned to support this system. Recycling and reuse of organics are efficient due to

Textbox 1 (continued): Beyond Waste Plan Update 2009 – Initiative #3 - Increasing Recycling for Organic Materials

minimal presence of contamination or composite products in the system. People use organic products widely and regularly to improve soil quality in urban, suburban, and agricultural areas.

Recommendations

- 1 — Lead by example in government.
- 2 — Increase residential and commercial organics recovery programs.
- 3 — Improve quality of recycled organic products.
- 4 — Develop a strategy to increase industrial and agricultural organics recovery.
- 5 — Propose solutions to statutory and regulatory barriers.
- 6 — Develop new products and technologies for organic residuals.

Milestones

- A: A strategy for increasing agricultural and industrial organics recycling is being implemented.
- B: Effective incentives for organics recycling are identified and pursued.
- C: Home composting programs are active and successful in every county.
- D: The quality of recycled organic products has improved.
- E: Most people (government, business, and the public) understand the benefits of healthy soils.
- F: Statutory and regulatory barriers to closed-loop organics recycling are addressed.
- G: A beneficial use hierarchy is created for residual organic material processing and uses.
- H: Soil carbon sequestration using recycled organic materials has increased based on research recommendations.
- I: Technical assistance, research, and/or capital expense funds support the development of at least two biomass-to-energy and biomass-to-fuel and co-products “organic refinery” projects.
- J: Organics recovery (including landscaping and food scraps) occurs in 50 percent of all state and local government buildings and institutions, including the Capitol Campus. State and local agencies and institutions are required to use compost as a landscape management tool to reduce water and pesticide use.
- K: Statewide residential and commercial recycling of organics is standard practice, supported by efficient collection and increased infrastructure. Large municipalities offer food waste collection programs to residential and commercial customers.
- L: Major retailers promote the use of natural yard care and pest control products, including compost.
- M: Food waste prevention is a focus of state and local government. This includes edible food recovery for redistribution to organizations serving hungry people and food waste prevention programs at the residential, commercial, and institutional level. Work will be supported by a guidance document developed by Ecology.

Reproduced with permission from Ecology’s Beyond Waste Plan, 2009 Update: Summary of the Washington State Hazardous Waste and Solid Waste Management Plan.

* Note that since the survey was designed, the Initiatives in the 2009 Plan Update have been replaced by Sections in the 2015 revision: The State Solid and Hazardous Waste Plan - Moving Washington Beyond Waste and Toxics (Ecology, 2015).

1.3.1 Survey scope

The survey targeted organics management in Washington State, which is defined broadly as the management of biodegradable wastes. This included handling, processing and marketing products made from agricultural wastes, manures, food scraps, yard and garden debris, and biosolids. The survey focused on the current timeframe (the last five years) and the future.

1.3.2 Survey participants

The survey targeted participants in the current organics industry, new technology developers, government agency personnel, finished product end-users, non-governmental organizations, and community members involved in waste management.

1.3.3 Objectives

Specific objectives of the needs assessment included:

- Identify existing **status** of current organics management in Washington State.
- Identify **barriers** preventing more beneficial organics management.
- Develop **priority areas for action** based on the size of the gaps and the respondents' assessment of the importance of the various needs.
- Understand participants' opinions about the **most productive scale and level of complexity** for future organics management.
- Gather evidence about priority **research needs** for furthering organics management in the state.

1.4 Pre-survey interviews

1.4.1 Methods

To formally support scoping conversations and survey design and to gather lists of individuals who should be targeted during the survey phase for their participation, semi-structured interviews were carried out with a range of knowledgeable experts in the organics industry and at Ecology. Pre-survey interview questions are available in Appendix A.

Once the survey had been reviewed by Washington State University's (WSU) Internal Review Board for human subjects research, pre-survey interviews were completed with six individuals with government, academic, and commercial experience in the organics management field.

1.4.2 Results

The pre-survey interviews supported the following key conclusions, which guided the development of the survey questions:

- In general, respondents agreed that the *Beyond Waste* measures (as summarized for participants) were a good basis for our survey. One person thought it important to stick to broader categories and end results.
- Additional issues that respondents wanted included in the survey were regulations and regulatory barriers, reintegrating organics management into soils management,

product stewardship for organics and fertilizers, end use of recycled organics products, and the value of green infrastructure organics.

- Respondents suggested that the survey also include a broader discussion of what other lenses could be used by people or the state (i.e., Ecology) for putting values on organic resources, as well as key barriers for processing and end use of different products made from organic wastes.

Semi-structured interviews also generated input that was helpful specifically for survey design and management. Generally, respondents suggested:

- A web-based survey would be a convenient and accessible format. One participant suggested that carrying out the survey with a group, either live or in webinar format, could prompt interesting discussion.
- Questions of a sensitive or proprietary nature could discourage participation.
- Keeping the survey clear and short to encourage participation. Most felt that respondents would be likely to be quite interested in the survey, and they therefore felt that people would be willing to spend 15-20 minutes answering the survey.
- Including mostly closed-ended questions. However, most interviewees noted the importance of providing opportunities for open-ended comments, so that survey respondents could voice their opinions. Several people felt that being too restrictive could be frustrating to our survey respondents, especially given their high degree of interest.
- Survey respondents would likely be well versed about some of the topics and not about others, which would be a challenge for survey design.
- Targeting survey respondents both by individual emails, and through general invitations to members of important subgroups within the waste management sector (e.g. Washington Organic Recycling Council, Washington State Recycling Association, biosolids managers).

1.5 Survey and follow-up interviews on current gaps, priorities, and research needs for organics management

1.5.1 Methods

The survey comprised nineteen questions: fourteen closed- and open-ended questions about organics management in Washington State, and five questions that were primarily demographic in nature (see Appendix B for survey). Questions were designed following suggestions from Dillman et al. (2009) to ensure adequate response rates and data quality. The survey was also tested by five representative respondents and was reviewed by the WSU Internal Review Board prior to being fielded.

Because there was no existing contact list for individuals in the group of respondents that were the focus of the survey—those involved in organics management in Washington State—the team spent considerable time collating lists of contact names and contact information. This included collating the team’s own contact lists, those of other colleagues, and those suggested by the

interviewees during the pre-survey interviews. It also included extensive Internet searches for member directories and lists for key organics groups, businesses and associations. These key groups included in the search for possible survey respondents included:

- Public agencies, such as the Washington Departments of Agriculture (WSDA) and Commerce, county solid waste authorities, county health districts, wastewater districts, and clean air agencies;
- Private sector companies and industries, such as composters, digester developers, equipment providers, recyclers and haulers, landfills, wastewater treatment facilities, and food processors;
- End users and marketers, such as farmers, landscapers, Washington Department of Transportation and roads contractors, soil blenders and fertilizer companies;
- Non-governmental organizations, such as Washington Organic Recycling Council, Northwest Biosolids, and Climate Solutions;
- Industry engineers and consultants;
- Community members involved in waste management issues;
- Associated Grocers organizational members and some member stores;
- Washington State Recycling Association (WSRA);
- Groups that may have opposed facility developments;
- Conservation District officials;
- Conservation Commission officials;
- Tribes, such as the Nooksak and Lummi (involved with shellfish issues), Tulalips, Chehalis, and Yakama;
- Association of Renderers;
- Biosolids managers;
- Ecology permit regulators;
- Public Works directors and recycling coordinators;
- Water quality experts;
- Air quality agencies and experts;
- Finance community (public and private);
- Relevant researchers at other regional institutions (e.g., Pacific Northwest National Laboratories, National Renewable Energy Laboratory, University of Washington);
- Utilities, such as Puget Sound Energy, Northwest Natural, Energy Northwest, and Public Utility District community;
- Bonneville Power Administration and the Bonneville Environmental Foundation;
- Legal community and lawyers who have represented industry companies;
- Elected officials;
- Port authorities;
- Farmers and farmer organizations, such as Seattle Tilth and Washington Tilth;
- Land conservancies, such as Forterra;
- Urban agriculture and community garden advocates;
- Food processors, such as Tree Top;
- Institutions that generate large amounts of organics (e.g. universities, campuses, and corrections facilities);
- Landscape companies (as both generators and end users of compost);

- Fish waste generators; and
- Lists of government managers and health department officials on the Ecology website.

Once these lists were collated, the team grouped respondents into three groups, based on how closely they matched the targeted survey group, and on whether individual addresses for individual respondents were available (allowing us to calculate a response rate):

- Group 1: Individuals who are known to be part of the targeted group, involved in organics management in Washington State in some capacity (306 individuals).
- Group 2: Email list serves for targeted constituencies (number of individuals unknown, at least some overlap with Group 1).
- Group 3: Government managers and health department officials (336 individuals, not all of whom were involved in organics management).

The survey was fielded during late June and early July of 2014. It was delivered in a web-based format (Survey Monkey, Palo Alto, CA), with both an initial announcement and follow-up reminders delivered via email. Data on the timing of survey completion was used to time follow-up reminders, with reminders sent until the number of new responses following a reminder was modest—three reminders after the initial distribution for Group 1 and two for Groups 2 and 3 (Figure 1.1; Dillman et al., 2009).

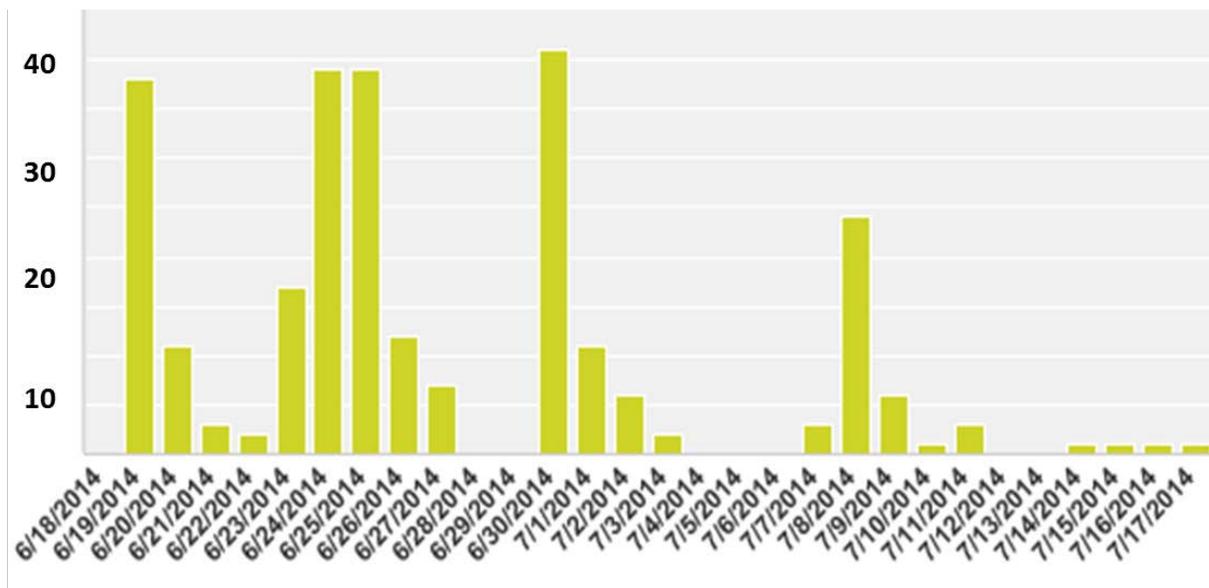


Figure 1.1: Number of new responses by date received from the survey, June 18 through July 17, 2014. Initial announcement was sent to Group 1 on June 19, with reminders on June 24, June 30, and July 8. Initial announcement was sent on June 25 to Group 2 and Group 3, with reminders on June 30 and July 8.

The total response rate from the core individual respondent group was 55% (168 responses), with an additional 10 responses from Group 2. Response rate from Group 3 was 28% (95 responses). This lower response rate from Group 3 was expected, given that not all individuals in this list were conversant in organics management issues. The demographic analysis of respondents generally indicated that responses were received from a range of individuals across the sector

(see Appendix C). One important exception to this is that the survey did not reach very many end users of recycled organic products, such as users in the agricultural sector, horticultural industry, the Washington Department of Transportation. This is likely to have implications for results, especially those related to product quality, usefulness, and price. In addition, just over half of responses came from individuals who had a government role—either regulatory or non-regulatory.

After the survey responses were gathered and an initial analysis was carried out, the team reviewed the findings with a handful of key industry representatives (fall 2015). The post-survey interview questions are attached as Appendix G. After completion of the WSU Internal Review Board process, interviews were carried out either by phone or email, based on the respondents' preferences. The individuals surveyed included:

- A county health department compost specialist,
- A private compost engineering consultant,
- A private composter,
- A compost researcher,
- A city solid waste manager,
- A regulator of fertilizers and organic farms program,
- A county solid waste manager,
- An extension researcher and educator, and
- A biochar industry advocate.

Where relevant, information from these surveys has been incorporated into the results summary provided below. Full results from the follow-up interviews are provided in Appendix H.

1.5.2 Analysis of survey responses

Responses were summarized within Survey Monkey, while statistical analysis of results was carried out using R (version 3.1.1, R Foundation for Statistical Computing, Vienna, Austria). Statistical analysis of responses for each question was carried out using a set of pairwise chi-squared tests if expected values for response categories were equal to or greater than 5. If expected values were less than 5, Fisher's exact test was used. To highlight differences in opinions rather than the number of individuals who were unsure about a particular topic, not sure/no opinion responses were omitted from the statistical analyses, including the counts of expected values described above. However, the frequency of these responses is included along with other frequencies in the results presented below.

Statistical analysis was also used to compare responses of government and non-government respondents. This was done to highlight any areas where the perceptions of governmental employees (including Ecology) differ significantly from those of the rest of the organics management sector.

Responses to open-ended questions were not analyzed statistically. However, to allow for an understanding of recurring themes across these answers, open-ended responses—new barriers, and comments and further detail about barriers mentioned in the associated multiple choice

question—were categorized. While this was inherently a subjective process, two researchers carried out the categorization, to improve consistency.

1.5.3 Understanding and interpreting survey responses

There are three important considerations when interpreting and using the results of this survey on the status of organics management in Washington State:

- It reflects one snapshot in time, and the perceptions of respondents on the current situation.
- While “average” response can be helpful for showing overall trends, they must be interpreted with caution. Tables provide significantly more detail about survey responses.
- Statistical differences can be driven by multiple different factors.

The survey results provide a snapshot in time of the perceptions and opinions of professionals currently in the organic waste management sector. It is important to keep in mind that the survey targeted the organic waste management sector that exists today, and was intended to capture their opinions and perceptions of the current situation. While these individuals have important experience and insight into the sector, they are also likely limited in their knowledge in some ways. For example, they may have incomplete knowledge about the ways that the sector will be changed—perhaps even transformed—by future changes in external factors (e.g. energy prices, political factors) and internal factors (e.g. new technologies). These results, therefore, do not cover—and were not intended to cover—all possible needs for organic management in Washington State. Despite this limitation, the survey should provide important insight into the perceptions and opinions of the organic residuals management sector as it currently exists. As such, it also provides an understanding of the strategies that may be most likely to find a receptive audience and willing partners.

Within this report, results are provided in two formats: as a summary bar chart, and as a table. Bar charts should be interpreted carefully. For questions where respondents indicated the degree of their opinion (e.g. benefits realized have been very little, little, some, big or very big), an average response was computed by converting each level to a number (e.g. very little=1, little=2, some=3, big=4, very big=5). This process *assumes* that respondents think of the difference between “very little” and “little” to be the same as the distance between all other responses, an assumption that may or may not be valid (Dillman et al., 2009). However, because this process also helps to provide a graphical representation that allows for readers to quickly grasp the overall degree of sentiment, authors decided that this approach was justified. Readers should, however, refer to the tables as well as the bar charts to fully understand the survey results.

Statistical differences between responses—identified with different letters (e.g., a, b, c) in all tables and figures—can either result from differences in the overall opinion of respondents, or from differences in the distribution of responses. For example, in the hypothetical results shown below, the “average” response is very different for element X and element Y (Figure 1.2). That is reflected in the statistical analysis, which indicates (in this case with a 95% certainty) that these results would be unlikely to occur just by chance if the opinion was the same. Thus, responses are likely a reflection of a real difference of opinion, rather than chance.

However, there are other ways that the population could differ than in the strength of the overall opinion. In the hypothetical results shown in Figure 1.3, you can see that the “average” strength of opinion is very similar for element W and element Z, but these two elements are still distinguishable statistically. By looking at the results in the table (Table 1.1), you can see that the results differ because the distribution of responses is different.

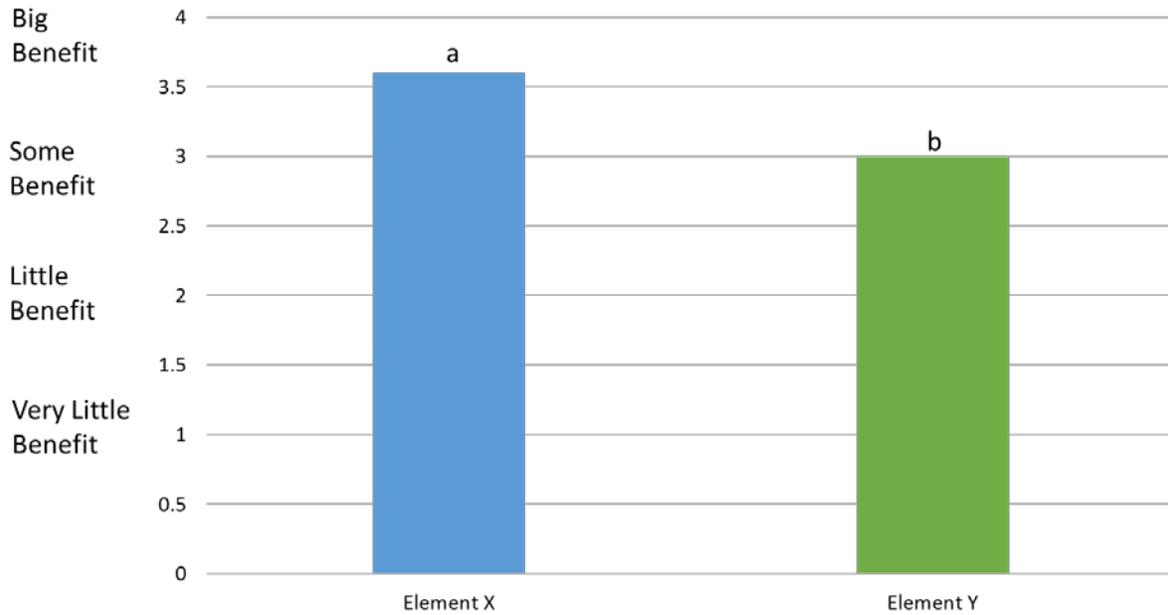


Figure 1.2: Hypothetical results showing how big of a benefit two different elements of organics management (X and Y) provide to Washington State. Results with the same letter are statistically similar, as indicated by Fisher’s exact test at $p < 0.05$.

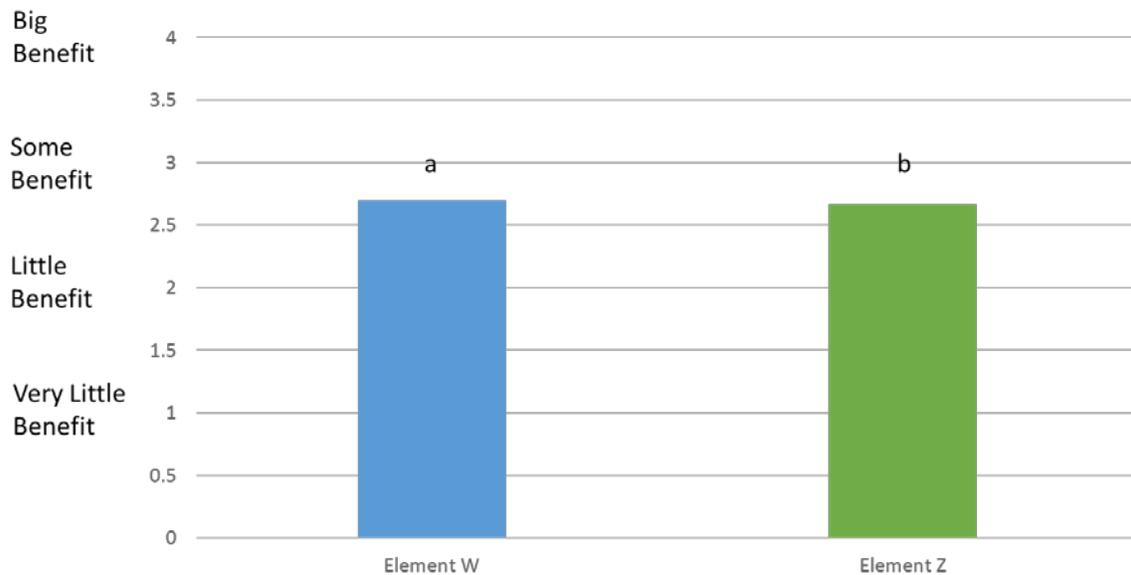


Figure 1.3: Hypothetical results showing how big of a benefit two different elements of organics management (W and Z) provide to Washington State. Results with the same letter are statistically similar, as indicated by Fisher’s exact test at $p < 0.05$.

Table 1.1: Hypothetical results showing how big of a benefit two different elements of organics management (W and Z) provide to Washington State. Results with the same letter are statistically similar, as indicated by Fisher’s exact test at $p < 0.05$.

Element of Washington’s organics management system	Very Big Benefit	Big Benefit	Some Benefit	Little Benefit	Very Little Benefit	Not Sure/No Opinion	Total Responses
	%	%	%	%	%	%	Number
Element W (a)*	0.8	5.9	53.0	21.0	6.3	13.0	253
Element Z (b)	1.2	10.3	35.2	24.1	7.1	22.1	253

*Answers followed by the same letter are not statistically different at the $p < 0.05$ level, as determined using the chi-squared test (if expected values were all equal to or greater than 5) or Fisher’s exact test (if this condition was not met).

1.5.4 Survey results and discussion

The questions asked in the survey were designed to provide insight into five key questions:

- What is the **current status** of organics management in Washington?
- What are the **barriers** preventing better management of organics?
- What are the **priority areas for action** to improve organics management?
- What do people working across the organics management sector think is the **most productive scale and complexity** for future organics management?
- What **research questions** would respondents like answered?

Full results reflecting on survey questions in each of these topic areas are available in Appendix D. Rather than discussing each question sequentially, this chapter highlights some of the broader lessons learned through the survey, illustrated with corresponding results.

1.5.4.1 What benefits are currently being realized?

Respondents were asked their opinion about which known benefits of organics management systems they felt have been realized in Washington (Question 1, Appendix B; Figure 1.4 and Table 1.2).

The benefits that respondents felt are currently being realized to the greatest extent (Figure 1.4 and Table 1.2) are:

- Improved soil quality and structure; and
- Reduced demand for landfill space.

Results clearly showed that respondents did not think that renewable energy production benefits are currently being realized (Figure 1.4). This is notable because this is an important goal of the Waste to Fuels Technology Transfer Partnership.

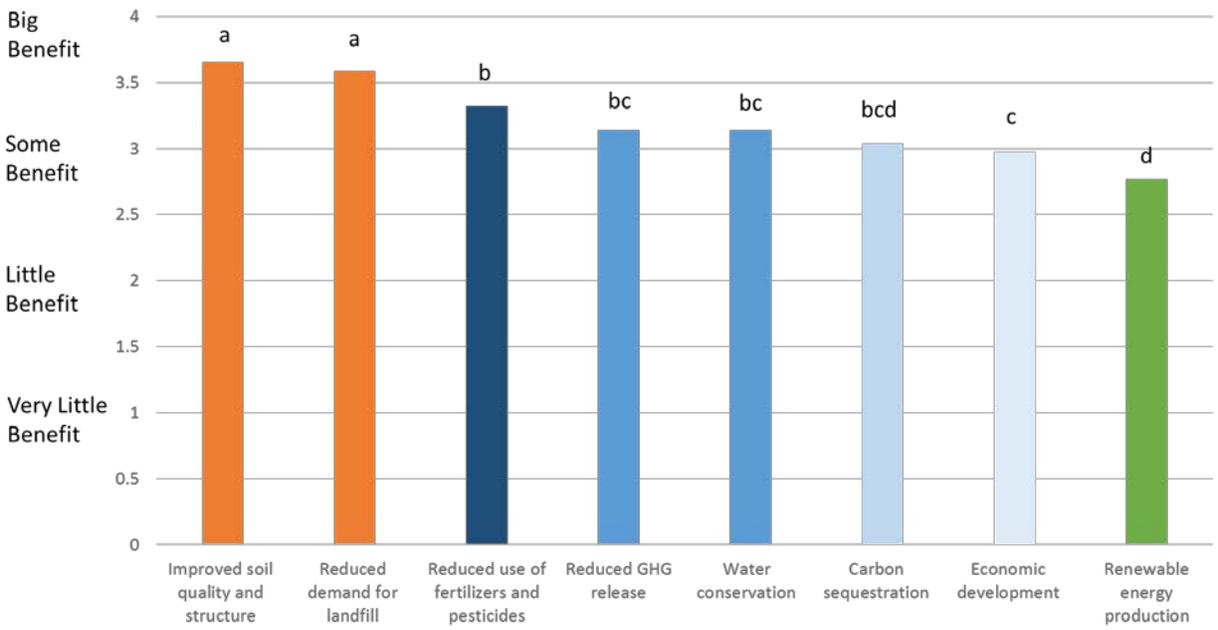


Figure 1.4: Extent to which respondents considered each benefit of Washington’s organics management system has been achieved. Elements followed by the same letter are not statistically different at the $p < 0.05$ level, as determined using the chi-squared test (if expected values were all equal to or greater than 5) or Fisher’s exact test (if this condition was not met).

Follow-up interviews asked nine key individuals working across the organics management sector to comment on what evidence there is that improved soil quality and structure is being achieved. One interviewee wrote that the survey results may reflect a general trend in knowledge that compost use is known to provide soil quality improvements on a site basis more than any proof that we have achieved soil structure or quality improvements on a regional or statewide basis. “The more organics use—especially on agricultural soils—becomes commonplace and talked about, the more realization [there is] of how depleted our soils have become, the more compost and organics will be used.” Another noted that as the acreage of organic and natural production systems has increased, so has demand for valuable and unique inputs. Many interviewees noted that there is a considerable regional body of research indicating that application of recycled organics (e.g. biosolids, compost) to soils improves a range of soil quality indicators (e.g. soil organic matter, microbial activity, water holding capacity).

Table 1.2: Percentage of respondents who considered benefits of Washington’s organics management system were being achieved at different levels. Benefits are organized from those considered largest (top row) to smallest (bottom row).

Benefit	Very Big Benefit	Big Benefit	Some Benefit	Little Benefit	Very Little Benefit	Not Sure/ No Opinion	Total Responses
	%	%	%	%	%	%	Number
Improved soil quality and structure (a)*	22.7	27.5	30.1	7.4	3.0	9.3	269
Reduced demand for landfill space (a)	18.9	28.2	32.2	6.3	3.7	10.7	270
Reduced use of chemical fertilizers and pesticides (b)	16.0	21.3	28.7	13.8	6.0	14.2	268
Reduced release of greenhouse gases (bc)	12.6	14.5	31.6	13.8	7.4	20.1	269
Water conservation (bc)	9.6	20.0	32.6	14.4	6.7	16.7	270
Carbon sequestration in plants, trees, or soils (bcd)	9.4	13.6	28.3	18.1	5.7	24.9	265
Economic development (c)	6.3	14.9	41.0	16.0	6.7	14.9	268
Production of renewable energy (d)	6.7	13.1	31.1	21.4	12.4	15.4	267

*Answers followed by the same letter are not statistically different at the $p < 0.05$ level, as determined using the chi-squared test (if expected values were all equal to or greater than 5) or Fisher’s exact test (if this condition was not met).

1.5.4.2 What benefits are priorities?

Using the same benefits discussed in the previous section, survey respondents were also asked how big of a priority they felt these benefits were (Question 14, Appendix B; Figure 1.5 and Table 1.3). Four benefits were highlighted as being of higher priority (Figure 1.5):

- Improved soil quality and structure;
- Water conservation;
- Reduced use of chemical fertilizers and pesticides; and
- Production of renewable energy.

Comparing the results in this and the previous section, there are several benefits—notably improved soil quality and structure, and reduced use of chemical fertilizers and pesticides—which are both high priority and survey respondents felt were being realized to a greater extent. Meanwhile, there are other benefits that respondents felt are not being achieved, although they are priorities. For example, respondents felt that water conservation is very important, but that it is being realized to a lesser extent. They also felt that renewable energy production was an important priority, and not being realized.

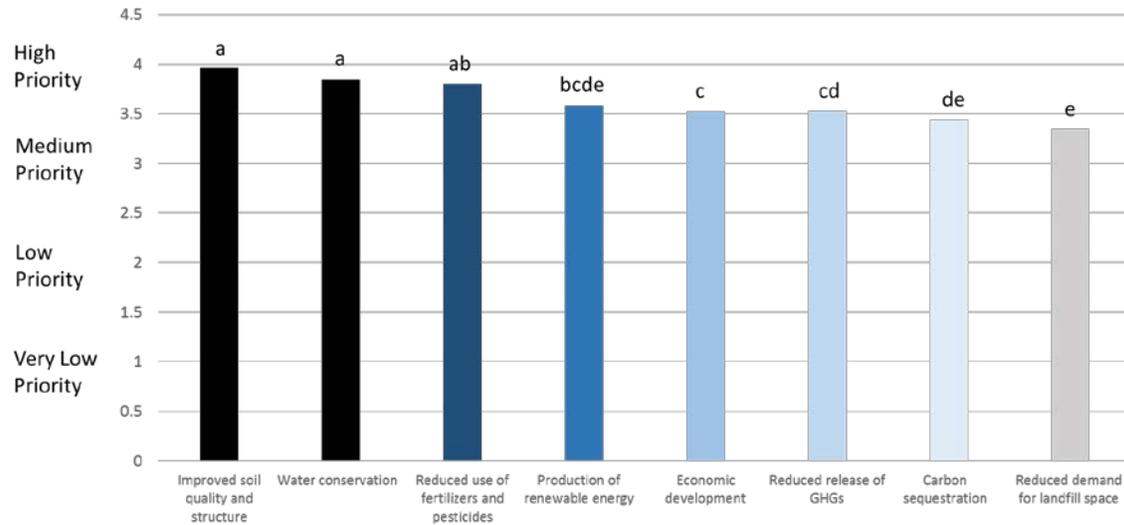


Figure 1.5: Extent to which respondents thought each benefit was a priority for investment of public resources. Elements labeled with the same letter are not statistically different at the $p < 0.05$ level, as determined using the chi-squared test (if expected values were all equal to or greater than 5) or Fisher’s exact test (if this condition was not met).

Table 1.3: Percentage of respondents who ranked each benefit as a certain priority for investment of public resources. Benefits are organized from those considered highest priority (top row) to lowest priority (bottom row).

Benefit	Very High Priority	High Priority	Medium Priority	Low Priority	Very Low Priority	Not Sure/No Opinion	Total Responses
	%	%	%	%	%	%	Number
Improved soil quality and structure (a)*	30.7	37.7	24.2	3.7	0.8	2.9	244
Water conservation (a)	24.3	41.6	23.5	4.9	2.1	3.7	243
Reduced use of chemical fertilizers and pesticides (ab)	27.4	35.5	25.7	4.9	3.7	2.9	245
Production of renewable energy (bcde)	20.5	35.3	25.0	10.3	4.9	4.1	244
Economic development (c)	15.6	33.7	32.5	9.1	3.3	5.8	243
Reduced demand for landfill space (cd)	12.3	34.8	29.1	13.5	6.2	4.1	244
Carbon sequestration in plants, trees, or soils (de)	17.8	26.5	22.7	14.5	5.0	13.6	242
Reduced release of greenhouse gases (e)	22.5	30.6	24.1	11.4	6.9	4.5	245

*Elements followed by the same letter are not statistically different at the $p < 0.05$ level, as determined using the chi-squared test (if expected values were all equal to or greater than 5) or Fisher’s exact test (if this condition was not met).

1.5.4.3 Barriers preventing more effective organics management

Respondents were asked to rate the extent to which they felt a variety of issues were barriers preventing better management of organics in Washington (Question 10, Appendix B; Figure 1.6 and Table 1.4). They were subsequently given an open-ended opportunity to mention barriers that they felt had been omitted from this list, or to comment about the elements that were provided (Question 11, Appendix B).

These barriers have been frequently discussed in recent years, both within and outside of Ecology. Available evidence also supports the fact that these are major barriers. For example, in a 2014 survey of 44 Snohomish County farmers using compost, 9 mentioned that there were plastics in the compost, and a third selected “reduce plastic contamination in finished compost” when asked how composters could help address challenges farmers have to using compost (Corbin et al., 2014).

It was not surprising to find that respondents in the organics management sector felt that NIMBYism (neighbor opposition; the name comes from the acronym to “Not In My Back Yard”), contamination, and odors, were major barriers preventing better management of organics in Washington (Figure 1.6 and Table 1.4). These barriers have been frequently discussed in recent years, both within and outside of Ecology. Available evidence also supports the fact that these are major barriers. For example, in a 2014 survey of 44 Snohomish County farmers using compost, 9 mentioned that there were plastics in the compost, and a third selected "reduce plastic contamination in finished compost " when asked how composters could help address challenges farmers have to using compost (Corbin et al. 2014).

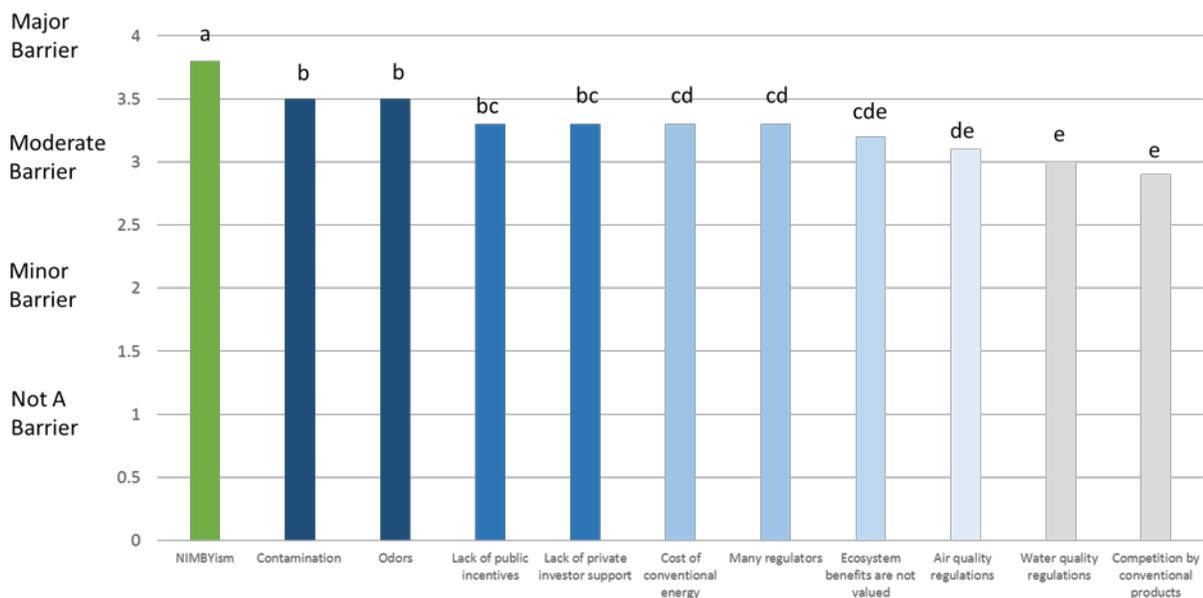


Figure 1.6: Extent to which respondents considered each issue a barrier preventing better management of organics in Washington. Elements with the same letter are not statistically different at the $p < 0.05$ level, as determined using the chi-squared test (if expected values were all equal to or greater than 5) or Fisher’s exact test (if this condition was not met).

In addition to these top three well-recognized barriers, lack of private investor support was seen as an important barrier by those who had an opinion. For this barrier, 26% of respondents said they were not sure or had no opinion about this barrier, indicating that further investigation may be merited (Table 1.4). Meanwhile, while regulations were barriers, respondents overall did not feel that they were the most important barrier (Figure 1.6).

Table 1.4: Percentage of respondents who considered different issues were barriers preventing better management of organics in Washington. Barriers are organized from those considered biggest (top row) to smallest (bottom row).

Barrier	Extreme Barrier	Major Barrier	Moderate Barrier	Minor Barrier	Not a Barrier	Not Sure/No Opinion	Total Responses
	%	%	%	%	%	%	Number
Neighbor opposition (NIMBYism) (a)*	27.5	35.9	21.5	9.2	1.2	4.8	251
Contamination in recycled organics products (b)	11.2	37.5	28.7	11.6	1.2	10.0	251
Odors associated with managing organic residuals (b)	12.0	39.0	29.5	15.6	1.6	2.4	251
Lack of public incentives (bc)	8.4	30.1	30.5	14.9	2.8	13.3	249
Lack of private investor support (bc)	7.6	25.3	22.9	14.9	3.2	26.1	249
Cost of conventional energy is relatively low (cd)	12.5	24.9	26.1	15.7	4.4	16.5	249
Different agencies of government regulate different organic residuals (cd)	12.5	25.3	30.5	15.7	4.4	11.7	251
Lack of value given to ecosystem benefits (cde)	10.0	24.9	32.9	16.1	6.0	10.0	249
Air quality regulations (de)	11.6	17.5	35.1	20.3	4.0	11.6	251
Water quality regulations (e)	8.4	17.2	34.8	22.0	7.2	10.4	250
Cannot compete with conventional products (e)	6.4	18.0	30.8	24.4	6.4	14.0	250

*Elements followed by the same letter are not statistically different at the $p < 0.05$ level, as determined using the chi-squared test (if expected values were all equal to or greater than 5) or Fisher's exact test (if this condition was not met).

Categorization of open-ended responses indicated a number of potentially important barriers that were not included in the multiple-choice question (identified in bold in the list of barriers mentioned, below):

- Regulations (27 mentions)
- **Lack of public awareness (24)**
- **Costs and economics (including transportation costs) (17)**
- NIMBYism (16)
- Contamination (16)
- Invest or fund incentives (14)
- Low energy costs/competition from conventional products and disposal options (14)
- **Scale issues (12)**
- **Innovation and technology development (12)**
- Odor (7)
- **Program direction and focus (5)**
- **Industry problems (5)**
- **Research (4)**
- **Low demand or low product quality (2)**
- **Lack of government leadership (1)**
- **Nutrient issues (1)**

In particular, lack of public awareness, costs and economics (including transportation costs), scale issues, and innovation and technology development each were mentioned 12 or more times, and may merit further attention. Responses to this question are provided in their entirety in Appendix E.

1.5.4.4 Priority areas for action to improve organics management

The survey asked individuals how big of a benefit they thought would be gained from resolving a variety of potential challenges to better organics management in Washington (Question 12, Appendix B; Figure 1.7 and Table 1.5).

Not surprisingly, the challenges that respondents felt would be most beneficial to solve included eliminating contamination, overcoming NIMBYism, and controlling odors and air pollution, the three top barriers (compare Figure 1.6 and Figure 1.7, above). However, there was also one additional challenge that rose to the top in terms of being beneficial to solve: getting more products made from recycled organics into use, especially by agriculture. Overcoming this challenge will likely require additional information (particularly as the survey did not do a good job capturing the opinions of end users of organic products), but it is clear that this is one priority that respondents feel would have a big impact.

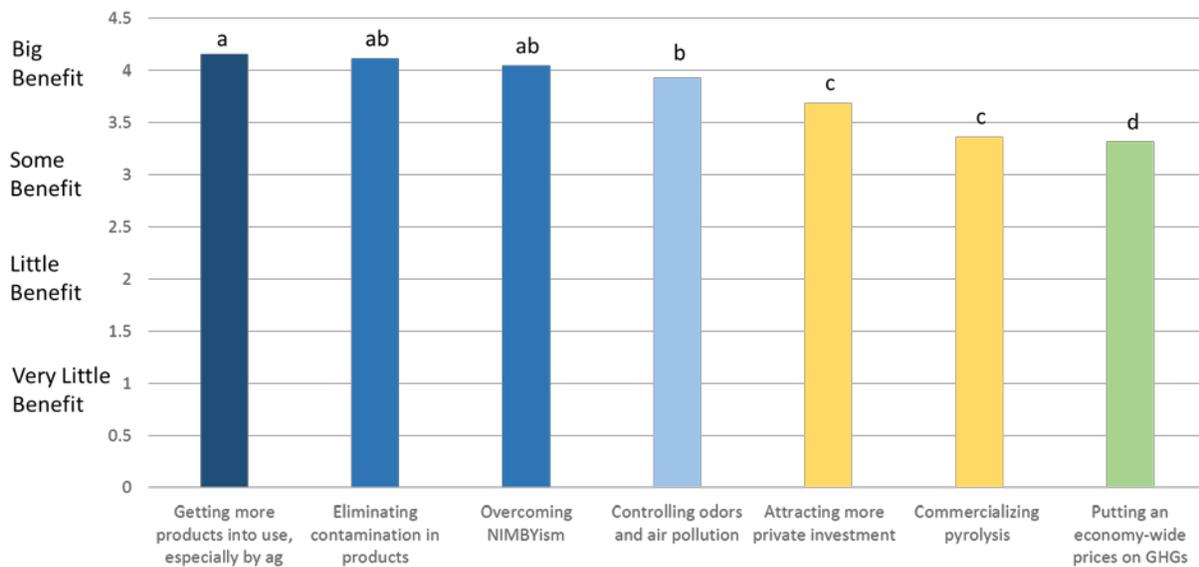


Figure 1.7: Extent to which respondents thought benefits could be gained from resolving challenges. Elements followed by the same letter are not statistically different at the $p < 0.05$ level, as determined using the chi-squared test (if expected values were all equal to or greater than 5) or Fisher’s exact test (if this condition was not met).

It is also interesting to note that the three challenges that survey respondents felt would be least beneficial to solve—attracting more private investment, commercializing pyrolysis, and putting an economy-wide price on carbon pollution—also had higher levels of “not sure/no opinion” responses than other challenges. This may indicate that more investigation is needed to determine whether or not solving these challenges would be impactful.

During post-survey interviews, individuals were asked specifically about addressing the challenge of contamination. More than one interviewee felt the current emphasis on downstream treatments (expensive new equipment and triple screening) may be insufficient. Several felt that resources would be better spent upstream, by keeping contaminants out of the organic material in the first place. Specific strategies mentioned included more education and training for voluntary compliance on the front end, rejecting unsatisfactory loads at the processing plant, requiring drivers to clean loads, and using other technologies to process food scrap streams, separate from or before composting.

Table 1.5: Percentage of respondents who considered different levels of benefits could be gained from resolving each challenge. Benefits are organized from those considered biggest (top row) to smallest (bottom row).

Benefit	Very Big Benefit	Big Benefit	Some Benefit	Little Benefit	Very Little Benefit	Not Sure/No Opinion	Total Responses
	%	%	%	%	%	%	
Getting more products made from recycled organics into use, especially by agriculture (a)*	35.1	44.1	14.3	1.2	1.2	4.1	245
Eliminating contamination in the recycled organics and products (ab)	35.1	38.8	18.8	1.6	0.8	4.9	245
Overcoming neighbor opposition (NIMBYism) (ab)	34.7	37.1	20.4	3.7	0.8	3.3	245
Controlling odors/air pollution from organics processing (b)	26.9	43.3	23.3	3.3	1.2	2	245
Attracting more private investment for organics recovery and processing (c)	21.2	28.6	27.4	5.3	3.3	14.3	245
Commercializing pyrolysis (lignocellulosic energy recovery/biochar) technology for woody materials (c)	13.2	21	26.8	7.8	6.2	25.1	243
Putting an economy-wide price on carbon pollution (greenhouse gases) (d)	21.7	20.9	18.0	11.1	13.1	15.2	244

*Elements followed by the same letter are not statistically different at the $p < 0.05$ level, as determined using the chi-squared test (if expected values were all equal to or greater than 5) or Fisher's exact test (if this condition was not met).

1.5.4.5 Scale and complexity for future organics management

Respondents were asked to consider all elements of organics management and then asked how much they agreed with the need to put greater emphasis on three different aspects of organics management (Questions 7 to 9, Appendix B). Respondents mostly “strongly agreed” with two of the statements, related to emphasizing successful source-separation and public participation, and to emphasizing economically managing organic residuals closer to their source. Agreement was more muted for the third statement, which was about emphasizing integrating additional technologies to produce green energy and other products in centralized facilities (Figure 1.8 and Table 1.6).

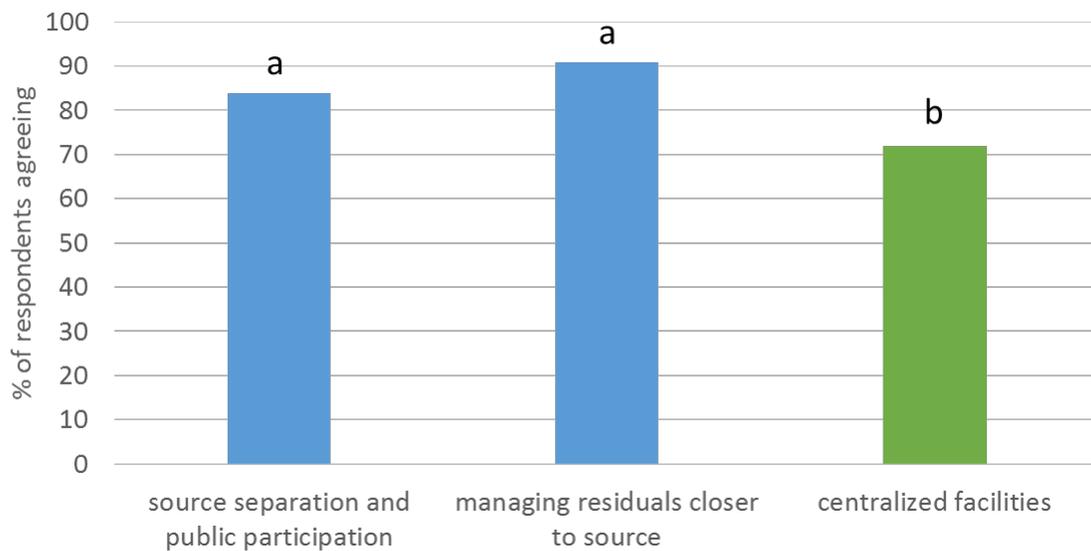


Figure 1.8: Extent to which respondents agreed with statements related to the scale and complexity of organics management. Questions labeled with the same letter are not statistically different at the $p < 0.05$ level, as determined using the chi-squared test (if expected values were all equal to or greater than 5) or Fisher’s exact test (if this condition was not met).

The researchers also asked questions about scale and complexity during follow-up interviews. Responses were quite diverse. Several interviewees said that a mix of large, more complex facilities and smaller facilities was likely important, depending on the location within the state, and the sources of waste generation and recycled organics used. One interviewee pointed out that the appropriate scale might also depend on the feedstock (e.g. separating food scraps and processing them separately in a smaller scale urban anaerobic digester may make sense as opposed to adding them to the compost feedstock stream). Another interviewee suggested that smaller, more decentralized facilities should be emphasized, because of a lower carbon footprint; more direct community engagement, support, and ownership; and less dependence on any single facility.

Table 1.6: Percentage of respondents who agreed to different degrees with statements related to the scale and complexity of organics management. Statements are organized from those for which there was highest agreement (top row) to lowest agreement (bottom row).

Level of scale and complexity	Strongly Agree	Agree	Somewhat Agree	Somewhat Disagree	Disagree	Strongly Disagree	Not Sure/ No Opinion	Total Responses
	%	%	%	%	%	%	%	Number
Greater emphasis on successful source-separation and public participation (a)*	39.8	30.3	13.6	2.4	2	0	12	251
Greater emphasis on economically managing organic residuals closer to their source (a)	40.9	36.9	13.1	3.2	1.2	2	2.8	252
Greater emphasis on integrating additional technologies to produce green energy and other products in centralized facilities (b)	17.9	30.6	23.4	11.5	7.9	1.6	7.1	252

*Questions followed by the same letter are not statistically different at the $p < 0.05$ level, as determined using the chi-squared test (if expected values were all equal to or greater than 5) or Fisher's exact test (if this condition was not met).

Together, these results suggest that there is not clear agreement about the most appropriate level of scale and complexity for organics processing facilities in Washington, though it is important to keep in mind that the answer may be different in different locations. There is also some suggestion that the organics management sector in Washington as a whole may not yet be well educated about the biorefinery concept, which incorporates a number of different organics processing technologies at a single facility, nor is there good understanding of the circumstances under which this may make sense. Scale and complexity (along with transportation and economics) also came up as an important area of inquiry when survey respondents were asked about impactful research questions, discussed in the following section.

1.4.4.6 Most impactful research questions to answer

Respondents were asked to articulate up to three questions about organics management that they would like research to answer (Question 13, Appendix B; these responses are provided in their entirety in Appendix F). Responses were categorized, and then grouped based on the number of times questions in each category were asked. Questions were placed in a single category; thus it is important not to over-interpret the rankings provided here. For example, questions about processing and scale sometimes included mention of one or more specific technologies, but were generally placed with processing and scale.

Categories of questions with the highest combined mentions (more than 12)

- *Contamination*, including source separation, materials ban (e.g., non-recyclable plastics), physical and chemical contamination, and the fate of organic contaminants in the soil (mentioned 18 times).
- *Scale of technology* and possible benefits of *distributed or decentralized* processing closer to the source (16 mentions).
- *Recycled organic products*, including product economics, market research and development, and the development of advanced products for specialized applications (15 mentions).
- *Economic issues*, with special focus on finished products and the cost of transporting raw feedstocks (14 mentions).
- *Odors*, including odor testing and standards and their impact on neighbors (14 mentions).
- *Benefits* of and the potential for using compost and other recycled organics (e.g., from anaerobic digestion (AD), pyrolysis, biosolids) *in agriculture* (13 mentions). Note that this category is closely related to the recycled organic products category, above. While we could have grouped this with recycled organics products, we chose to keep this category separate, as the issue of use of organics products in agriculture was already noted as important in a multiple choice question (see Figure 1.7 and Table 1.5, above).

Categories of questions with moderate combined mentions (between 7 and 12)

- *Life-cycle assessments* (LCA), including LCA comparisons of processing methods and technologies, as well as LCA comparisons of different recovery strategies (12 mentions).
- *Anaerobic digestion* and related issues, including co-digestion, biogas utilization, nutrients, wastewater treatment plants, and food scrap digesters (11 mentions).
- *Policy*, including carbon taxes, incentives and other policy-related issues (11 mentions).
- *Pyrolysis* and *biochar* (9 mentions).

- *Regulatory issues*, including making improvements to the regulatory system and practice (9 mentions).
- *Composting*, including nutrient retention, economics, compostable plastics, and optimizing process for different environmental conditions and feedstocks (7 mentions).

Categories of questions with lowest combined mentions (less than 7)

- *Concentrated animal feeding operations' (CAFOs) manure management*, including manure nutrient balances, application rates, and improving water quality (6 mentions).
- *Soils*, including valuation and impacts of organic amendments (5 mentions).
- *Promotion and public education* (5 mentions).
- *Biorefinery*, including work on anaerobic digestion plus composting, and other combinations of organics technologies or categories (4 mentions).
- *Biosolids* (4 mentions).
- *Financing and funding*, including funding for new technologies (4 mentions).
- *Waste reduction efforts* (4 mentions).
- *NIMBYism*, and how to overcome it (3 mentions).
- *Greenhouse gases* (2 mentions).
- *Bioretention systems* (2 mentions).
- *Carbon sequestration* (2 mentions).
- *Minimal processing* (1 mention).
- *Organics inventory* (1 mention).
- *Incineration* (1 mention).

There are multiple recurring themes among these results. Several of the topic areas receiving a large number of mentions relate to the products from organics technologies (e.g. contamination, recycled organic products, benefits of compost and other products in agriculture). In addition, questions about scale—including the specific technologies appropriate at various scales—economics, and transportation or transportation costs were somewhat inter-related, and represent a second area with high levels of interest. Third, there were a large number of questions about specific technologies for processing organics (anaerobic digestion, pyrolysis, composting) and about comparing or combining technologies, with a focus on life-cycle assessments.

To further explore the frequent product-related questions, researchers asked follow-up interviewees what needs they saw for ongoing technology research related to contamination, product development, and agricultural use of compost. Research topics the interviewees identified included:

- Research that compares economic costs and performance of various strategies for addressing contamination, as well as potential funding mechanisms.
- Research about persistent chemical contaminants in recycled organic products (e.g. biosolids, compost), including acceptable background levels, levels of natural occurrence, and additional buildup from recycled organic products.
- The amount of organics needed to attain various levels of improvement in soil quality in various applications (including agricultural).
- Research about how the impact of various compost applications varies with different soil types.

- Research on storm water low impact development (LID) use, including the development of blends.
- Research into microbiological population dynamics during composting, curing, and application, especially as it relates to plant pathogen reduction and nutrient optimization. Can specific feedstocks and processing methodologies be used to develop a compost with high pathogen-reduction qualities for particular pathogens and crops?
- Research into biochar and compost blends.
- Research that investigates whether transporting organics spreads disease and pathogens.
- Research that supports reduction of regulatory hurdles (e.g., flat bans on outdoor furnaces that could produce biochar, heat and energy, bans on industrial hemp).
- More research on agriculturally related compost use and improvements, as much of this research is from the urban horticulture world.
- Research showing the costs and benefits of moving urban organics back to rural agricultural production. This could include valuations of the improvements to soil quality and moisture retention, as well as other factors.
- Research into possible policies and price supports that might provide incentives for wider agricultural use. Specific approaches mentioned that could be investigated include (but are not limited to) clarifying what price supports already exist for farmers or for chemical fertilizers and how they might be applied to organics, and investigations into whether the solid waste tax could be used to subsidize the use of compost on farms.
- A multi-year compost trial and significant work to evaluate the nutrient release of compost over the short term and long term. This work could build upon existing research trials being carried out by WSU Snohomish County Extension.
- Trials specifically examining the nutrient implications of fall compost applications, including questions about nutrient needs, use of cover crops, and whether compost positively or negatively impacts existing concerns about water quality and nutrient leaching.
- Research on leaching of nutrients from compost application, specifically phosphorus.
- Research examining the impacts of compost application on pesticide and fungicide practices.
- Research on compost teas, which have the potential to be incorporated into irrigation systems, potentially at a lower cost (though also potentially with smaller benefits) than compost.

Follow-up interviews also asked respondents whether scale and transportation were topics that technology research and development could provide some insight into, and if so, what areas would be most likely to make a difference. While some respondents felt that there was likely little that *technology* research could do, others mentioned:

- Research into odor issues, which can be related to scale.
- Research into distribution system options, such as the possibility of satellite sites where finished compost would be stockpiled on a farm or other decentralized site.
- Tools and technology to improve handling, transporting and processing.
- Life-cycle analyses of combined organics processing options (e.g. composting, AD-composting, biochar-AD-composting), looking at environmental, economic, resource, and social impacts.

Many additional specific research questions were provided by survey respondents, and are included in Appendix F.

1.6 Conclusions

Results from the survey of gaps, priorities, and research needs for organics management indicated that there are several perceived benefits from improved organics management, such as improved soil quality and structure, and reduced use of fertilizers and pesticides. When interpreted in light of other survey results and in-depth surveys, it is likely that respondents feel that improved soil quality and structure is being realized when the products are applied, and not in areas where they are not applied. Survey respondents feel these benefits are high priorities, and are being realized to a great extent currently. Other high priority benefits—water conservation, renewable energy production—are being realized to a lesser extent.

Important barriers include both well-recognized ones, such as opposition to facilities from neighbors, contamination, and odors, and less-well recognized barriers, such as lack of investor support. Large numbers of survey respondents were unsure how big of a barrier lack of investor support was, indicating that additional investigation may be warranted. Lack of public awareness, costs and economics, scale issues and innovation and technology development were additional barriers not included in the survey that respondents mentioned frequently in open-ended responses. These may therefore also merit additional study.

Not surprisingly, survey respondents felt that addressing opposition to facilities from neighbors, contamination, and odors would be likely to provide a big benefit to organics management. In addition, getting more products into use by agriculture is seen as an achievement that would provide a big benefit—in fact, a larger benefit than any other challenge. There were also several challenges (attracting more private investment, commercializing pyrolysis, putting an economy-wide price on greenhouse gases) which survey respondents had high levels of uncertainty or no opinion about.

When asked, respondents provided a large number of specific questions about organics management that they would like research to answer, covering a diverse range of topics. Among these, there were many questions relating to the products from various organics recovery technologies, including those touching on contamination, technology development, economics and marketing, using compost and other recycled organics in agriculture. A second area of interest included questions related to scale and economics for organics processing, such as transportation and transportation costs for both feedstocks and products. Third, there were a large number of questions both about specific technologies for processing organics—anaerobic digestion, pyrolysis, composting—and about comparing or combining technologies, with a focus on life-cycle assessments.

1.7 References

- Altschuld, J. 2004. Emerging Dimensions of Needs Assessment. Performance Improvement, Vol. 43, No. 1. Available online at www.ispi.org.
- Brown, S., Kruger, C.E., Subler, S. 2008. Greenhouse Gas Balance for Composting Operations. *Journal of Environmental Quality* 37, 1396-1410.
- Brown, S., Kurtz, K., Bary, A., Cogger, C. 2011. Quantifying benefits associated with land application of organic residuals in Washington State. *Environmental Science and Technology* 45, 7451-7458.
- Corbin, A., Harness, H., Kintzi, J. 2014. Compost use in agriculture, research and demonstration project. Snohomish County Extension, Washington State University. Everett, WA. Available at <http://ext100.wsu.edu/snohomish/compost/>.
- Cordell, D., Drangert, J.O., White, S. 2009. The story of phosphorus: Global food security and food for thought. *Global Environmental Change* 19, 292-305.
- Dillman, D.A., Smyth, J.D., Christian, L.M. 2009. *Internet, Mail, and Mixed-Mode Surveys: The Tailored Design Method*, Third Edition. John Wiley and Sons, Inc. Hoboken, NJ.
- Frear, C.S., Yorgey, G.G. 2010. Introduction to anaerobic digestion. Chapter 2 in Research Report 2010-001. Center for Sustaining Agriculture and Natural Resources, Wenatchee, WA. <http://csanr.wsu.edu/publications/researchreports/cffreport.html>.
- Kaufman, R. 1972. *Educational system planning*. Englewood Cliffs, NJ: Prentice-Hall.
- Kaufman, R. 1988. *Planned educational systems: A results-based approach*. Lancaster, PA: Technomic.
- Kaufman, R. 1999. *Mega planning: Practical tools for organizational success*. Thousand Oaks, CA: Sage Publications.
- Kaufman, R., Oakley-Brown, H., Watkins, R., Leigh, D. 2003. *Strategic planning for success*. San Francisco: Jossey-Bass/Pfeiffer.
- Kaufman, R., Rojas, A.M., Mayer, H. 1993. *Needs assessment: A user's guide*. Educational Technology Englewood Cliffs, NJ.
- Masse, D.I., Talbot, G., Gilbert, Y. 2011. On farm biogas production: A method to reduce GHG emissions and develop more sustainable livestock operations. *Animal Feed Science and Technology* 166-167, 436-445.
- McConnell, D.B., Shiralipour, A., Smith, W.H. 1993. Agricultural impact – compost application improves soil properties. *Biocycle* 34 (4), 61–63.
- Silva, M.T.B., Menduina, A.M., Seijo, Y.C., Viqueira, F.D.F. 2007. Assessment of municipal solid waste compost quality using standardized methods before preparation of plant growth media. *Waste Management Research* 25 (2), 99–108.
- Ecology. 2009. *Beyond Waste Plan, 2009 Update: Summary of the Washington State Hazardous Waste and Solid Waste Management Plan*. Publication No. 09-07-026. Washington State Department of Ecology, Olympia, WA. Available online at <https://fortress.wa.gov/ecy/publications/summarypages/0907026.html>.
- Ecology. 2010. *2009 Washington Statewide Waste Characterization Study*, completed by the Washington Department of Ecology and Cascadia Consulting Company. Washington Department of Ecology Publication 10-07-023. Available online at <https://fortress.wa.gov/ecy/publications/documents/1007023.pdf>.
- Ecology. 2015. *The State Solid and Hazardous Waste Plan - Moving Washington Beyond Waste and Toxics*. Publication No. 15-04-019. Washington State Department of Ecology,

Olympia, WA. Available online at

<https://fortress.wa.gov/ecy/publications/SummaryPages/1504019.html>.

Yorgey, G.G., Frear, C.S., Kruger, C.E., Zimmerman, T.J. 2014. The rationale for recovery of phosphorus and nitrogen from dairy manure. Washington State University Extension Fact Sheet FS136E. Washington State University, Pullman, WA. Available online at <http://cru.cahe.wsu.edu/CEPublications/FS136E/FS136E.pdf>.

2. Converting Composting Facilities into Biorefineries

Manuel Garcia-Perez, Jesus Garcia-Nunez, Brennan Pecha, Craig Frear, Shannon Mitchell, Chad Kruger, and Liang Yu

2.1 Abstract

Researchers at Washington State University continued previous investigations of biorefinery concepts by evaluating the potential to integrate emerging technologies—pyrolysis for biochar production, pellet formation, and anaerobic digestion with compressed natural gas (CNG) production—into a baseline composting facility. This baseline facility is a hypothetical facility used to model realistic scenarios based on real scale inputs. The hypothetical composting facility was representative of a large size composting facility in Washington State processing 160,000 wet tons per year, with an assumed waste stream of 76.9% yard trimmings, 19.2% food scraps, and 3% wood. Material flow and economic calculations were done in Microsoft Excel, following the methodology recommended by Levis and Barlaz (2013), and were based on mass balance equations with performance indicators obtained from the literature. The economic analysis included capital costs, operation and maintenance costs, and revenue. The total capital investment to build the facility was estimated at \$28 million. The model indicated that if none of the capital cost was financed, the gross earnings would be \$6.3 million per year, and the net earnings (after taxes) would be \$4.0 million per year. If financed at 5.12% for 20 years, the capital cost would be \$2.3 million per year. Operation and maintenance costs would be \$4.8 million per year. Most of the revenue came from tipping fees (87%), with the rest from sales of the composted material (13%). The return on investment (ROI) was 14%, which is considered competitive with current commercial interest rates.

A literature review was conducted to better understand the benefits and limitations of integrating emerging technologies—AD, pyrolysis, and wood-fuel pellet production—with composting facilities. This review focused specifically on synergies between composting and emerging technologies. Anaerobic digestion can be effectively integrated with composting for treatment of decaying material. Pyrolysis—whose products include biochar, heat, and electricity—and pellet production can effectively integrate with composting for treatment of woody waste. Composting seems to have intrinsic advantages on the processing of blends of both materials. Anaerobic digestion is adept at treating waste either in a slurry or dry reactor. Slurry digesters can produce considerable amounts of liquid effluent, which could be problematic for the compost facility. However, the liquid effluent can be used as water inputs to the compost feedstock, compost piles, or nutrient recovery units. Nutrient recovery can be installed, leading to the recovery of saleable fertilizer and recycled water. The choice of AD and pyrolysis reactors is important to consider as the industry determines ultimate co-product characteristics and market values. Production of wood-fuel pellets, one of the most successfully traded biomass commodities, is promising: the main advantages of pellets are their high density, low moisture content, and high energy value.

Models were created for three emerging organic waste management technologies: pyrolysis for biochar production, pellet formation, and AD with CNG production. Different scenarios were analyzed to explore potential paths for the evolution of composting facilities into biorefineries, each considering an existing composting unit gradually adding emerging technologies. One set of scenarios compared adding pellet production vs. adding slow pyrolysis as alternatives for processing woody waste. Pellet production had the higher return on investment (88%), followed by pyrolysis for biochar and heat (46%) and pyrolysis for biochar and electricity (21%). All these returns were higher than the baseline composting facility's ROI (14%). The ROIs for the pyrolysis systems may be optimistic because the highest biochar market price for all char produced was assumed. In all cases the return on investment is competitive, suggesting that these technologies can increase the profit due to the higher value of the products obtained relative to compost. The second path to convert the composting facility into a biorefinery is to add an AD process for food scraps. A separate scenario was developed that considered adding an AD process capable of processing 120 tons of food scraps to the baseline composting facility. This concept had an ROI of 34%, which is higher than the ROI for the composting facility alone, although this ROI estimate does not include taxes and operations and maintenance costs. Even in this optimum case, the capital cost for the AD system (\$14.8 million) was significantly higher than the cost for pyrolysis or the cost for pellet production (\$2.1 and \$4.7 million, respectively). These results indicate that a less expensive AD system may be needed to more economically treat putrescible material, to initially stabilize the waste and capture energy prior to composting. However, both suggested paths—adding a woody-waste processing technology, or adding AD for energy capture—provided increases in profits, and in addition, would allow existing systems to process larger volumes of organics on a given land area, which may be important in an urban context.

These results suggest that well-designed biorefineries can achieve higher rates of return on investment than a composting facility, though those rates—as well as the associated capital costs—vary depending on the size of the plant, the feedstock used, and the emerging technologies that are integrated with the composting units.

2.2 Background

In 2010, the United States (US) generated approximately 250 million tons of municipal solid waste (MSW) (EPA, 2011). The Environmental Protection Agency (EPA) has suggested three general strategies for reducing the amount of MSW heading to landfills and incineration units, including (1) source reduction and reuse, (2) recycling and composting, and (3) energy recovery (EPA, 2013; Kreith, 1994). In the State of Washington, approximately 5 million tons of MSW is disposed of annually, with about 44% serviced through landfills. Other waste is recycled (21%), diverted (19%), composted (9%), or combusted (8%) (Ecology, 2010a; 2010b). While Washington has been comparatively successful in regards to landfill diversion, a significant portion of landfilled MSW is potential feedstock for additional diversion, particularly through organic waste recycling, as 2.7 million tons (55%) of organics, wood, and paper products are still moving as MSW into the landfill stream (Figure 2.1). Of these organics, food scraps (vegetative

and non-vegetative) represents about 18%—or 0.9 million tons of landfilled material (Ecology, 2010b).

While all diversion options are of interest for treatment of these residual organics and food scraps, composting is of particular interest as it is a robust technology capable of processing many types of organic wastes. However, with these additional flows and the growing interest in this diversion, many existing composting facilities are at or over their maximum capacities (Ecology, 2010a). With maximum capacity come processing concerns related to odors and plastic contaminants, requiring the development of new or larger compost facilities with improved processing capabilities. With increased flow and ever-growing concerns related to air and water quality, climate and contaminant issues, the pursuit of economies of scale in compost operations come to the forefront, introducing the concept of the compost facility as a biorefinery.

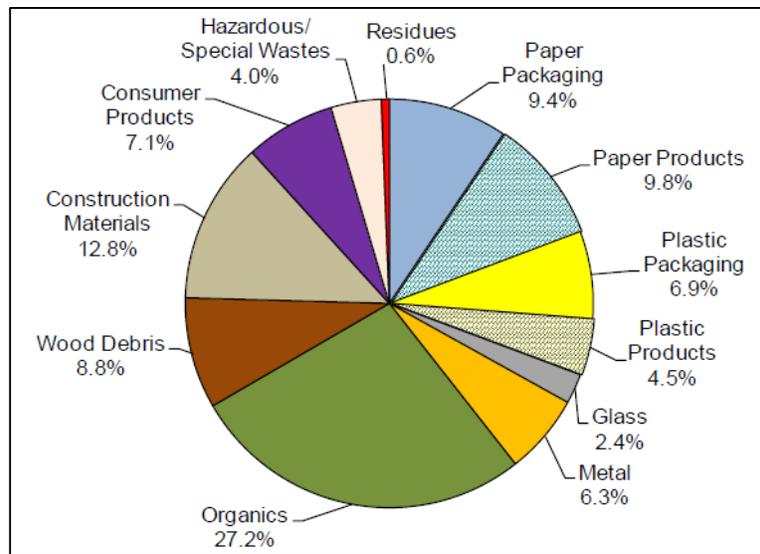


Figure 2.1: Disposed waste stream composition in Washington State in 2009 (Ecology, 2010b).

2.2.1 Composting

While composting facilities range from small to large in size, this report is focused on large facilities. There are 13 large composting facilities in Washington (Table 2.1) and 60 total regulated facilities. Overall, more than 1 million tons of feedstock is processed through composting facilities annually (Ecology, 2013). The largest facility is Cedar Grove in Maple Valley, WA, which processes 248,000 tons of organic waste per year.

On the economic side, the soil amendment market for the compost product is rather limited (Thorneloe et al., 2005; 2001; Thorneloe and Weitz, 2004; 2003), although tipping fees—or the money charged for waste drop-off—in urban areas can be significant, allowing for economic viability of these facilities. Feedstock commonly used at composting facilities is food scraps, yard and wood debris, and agricultural waste (Figure 2.2).

Table 2.1: Composting facilities in Washington State that received more than 20,000 tons of feedstock per year (Ecology, 2013).

Facility name	Feedstock composted (1,000 ton year⁻¹)
Cedar Grove (MV)	248.0
LRI	139.4
Cedar Grove, Everett	132.4
Pacific Top-soils	91.1
Boise White paper	70.6
Barr-tech	67.1
Silver Springs	64.3
Pierce Compost	54.8
Royal Organic	48.9
Lenz Enterprises	42.9
Nat. Selection Farms	39.5
Sunnyside Dairy	24.0
Green Hills farm	20.2

Large facilities accomplish their aerobic composting process through a variety of methodologies including windrow, aerated static pile (ASP), and in-vessel (e.g., GORE Cover System) (Sherman, 1999). Each of these methodologies cycles the processes through both mesophilic (<45°C) and thermophilic phases (45 to 80°C), but they differ in regard to their pile maintenance, aeration process and gaseous and moisture control methods (Ecology, 2011). Regardless of process choice, the compost process produces not just a finished compost product, but also leachate and gases or odors. Some contaminants, such as small plastic, also remain in the final compost.

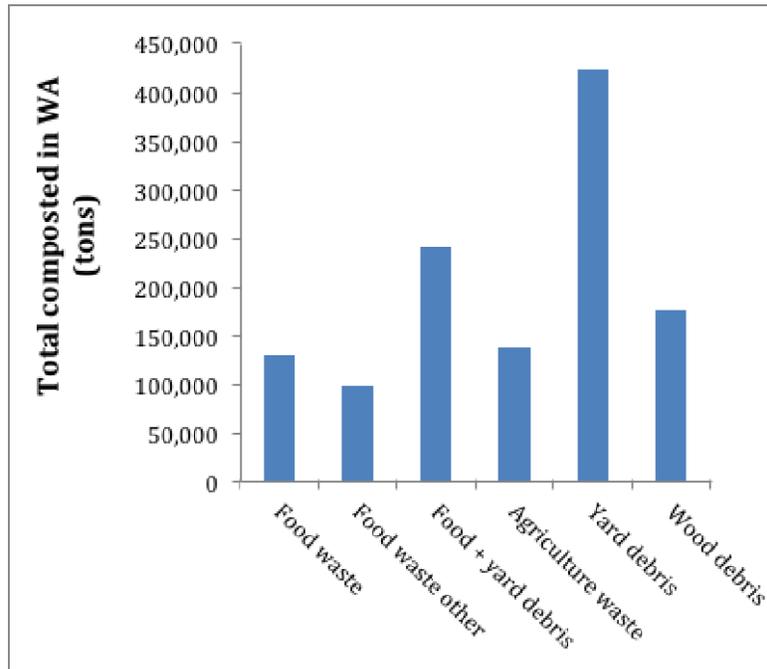


Figure 2.2: Common compost feedstock received by Washington facilities (Ecology, 2013).

The term “leachate” refers to liquid that passes through solids and extracts solutes as it percolates through the material. The leachate is recovered by drainage systems and then is collected in a treatment tank. Treatment methods involve removal of suspended solids, as well as the reduction of biochemical oxygen demand. The most common method for meeting suspended solids and biochemical oxygen demand specifications is to store leachate in settling chambers with an aeration method. The treated effluent can then be discharged from an overflow channel into main sewer drains or reused on-site. The sediment is usually landfilled or applied to the land as a soil amendment (Manser and Keeling, 1996).

Odor is a major concern. During the biological processing as much as half of the carbon and other elements (nitrogen and sulfur) are off-gassed as gases of a particularly noxious nature (Table 2.2). Odor issues have only grown more problematic as compost facilities, particularly those in municipal zones, are pushed towards the higher flow rates containing the more putrescent organic materials (i.e., food scraps and lawn clippings) that result from increased diversion programs (Ma et al., 2013a).

Table 2.2: Selected odorous compounds released during handling and decomposition of organic material (IWMB, 2007).

Compound	Odor Descriptor
<i>Volatile sulfur compounds:</i>	
Methyl-mercaptan	Pungent, cabbage, skunk, garlic
Hydrogen sulfide	Rotten egg
Diethyl sulfide	Pungent, garlic-like
<i>Volatile nitrogen compounds:</i>	
Skatole	Fecal, nauseating
Ethylamine	Ammonia-like, irritating
Ammonia	Pungent, sharp, irritating
<i>Volatile fatty acids:</i>	
Propionic acid	Rancid, pungent
Butyric acid	Rancid butter, body odor
<i>Terpenes:</i>	
α -Pinene	Sharp, turpentine
<i>Ketones and aldehydes:</i>	
Butanone	Sweet, solvent

Ultimately, the odor control strategy must address all facility activities that produce emissions. The control strategy therefore considers compost composition, material holding time, stockpiling protocols, materials handling, and site conditions (Ma et al., 2013a). Venting of active and curing compost gases to biofilters is the best available control technology when managing volatile organic compound (VOC) emissions (Card and Schmidt, 2012). There are two strategies for solving odor problems during active composting: (1) well-managed piles to limit anaerobic environments and the need for high air flow rates, and (2) capturing composting gases and

treating them with a biofilter (IWMB, 2007; Haug, 1993). In addition, incorporation of other technologies and facilities across all aspects of the compost yard can help control odor beyond those emitted from active piles (Ma et al., 2013a).

The effort to divert greater amounts of organics is increasing, as a result of collection from wider and more diverse waste collection points. The potential for contamination of compostable material is greater in this case. High levels of non-compostable material can lead to on-site trash control concerns. Importantly, contamination within the finished compost product is a concern for high-value compost (Barrows, 2011). Control methodologies can occur across multiple access points along the value chain, including controls at consumer and industry production sites and material recovery facilities. The use of picking stations (manual removal) and contaminant removal technologies at the composting facility is necessary for MSW feedstock (BioCycle, 2005).

In order to continue implementing composting at the large commercial scale, citizens need to be educated about the benefits of commercial composting and how it will affect them. Communities as well as associated industries increasingly aim to make their waste management model more “green” through a combination of technology enhancements and policy and regulation. University partners continue to develop new technologies and processes so as to solve existing challenges of MSW organic waste diversion, while also completing assessments detailing the *status quo*, emissions, and environmental concerns occurring at these facilities (McDonald, 2011).

As part of this assessment and focus on sustainable organics management, WSU researchers have begun to re-evaluate large composting facilities and to consider the possibility of a biorefinery. Biorefinery refers to an integrated system of technologies that maximize the use of waste streams and by-products for the production of multiple, valued co-products while also enhancing overall organics processing efficiency, the use of economies of scale, and the use of capital and labor. The overarching goal of a well-conceived biorefinery is to best address emerging environmental concerns—nutrients, energy, water, air, climate, food, and human health—in an economically viable manner.

2.2.2 Biorefinery

Washington State University researchers have developed a vision of a solids waste handling biorefinery (Figure 2.3). This vision includes a baseline composting facility with recycling of contaminants: metals, glass, plastics, and usable paper. It also emphasizes the use of additional technologies to more effectively treat particular organic streams reaching the facility. For example, anaerobic digestion can optimize wet and putrescent material treatment, and pyrolysis can optimize dry wood material treatment. By focusing treatment of particular feedstock to more ideal conversion technologies, important gains in emissions management is accomplished. Additional processing units are added in order to maximize co-products such as nutrient recovery, greenhouses, and biogas purification while also providing additional environmental gains.

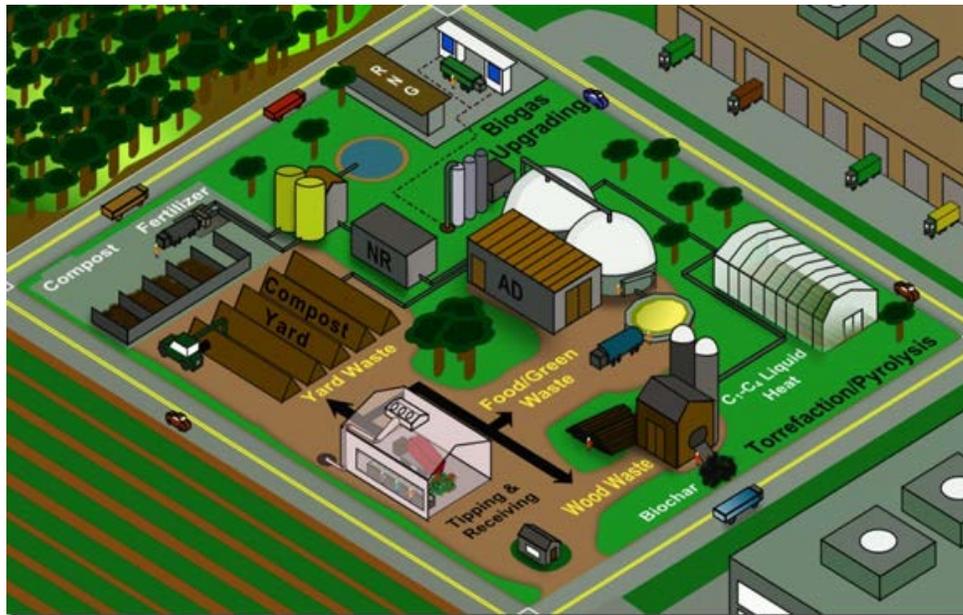


Figure 2.3: Composting biorefinery vision.

2.3 Objectives

To transform the organics waste management industry from its current form, based only on aerated compost pile systems, into an economically viable, integrated biorefinery, entrepreneurs need to understand the potential alternative technologies available and how to optimize their integration. They also need information that compares the integrated biorefinery to existing composting facilities, in terms of environmental and socio-economic components. The goals of this study were therefore to:

- (1) Set up a baseline compost model that characterizes the mass and energy balance of existing composting facilities,
- (2) Explore emerging technologies to integrate with a compost facility, and
- (3) Analyze these emerging technologies' mass and energy flow and economics.

The results of this project are expected to serve as a framework for a future composting biorefinery life cycle assessment to be completed in later biennium work.

2.4 Methods

This project's focus was the development of biorefinery model units to work with the baseline composting facility. Models were created for emerging organic waste management technologies: pyrolysis, pellet formation, and AD with CNG production. The strategy to evaluate compost biorefineries as a new technique to process organics from MSW are shown in Figure 2.4. First, the baseline composting model was created (Task 1). Then, emerging technologies were reviewed and modeled (Task 2).

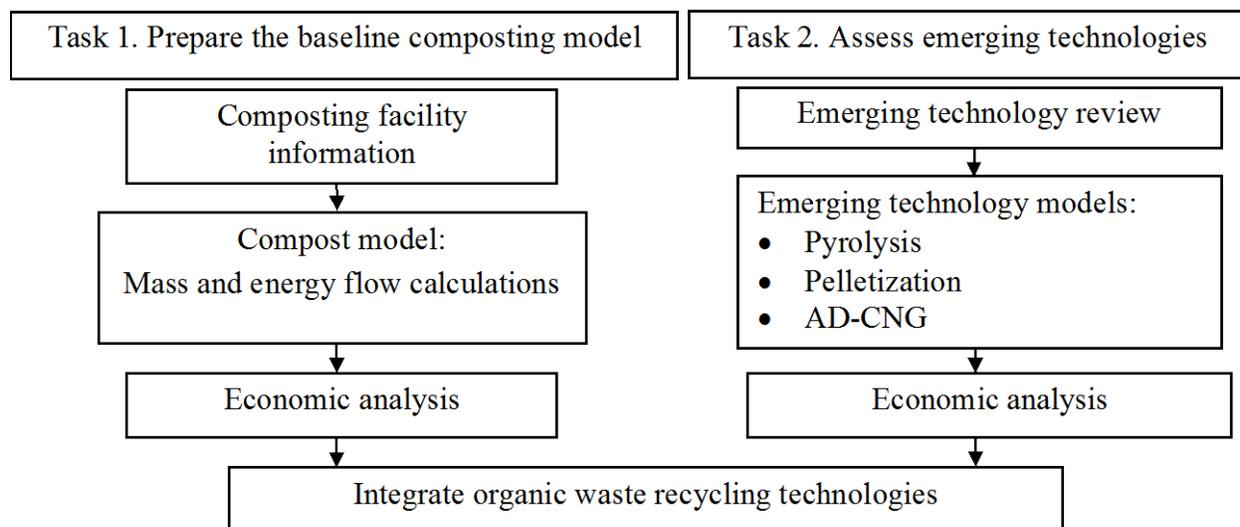


Figure 2.4: Strategy to evaluate biorefineries processing organics from MSW.

A composting facility baseline scenario targeted a large commercial composting technology used in the state of Washington, treating a combination of yard waste and food scraps. Industry partners such as Washington Organic Recycling Council members and PacifiClean/Cedar Grove were requested to supply expert opinion regarding needed baseline management, technology, performance and financial information that was used to update and refine values gleaned from scientific and trade literature. Mass and energy balances and economic analyses were carried out using Microsoft Excel.

The unit operation review was a follow-up from a previous review; however, this review focused on benefits of combining different unit operations with a compost facility. The types of products from anaerobic digestion, pyrolysis, and wood-fuel pellet production were the focus of the discussion.

The unit operations that were modeled were considered as an add-on to the baseline composting scenario. The products of this task were specific mass and energy balance models. Based on the mass and energy balance and unit operation needs, an economic analysis was conducted. The specific add-on processes that were modeled were:

- Pyrolysis for biochar and heat,
- Pyrolysis for biochar and electricity,
- Wood-fuel pellet production, and
- Anaerobic digestion with compressed natural gas production.

2.5 Results and discussion

2.5.1 Part 1 – Baseline compost model

The technical information used to build this hypothetical composting facility was obtained from:

- A literature review,

- Surveys with compost operators in the state of Washington,
- The state law that governs the construction of facilities (WAC 173-350-220; WAC 173-350-040; Ecology, 2013), and
- The Guide for Siting and Operating Composting Facilities developed by the Washington State Department of Ecology (Ecology, 2011).

2.5.1.1 Model assumptions: Inputs and process conditions

To build the baseline scenario for this study, a hypothetical composting facility was created that is representative of a large size composting facility in Washington processing 160,000 wet tons per year. The assumed waste stream was 76.9% yard trimmings, 19.2% food scraps, 3% wood, 0.5% miscellaneous organics, and 0.5% miscellaneous inorganics (Table 2.3). This distribution of the waste stream was selected based on the report by Levis and Barlaz (2013) and the mass fraction was selected considering the kind of wastes processed by composting facilities in Washington State.

Different types of composting designs could have been modeled. For this study, an in-vessel system using a GORE Cover System with aerated windrows was modeled, as it is presently used at the Cedar Grove composting facility and is actively marketed as a technology suitable for high precipitation areas like the Pacific Northwest (approximately 40 inches annual precipitation in western Washington). The GORE Cover System is similar to an aerated static pile system, but the piles are covered with a breathable expanded polytetrafluoroethylene fabric. The GORE aeration system also uses positive pressure, but aeration is controlled based on the oxygen concentration.

Table 2.3: Composition of municipal solid wastes to be processed in the baseline scenario (Komilis et al., 2004; Levis and Barlaz, 2013).

N ^o	Fraction	Mass (%)	Moisture (wt. %)	C (DW %)	N (DW %)
1	Yard Trimmings, Leaves	30.3	38.2	41.1	1.0
2	Yard Trimmings, Grass	25.5	82.0	43.4	1.8
3	Yard Trimmings, Large	21.0	15.9	45.1	0.3
4	Food Waste – Vegetable	5.2	77.0	38.5	3.0
5	Food Waste – Non-Veg	14.0	57.0	45.0	6.0
6	Wood	3.0	16.0	50.0	0.3
7	Newsprint	0.1	13.0	43.7	0.2
8	Corr. Cardboard	0.2	17.0	36.9	0.2
9	Bags and Sacks	0.2	22.0	42.2	0.1
10	PET – Containers	0.2	10.0	61.4	0.052
11	Plastic Film	0.2	14.0	79.1	0.42
12	Ferrous Cans	0.05	13.0	0	0
13	Ferrous Metal – Other	0.05	13.0	0	0

Specific dedicated odor controls were assumed. Air from the receiving, mixing, grinding building was removed via negative air pressure and treated using a biofilter. A biofilter between the GORE cover and compost pile was also assumed. During active composting, odorous compounds dissolve in a condensation layer that forms on the inside surface of the cover. The

system has been shown to reduce volatile organics and ammonia emissions by over 90% relative to windrow composting of similar green wastes (Card and Schmidt, 2012). Around the compost yard, odors would be managed in other ways. A mister would control dust and lower the release of odors while adding moisture to the feedstock. Leachate odor controls would be accomplished by monthly removal of sediments from ponds, with the ultimate fate of the sediments being blending with other feedstock during the feedstock mixing phase. Stored leachate would be aerated. To minimize dust and odors, the compost pad would be cleaned every two days.

The composting design and operational parameters were specified, describing the hypothetical composting facility (Table 2.4). The composting facility would consist of 64 windrows (165 x 26 x 12 ft³), 32 for active composting (28 days), 16 for maturation (14 days), and 16 for curing (14 days). The carbon to nitrogen ratio (C:N) was assumed to be 30. The initial water content was assumed to be 55% and it would be expected to drop to 50% after active composting. These large piles could have decreased performance in terms of process and odor control because they may be prone to developing anaerobic conditions if the piles are not adequately aerated (Ma et al., 2013a). Yet excessive aeration can heighten emitted odors (IWMB, 2007), as well as increase operating costs and potentially negatively impact moisture and biology.

The composting facility would contain these systems: scale house and office, tipping building, grinding and mixing, biofilter, active composting, maturation, curing, screening and storage, storm water pond, and leachate holding tank (Figure 2.5). The basic operation is to receive material through a tipping building, unload, prepare, grind, and mix the material, make piles, maintain piles, cure, screen, grade, and sell.

Table 2.4: Design and operational parameters of the hypothetical composting facility.

Parameter	Units	Value
Throughput capacity of the unit	Wet tons per year	160,000
Number of windrows	-	64
Dimension of windrows	feet	165 x 26 x 12
Number of windrows used for active composting	-	32
Number of windrows used for maturation	-	16
Number of windrows used for curing	-	16
Total active composting time	Weeks	4
Total maturation time	Weeks	2
Total curing time	Weeks	2
C:N targeted at the beginning of active composting	kg C kg ⁻¹ N	30
Minimum initial water content for active composting	wt. %	55
Moisture content after active composting	wt. %	50
Moisture content after curing	wt. %	50

A drawback to the current composting technology for organics in MSW is plastic contaminants. The amount of small plastics contamination in the final compost material may limit the sale price. The sorting process prior to grinding and mixing is very important, as is having plastic contaminant removal technologies. These steps were not included in this modeling effort because data regarding these steps were not available. In addition, further studies are needed to assess the impacts of different picking stations on emissions.

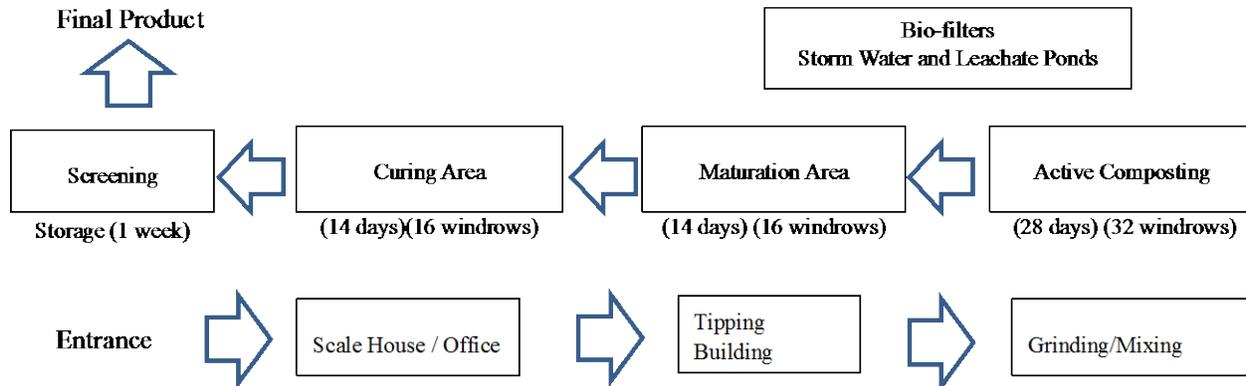


Figure 2.5: Aerial view of the hypothetical 160,000 tons per year composting facility.

The facility would be built over curbed asphaltic concrete pads that prevent contamination of soil and groundwater. It will also facilitate the collection of storm water, separate from collected leachate, by using the facility’s slope and design to minimize storm water infiltration into the leachate collection system.

Specific aspects of the hypothetical compost facility are described in Table 2.5, broken down by general unit operation, and summarized in a schematic (Figure 2.6). These specifics were obtained from Levis and Barlaz (2013), Komilis and Ham (2004), US DOE (2003), and Krogmann and Woycechowski (2000).

Table 2.5: Specifications and assumptions of the hypothetical compost facility, broken down by general unit operation. These specifics were obtained from Levis and Barlaz (2013), Komilis and Ham (2004), US DOE (2003), and Krogmann and Woycechowski (2000).

<i>Unit Operation</i>	<i>Specifications</i>
Tipping building	<ul style="list-style-type: none"> • Feedstock is dumped into the tipping building • Negative air pressure transports odors into a biofilter • Volume of the building is 40 m x 30 m x 5 m, or 6,000 m³ • Air system exchanges the mixing room air 4 times every hour • The air system flow is 24,000 m³ h⁻¹ • Mixing and grinding equipment (as detailed later) are included within this negative air space
Incoming feedstock	<ul style="list-style-type: none"> • Feedstock is screened and large materials > 2 inches are separated • Unders are sent to mixing and overs are sent to a secondary screen to remove contaminants • The pH of the incoming material is tested and feedstock is mixed to a desirable pH • 100 tons of wood chips are maintained at the facility as a bulking agent if needed • 100 tons of inoculate (recycled brown material) is close to tipping building for blending • Commercial waste collection company drops waste off • Trucks arrive during a 4 hour period each day • Facility receives material 240 days per year, Monday to Friday (667 wet tons per day)

Table 2.5 (continued): Specifications and assumptions of the hypothetical compost facility, broken down by general unit operation. These specifics were obtained from Levis and Barlaz (2013), Komilis and Ham (2004), US DOE (2003), and Krogmann and Woycechowski (2000).

<i>Unit Operation</i>	<i>Specifications</i>
Incoming feedstock (continued)	<ul style="list-style-type: none"> • Capacity of a 12-wheeler truck is 16 tons of green waste • Capacity of a high-end dump truck is 21 tons of green waste • 10 trucks enter the facility each hour for 4 hours each day • Compost material stays at the facility for 10 weeks • Compost facility has an area to store 60,000 tons of material
Grinding and blending	<ul style="list-style-type: none"> • Feedstock is added to a conveyor • The conveyor contains a screen, small particles fall out and large material is ground • The material passes beneath a magnet, which removes metal contaminants • Bulking agent and inoculate are mixed with feedstock using a front-end loader • Bulking agent allows for 30% free air space • The mixture is loaded into the mixer/grinder using front-end loaders • The mixture is ground and mixed in the tub grinder • The mixture is then dropped on an enclosed conveyor • Moisture (treated leachate or storm water) is added on to the material, if it is too dry, while on the conveyor and the mixture is dropped into the active composting section
Composting piles	<ul style="list-style-type: none"> • Front-end loaders move mixture to the correct location of a phase I cell GORE Cover System • The GORE cover is pulled over the pile • Air is forced up through the piles • Phase II cells are built similar to phase I cells • Oxygen and temperature are monitored • 10% oxygen is needed to avoid anaerobic odor • Active composting temperature > 55°C for three consecutive days to destroy pathogens • After 4 weeks in active composting, the pile is moved to the maturation area • Maturation occurs for 2 weeks • Compost/mulch is moved to 16 uncovered piles for 2 weeks of aerated curing (phase III) • 6% of the aerobic decomposition happens in the active composting, 30% in the maturation step and 10% in the curing step • GORE covers last 8 to 9 years • The capacity of each windrow is 450 tons (165 x 26 x 12 ft³)
Finished compost	<ul style="list-style-type: none"> • Compost continues to cure • Moisture and oxygen levels are managed • Piles are covered with a blanket that sheds water but allows the pile to breathe • The finished pile is kept on forced air to maintain aerobic conditions • The piles are turned every month to evenly distribute moisture • Compost material is tested following standard methods • Compost is piled to a 35 foot mountain, with a capacity of 20,000 tons of finished product (approximately 1 week of production)
Screening	<ul style="list-style-type: none"> • Contaminants in the final compost are screened for compost, mulch, and potting mix blend • Overs are returned to the beginning of the compost process, as a source of inoculate • Material that is 0.2 to 2 inches is used as packing for the biofilter

Table 2.5 (continued): Specifications and assumptions of the hypothetical compost facility, broken down by general unit operation. These specifics were obtained from Levis and Barlaz (2013), Komilis and Ham (2004), US DOE (2003), and Krogmann and Woycechowski (2000).

<i>Unit Operation</i>	<i>Specifications</i>
Storm water and leachate handling system	<ul style="list-style-type: none"> • Runoff prevention system includes covered areas (roofs), diversion swales, and ditches • Storm water is diverted from feedstock preparation, active composting, and curing • 2 large retention ponds capture rainwater • Leachate is collected, stored and treated • Leachate and storm water ponds are aerated and inspected daily • 300 L of leachate is produced for each ton of organic material processed • Composition of the leachate is reported by Krogmann and Woycechowski (2000) • The collection system was calculated based on a 25-year storm event (WAC 173-350-100) • Leachate storage was calculated based on the capacity to store the normal maximum volume • Leachate removal and use was considered in the calculations • Tank freeboard was 20 inches (avoid overtopping from wave action, overfilling, precipitation) • The leachate tank followed requirements of WAC 173-350-220(3)(e)
Odor control (biofilters)	<ul style="list-style-type: none"> • Odors from the receiving building are controlled with a biofilter • Odors from composting are treated with the GORE cover and the biofilter under the cover • Other sources of odors are not treated (leachate/storm water treatment, general grounds area) • Air is evenly distributed through the biofilter • Shredded wood chips make up the biofilter • Moisture content remains between 50 and 65% • Back pressure is measured to determine wood-chip replacement • Wood chip filters are replaced every 14 to 18 months
Operators	<ul style="list-style-type: none"> • Workers are properly trained regarding safety, compost basics, and good management practices according to WAC 173-350-220(4)(vi)(a) • The facility has a “sanitary station” and space for staff to wash and change clothes • 32 workers are needed in total based on Komilis and Ham (2004) and Levis and Barlaz (2013)
Diesel consumption and emissions	<ul style="list-style-type: none"> • Grinder energy requirement is 10.6 kWh ton⁻¹ and fuel consumption is 0.25 L kWh⁻¹; they use 1.3 L of diesel per ton of MSW (approximately 2.6 L ton⁻¹) • Front-end loaders use 0.33 kWh ton⁻¹ and fuel consumption is 0.26 L kWh⁻¹ • Front-end loaders transport 3,004 tons • Density of diesel is 0.85 kg L⁻¹ and its low heating value is 42.5x10³ kJ kg⁻¹
Electricity use	<ul style="list-style-type: none"> • The power of the fans is 5.6 kW and the efficiency of the fans is 65% • Fans only operate 25% of the time (6 h day⁻¹) • Office area needed is 1133.3 m² based on 667 ton day⁻¹

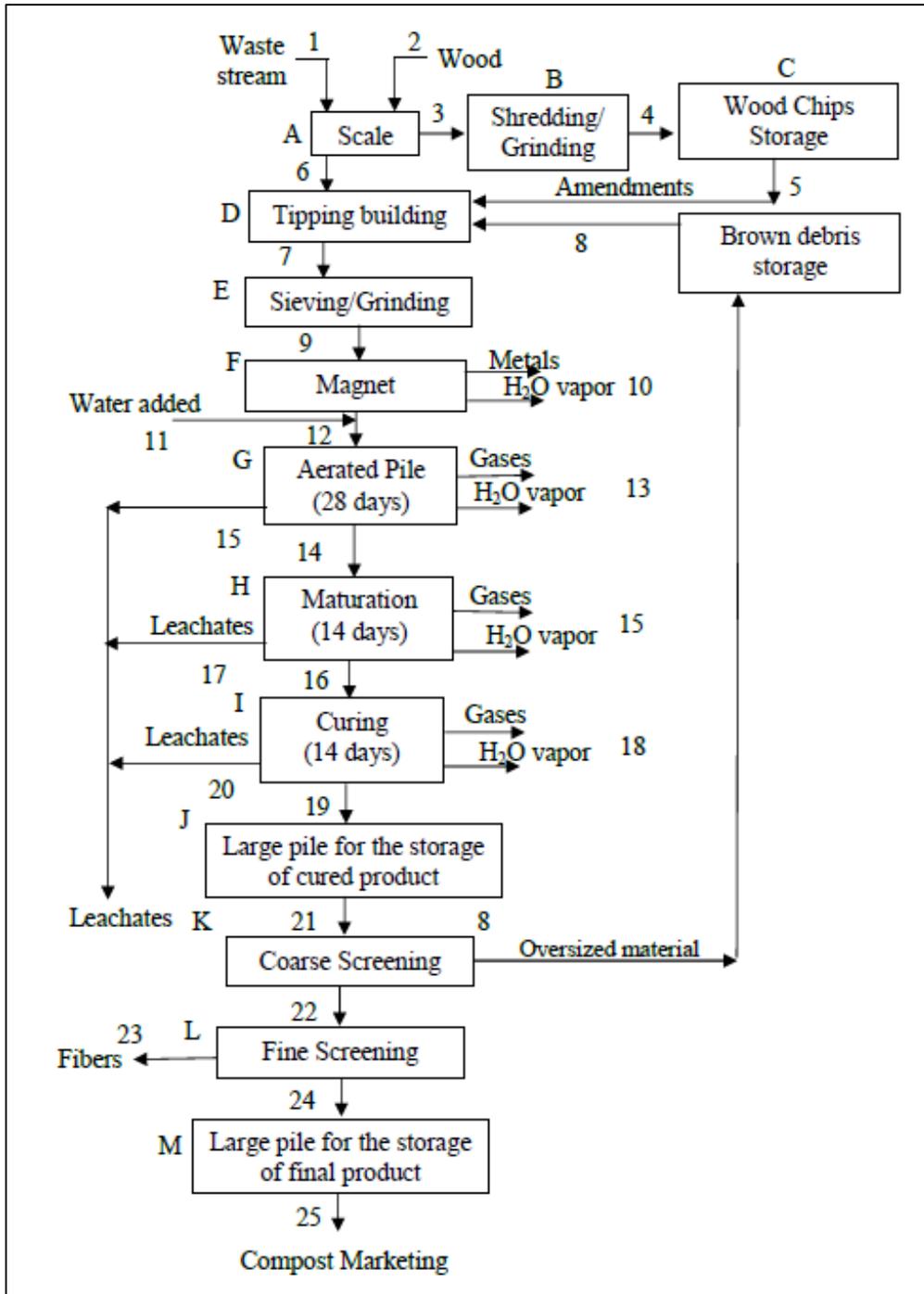


Figure 2.6: Detailed composting model flow diagram.

2.5.1.2 Mass, energy, and economic calculations

The compost model calculations follow the report by Levis and Barlaz (2013). Material flow and economic calculations were performed in a Microsoft Excel workbook. The calculations are based on mass balance equations and estimated values based on assumptions inherent in the hypothetical design described above (Figure 2.7).

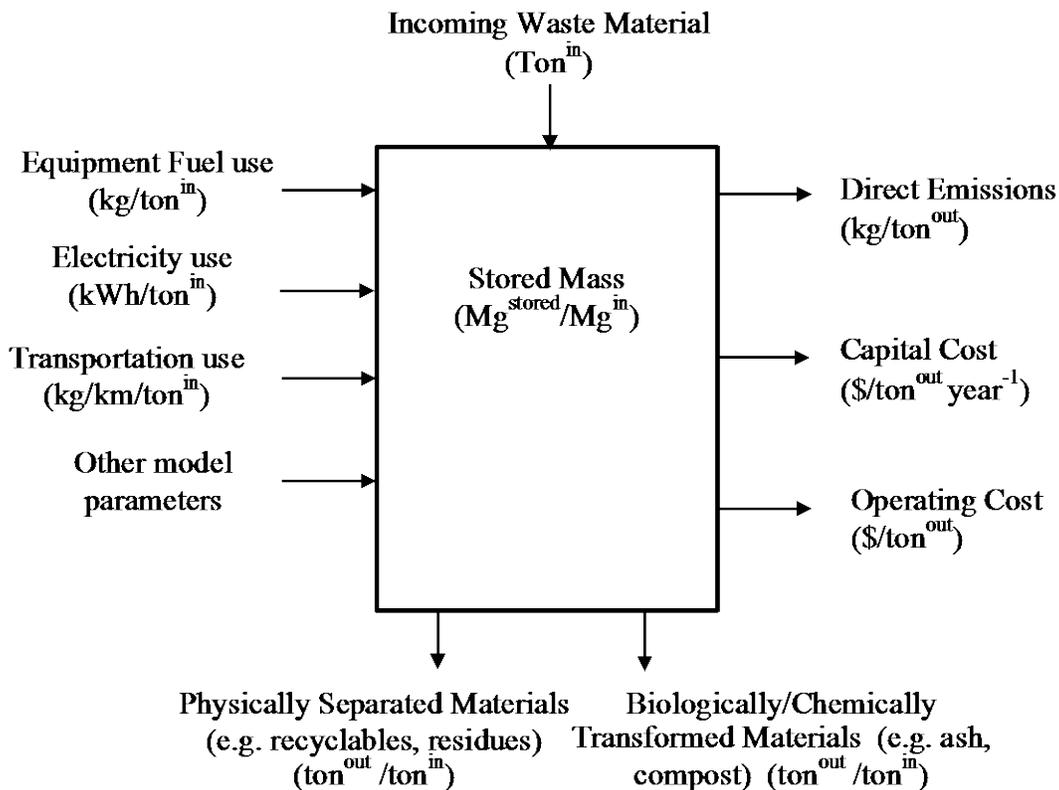


Figure 2.7: Summary of model input and output information (Levis and Barlaz, 2013).

The economic analysis included capital costs, operation and maintenance (O&M) costs, and revenue. Capital costs included land purchase, facility installment, and equipment purchase. The O&M costs included labor, overhead, fuel consumption, electricity usage, and equipment maintenance. Costs were obtained from sales literature, equipment manufacturers, composting facility operators and other literature, as referenced. Detailed calculations can be found in Appendix J.

2.5.1.2.1 Mass and energy balances

Estimated moisture content and C:N ratio of the initial compost mixture was close to the expected values (Levis and Barlaz, 2013): moisture content was 48.15% by weight and the C:N was 30.86. The content of yard trimmings and wood in the assumed feedstock stream was such that more wood to increase the porosity of the windrow was not needed. The dry material feedstock was equivalent to 0.52 ton per wet ton of waste material processed. That means that out of the 667 tons processed per day, 346 tons corresponded to dry material and 321 tons corresponded to water.

The material entering the active composting pile was 763 ton day⁻¹ because the incoming feedstock (667 ton day⁻¹) was moistened with water (leachate or storm water). An important loss in mass happened in the active composting step, through leaching, drying or through aerobic degradation. The loss was close to 192 ton day⁻¹ (Table 2.6); 77 ton day⁻¹ was lost during maturation and curing. In the end, the facility produced 0.22 dry tons per ton of wet material

processed; 0.45 wet tons per ton of wet material processed; 0.43 dry ton per ton of dry material processed.

Table 2.6: Calculated material flow during composting.

Material	Total (ton day⁻¹)	Sum total (ton day⁻¹)
Leaving active composting		
Organic solids	260	570
Ash	25	
Leaving maturation		
Organic solids	231	512
Ash	25	
Leaving curing		
Organic solids	221	493
Ash	25	
First screen – oversized		
Organic solids	11	24
Ash	1*	
Second screen – fibers		
Organic solids	82	172
Ash	5*	
Compost Product		
Organic solids	129	297
Ash	20*	

* Note: The screened ash components do not add up to the ash coming into the first screen because of rounding errors.

2.5.1.2.2 Leachate

The amount of water entering the system was 323 ton day⁻¹, and the water leaving the system as 246 ton day⁻¹, so approximately 77 ton day⁻¹ of water was lost. The leachate was assumed to be 100 ton day⁻¹, containing 5% of organic matter (Krogmann and Woycechowski, 2000). In order to achieve the 55% moisture needed in the composting pile, 97 ton day⁻¹ of water were added, which was similar to the amount of water that leached out of the composting piles. Thus, it is not expected that the facility will require fresh water to reach the moisture content for the active composting step.

2.5.1.2.3 Emissions during active composting and curing

To model the emissions during the active composting and curing phases, Levis and Barlaz (2013) proposed the following emission estimates: 1.7% of the released C is methane (CH₄), 98.3% of the released C is biogenic carbon dioxide (CO₂) (Boldrin et al., 2009), 4% of N loss is emitted as ammonia (NH₃), 0.4% is released as nitrous oxide (N₂O), and 95.6% is released as N₂ (Beck-Friis et al., 2001; Boldrin et al., 2009). Volatile organic carbon emissions depend on volatile solids (VS) loss during the curing phase: 0.238 kg VOC Mg⁻¹ VS was assumed (Cadena et al., 2009). The biofilter on top of the windrow and under the GORE cover allowed for some odor control. It was assumed that 15% of the CH₄, 48% of the NH₃, and 18% of the VOCs were removed from this biofilter layer under the covered pile (Amlinger et al., 2008; Pagans et al., 2006). The estimated gases released from the covered pile and the curing pile (Table 2.7) may be underestimated for methane if the aeration system malfunctions, and if the tall windrows (12 feet) are too deep—the recommended height is 10 feet (Ma et al., 2013a).

Table 2.7: Estimated emissions from composting.

Molecule	Total released (ton day ⁻¹)
VOCs	0.000452
CO ₂	167.4
CH ₄	1.0
NH ₃	0.164
N ₂ O	0.042
N ₂	6.461

2.5.1.2.4 Diesel consumption and associated emissions

Diesel consumption from the front-end loader and tub grinder was approximately 3,000 L day⁻¹ (Table 2.8). The NO_x and CO emissions were higher for the tub grinder compared to the front-end loaders.

Table 2.8: Diesel and associated emissions (Levis and Barlaz, 2013; Komilis and Ham, 2004).

Type of vehicle	Diesel use L day ⁻¹	HC kg day ⁻¹	CO kg day ⁻¹	NO _x kg day ⁻¹	PM _{total} kg day ⁻¹	SO _x kg day ⁻¹	CO ₂ kg day ⁻¹
Front end loader ¹	1,202	11.3	38.6	15.6	10.9	13.5	3,360
Tub grinder ²	1,767	30.0	121.3	197.9	19.8	23.0	4,948
Total	2,968	41.3	160.0	213.0	30.6	36.4	8,308

¹refers to a tracked loader ²refers to a chopper/stump

2.5.1.2.5 Electricity usage

Electricity is used during material screening as well as for aeration. Electricity is also used in the office area. The fans used to aerate the windrows use the most electricity on plant (Table 2.9). The electricity consumed was equivalent to 211 kWh ton⁻¹ of wet material processed, similar to values listed in Zhang and Matsuto (2011) for a 667 wet ton day⁻¹ composting facility.

Table 2.9: Estimate of electricity consumed each day (Levis and Barlaz, 2013; Komilis and Ham, 2004; US DOE, 2003).

Equipment/Area	Electricity use estimate (kWh)
Fan in tipping building	900
2 fans per windrow or 128 fans	6,617
Two screens, 1 kWh per ton processed	986
Office area	913
Total	9,415

2.5.1.2.6 Capital cost estimation

The land required for the installation was calculated using the parameter proposed by Levis and Barlaz (2013), equivalent to 0.4 ha ton⁻¹ day⁻¹. In our case, 667 ton day⁻¹ was being processed, so consequently the area required would be 266.8 hectares (660 acres). This is an important parameter in the design of the composting unit because it is directly related with odor emissions (Levis and Barlaz, 2013).

Using the Marshall and Swift Index (refer to <http://www.marshallswift.com/>) to estimate current cost from older values, a total land and construction cost for April 2015 was obtained. The land and construction estimate was \$4.7 million (Table 2.10). The main equipment cost estimate was \$14 million (Table 2.11). Including other engineering costs, the total capital estimation was \$28 million (Table 2.12).

Table 2.10: Land and construction cost estimates (Levis and Barlaz 2013; Komilis and Ham, 2004; Marshall and Swift Indices were 1,558.7 and 1,596 for 2013 and 2015, respectively).

Parameter	Estimate 2013 (\$)	Estimate 2015 (\$)
Land	666,667	682,620
Grading	628,000	643,028
Paving	1,640,000	1,679,245
Fencing	260,180	266,221
Offices	487,333	488,995
Tipping building	908,003	929,731
Total land and construction	4,590,003	4,699,842

The capital recovery factor was calculated using the following equation:

$$e = i(1+i)^N / (1+i)^N - 1$$

Where: *i* is the interest rate (decimal) and *N* is the lifetime of the equipment (years). In our case, the interest of the bank was assumed to be 5.12% and the number of years 20 ($e = 0.081061$). The yearly payment would then be \$2.3 million year⁻¹.

Table 2.11: Main equipment cost estimates (Levis and Barlaz, 2013; Komilis and Ham, 2004; Marshall and Swift Indices were 1,558.7 and 1,596 for 2013 and 2015, respectively).

Equipment	Number of Units	Cost per Unit	Equipment Life (years)	2015 Corrected Estimate (\$)
Scale	1	50,000	10	116,216
Front-end Loaders	10	222,506	10	5,171,770
Pre-screen	1	148,337	10	344,784
Tub Grinder	1	370,843	10	861,960
GORE cover system	1	500,000	20	581,082
Aeration system	64	50,000	20	3,718,925
Cover equipment	2	75,000	20	174,325
Belt conveyors	4	45,000	10	418,379
Miscellaneous truck	1	50,000	10	116,216
Water truck	1	150,000	20	174,324
Excavator	1	230,000	10	534,595
Post-screeners	2	148,337	10	689,567
Bobcat	1	44,501	10	103,434
Biofilter + fan	1	748,800	20	870,228
Leachate tank	1	150,000	20	174,324
Total 2015 estimate				14,050,134

Tire cost and lifetime data was collected from Nunnally (2007)

Table 2.12: Total capital cost estimates (Levis and Barlaz, 2013; Seider et al., 2009).

Other Engineering costs were calculated as a % of the construction costs:	Estimate (\$)
Direct project cost (DPC)	14,050,134
Engineering, design and supervision: 0.15 * DPC	2,107,520
Management overheads: 0.1 * DPC	1,405,013
Installed project cost (IPC)	17,562,668
Commissioning: 0.05 * IPC	878,133
Contingency: 0.1 * IPC	1,756,266
Contractor Fee: 0.1 * IPC	1,756,266
Interest during construction: 0.1 * IPC	1,756,266
Total plant costs (TCP)	23,709,602
Land acquisition + construction	4,699,842
Final capital cost (TCP + land acquisition costs)	28,409,444

2.5.1.2.7 Estimation of operation and maintenance costs

Operation and maintenance costs are the costs associated with processing a mass of material through the composting facility. The primary O&M costs are fuel and electricity, equipment maintenance, and personnel or labor.

Diesel costs were calculated by multiplying the total diesel use by the current price of diesel (Table 2.13). Electricity costs were calculated using a similar approach. The cost of water, bulking agent and chemicals was considered to be 50% of the cost of diesel plus electricity.

Our estimate of the diesel cost was close to the estimate given by PacifiClean for a 75,000 ton year⁻¹ plant (\$360,000 year⁻¹). If the capacity is 2.1 times larger than the design presented by PacifiClean, then it would lead us to expect the fuel consumption is approximately \$756,000 year⁻¹. Cost of electricity was also very close to PacifiClean's estimate for a 75,000 ton year⁻¹ facility. They expect to pay close to \$80,000 year⁻¹, thus a unit 2.1 times larger would be paying \$168,000 year⁻¹.

Overall, our estimated operations cost was \$7 ton⁻¹. This is comparable to the operating cost for electricity, fuel, water and bulking materials reported by Zhang and Matsuto (2011) of \$4.7 ton⁻¹ of material processed. According to Zhang and Matsuto (2011) the cost of electricity, fuel, water, bulking materials and chemicals is typically between \$8 and \$80 per ton.

Table 2.13: Cost of diesel, electricity, water, bulking agent, and chemicals (estimated from Zhang and Matsuto, 2011).

Parameter	Annual cost estimate (\$ year⁻¹)
Cost of diesel – retail price of \$3 gallon ⁻¹ or \$0.8 L ⁻¹	569,931
Cost of electricity – \$0.052 kWh	176,520
Cost of Water, Bulking agent and Chemicals (50% of diesel + electricity)	373,090
Total	1,119,272

The itemized annual maintenance cost (\$0.36 million) calculated was close to 1.3% of the capital cost (\$28 million) (Table 2.14). This number is low based on recommendations from Seinder et al. (2009); recommended maintenance costs are close to 5% of the capital when handling solids. Labor was estimated at 32 workers (Table 2.15) with assumed benefits corresponding to 29% of their base salary. The overall O&M estimate was \$4.8 million year⁻¹ (Table 2.16). Labor was the largest expense.

Table 2.14: Maintenance cost estimate (estimated from data reported in: Komilis and Ham, 2004).

Parameter	Annual cost estimate (\$ year⁻¹)
Front-end loader tires	80,000
Bobcat tires	4,800
Front-end loader	30,000
Tub grinder	5,000
Screens	6,000
Odor control system	10,000
Fans for aeration system	192,000
Contingency	32,780
Total maintenance costs	360,580

Table 2.15: Estimation of labor costs (Levis and Barlaz, 2013; Komilis and Ham, 2004).

Appointment	Number of workers	Annual salary (\$ year⁻¹)	Total salary and benefits (\$ year⁻¹)
General Manager	1	115,200	148,608
Engineers	2	96,000	247,680
Secretary	1	38,400	49,536
Balance and feedstock odor controller	1	38,400	49,536
Blends preparation	2	38,400	99,072
End load operators	16	38,400	792,576
Operators controlling/sampling piles	2	38,400	99,072
Odor specialist	1	38,400	49,536
Cleaning and Maintenance	2	38,400	99,072
Laboratory quality control	1	57,600	74,304
Marketing and commercialization	2	76,800	99,072
Public relations	1	76,800	99,072
Total	32		1,907,136

Table 2.16: Summary of compost facility economic estimates.

Parameter	Estimate (\$ year⁻¹)
Diesel	569,931
Electricity	176,520
Water, bulking agent and chemicals	373,090
Maintenance	360,580
Labor	1,907,136
Property taxes ¹	852,283
Operating overhead ²	517,039
Total O&M estimate	4,756,311

¹ 3% of the Capital Investment; (Seider et al., 2009).

² 22.8% of the maintenance and labor costs; (Seider et al., 2009).

2.5.1.2.8 Comparison

The capital cost for this proposed 667 ton day⁻¹ facility was \$28 million. This is comparable to the capital cost for a Portland, Oregon facility of similar capacity (600 ton day⁻¹), which cost \$20 million in 1998. Correcting for capacity and inflation, the cost of the Portland facility in 2015 would be \$30 million. Our estimated operation and maintenance costs of \$4.8 million were lower than the estimate for the Oregon facility (\$7 million year⁻¹, corrected for 2015 dollars) (Table 2.17).

Table 2.17: Composting costs for three large facilities (Diaz et al., 1993).

Facility	Year	System	Capacity ton day ⁻¹	Capital Cost Million \$	O&M \$ year ⁻¹	Tipping Fee \$ ton ⁻¹
Portland, OR	*	Drum/ASP	600	20	5,000,000	42
Pembroke, FL	†	ASP	667	48.5	N/A	N/A
Dade, FL	1990	TW	800	25	N/A	24

* Closed in mid-1993.

† Undergoing modifications at time information was published.

TW – Turned Windrow, ASP – Aerated Static Pile.

2.5.1.2.9 Revenues

The value of the produced soil amendment will vary significantly based on quality and availability of markets. Bagged compost demands the highest price, but if markets are not available, facilities may rely solely on bulk sales. The default sales price selected was \$20 ton⁻¹, which assumed mostly bulk sales. If most sales are bagged compost, then the price could be greater than \$100 ton⁻¹. Tipping fees were assumed to be \$60 ton⁻¹. This estimate for tipping fees was higher than compost sales if sold at the bulk price (Table 2.18).

Table 2.18: Annual revenues.

Parameter	Estimate (\$ year ⁻¹)
Tipping fees - \$60 ton ⁻¹ processed	9,600,000
Compost - \$20 ton ⁻¹ compost product	1,424,538
Total	11,024,538

2.5.1.2.10 Gross earnings and net earnings

Gross earnings were calculated by subtracting annual cost from annual sales, providing an estimated \$4 million in earnings before taxes (Table 2.19).

Table 2.19: Summary of gross earnings.

Cost breakdown	Estimate (\$ year ⁻¹)
Annual revenues	11,024,538
Capital	2,302,899
Operation & Maintenance	4,756,311
Gross earnings (before taxes)	3,965,327

Because the gross earning was between \$0.3 million and \$10 million, the federal taxes were considered to be 34% or \$1.3 million (Seider et al., 2009). The net earnings would therefore be \$2.6 million year⁻¹. If 0% of the capital cost were financed, the gross earnings would be \$6.3

million year⁻¹. In this case, the federal taxes would be \$2.2 million year⁻¹, so the net earnings would be \$4.0 million year⁻¹. The ROI would be 14%, which is considered acceptable and competitive with current commercial interest rates.

2.5.1.3 Summary

The results from the baseline model of a hypothetical composting facility showed that revenue from composting facilities is tipping fee-driven rather than compost sales-driven. Building a composting facility is costly, but a business plan where capital costs are not financed could have an acceptable return on investment of approximately 14%. Coupling composting facilities with other economical systems is in the interest of facilities processing more organic waste and generating more revenue from tipping fees and co-products. The main challenge of building composting facilities in urban settings is the large area needed to avoid odor issues. Waste processing technologies with small footprints and efficient odor control are needed for the processing of organic wastes in urban areas where space is limited.

2.5.2 Part 2 – Emerging technologies to integrate with a compost facility

Emerging technologies for potential integration with a composting facility were reviewed and the benefits discussed. The technologies were organized by the types of waste they efficiently treat, either readily biodegradable waste (e.g., food scraps) or stable organic waste (e.g., wood waste). A focus was placed on AD for conversion of food scraps and pyrolysis and pellet production for conversion of wood waste.

2.5.2.1 Conversion of readily biodegradable organic wastes

Composting of wet biomass, particularly putrescent material like food scraps or fresh green grasses, can be problematic, requiring a scientific analysis to determine optimum technologies for their effective treatment and stabilization. Particular problem areas include:

- low pH and high volatile fatty acid (VFA) content;
- release of ammonia and volatile organic compounds (VOCs);
- increased production and release of greenhouse gases (GHGs);
- negative effect on pathogen control from variable temperature regimes; and
- negative effect on facility economics through impacts to product quality, energy inputs, and mass flows.

A cursory analysis of the functions of AD can show the synergistic effects of a combination of AD with composting on addressing these concerns. While dry and wet anaerobic digestion systems have potential for integration with composting facilities, wet AD will be a focus of this first modeling effort. In addition, a variety of temperature regimes can be used for maintaining the microorganisms, including thermophilic, mesophilic and psychrophilic regimes. For the purposes of this study, a mesophilic operation will be considered.

2.5.2.1.1 Anaerobic digestion-composting systems

Anaerobic digestion technology is a biological waste treatment process that occurs in an enclosed and oxygen-free environment. Two general methods of AD are used: dry reactors or slurry (wet) reactors. Dry systems are of particular interest to compost facilities as their operation fits nicely into existing infrastructure and practice. In essence, many of the dry systems are batch operations whereby incoming feedstock, pre-selected for AD treatment, is loaded by front-end loaders to dedicated anaerobic bays for a 15-40 day batch treatment. The treatment typically

involves the spraying of inocula (i.e., AD effluent) through the pile. The liquid leaching under the pile is composed of a leachate high in volatile fatty acid content for rapid conversion to methane in short-retention methane reactors. The resulting effluent from these methane reactors is then recycled back to the batch pile for continuous degradation and inoculation. Engineering controls are required to maintain effective pile leaching with appropriate bulk density. It is also important to monitor and moderate pH and ammonia concentration (Frear et al., 2012).

Compost facilities are familiar with the use of front-end loaders to generate batch piles and are knowledgeable about leachate management, so the dry AD system fits nicely into their field of expertise, system structure and waste and wastewater management. Advantages of the slurry (wet) system rest mainly in the improved kinetics and potential for biogas production due to conditions that are preferable for microbial growth. Wet systems that incorporate nutrient recovery for a fraction of the AD effluent allows for recycling of the effluent and reduction of other concerns, including the water balance concern. This concern is a result of wet AD reactors producing large volumes of dilute effluent in need of treatment, storage, and disposal. An additional concern is recalcitrant contaminants. Dry, batch systems do not need to handle contaminants upfront as the leaching and digestion process will proceed without their interference. The same cannot be said for wet systems, which must remove the majority of contaminants prior to digestion. Dry, batch systems, however, will still need to remove the contaminants on the back end of the process (Frear et al., 2012).

Benefits of AD for waste treatment and stabilization are numerous. AD is capable of providing improved fertilizer quality from organic waste material while reducing odors, greenhouse gas emissions, and solids. Mata-Alvarez et al. (2000) demonstrated that VOC and ammonia emissions from a compost operation utilizing primarily food scraps can be lowered from a mean of 747 g MT⁻¹ to a mean of 101 g MT⁻¹ through the use of a sequential AD-compost operation. Because AD is operated in a confined system, the ammonia produced is more easily volatilized and collected, resulting in downstream high-value fertilizer sales and reduction of the ammonia emissions that would result from composting alone. Drennan and Distefano (2010) also showed odor reduction from an AD-compost system. Composting residual AD solids achieved low levels of VOCs after 10-15 days and low volatile sulfur compound emissions after 15-20 days.

Methane emissions from AD are entrapped and utilized for carbon offset, as well as for the production of renewable energy. AD systems capture and use methane for energy production, either in the form of combined heat and power (CHP) or CNG (Holm-Nielsen et al., 2009). Utilizing this energy source for the composting process can decrease energy use costs. Energy consumption for composting was estimated at 25.2 kWh ton⁻¹ for aerated static piles (de Bertoldi et al, 1983). Additional economic benefits can result from the reduction of mass as high as approximately 60% during AD, as a large fraction of VS is converted to methane, opening up additional space for composting (Frear et al., 2012).

The benefits of AD are clear; however, it is not without its drawbacks. Inclusion of AD into a combined AD-composting process introduces additional capital and operating expenses to the overall system. Anaerobic digestion requires additional techno-economic analyses of the combined treatment effect, although early analyses of AD systems receiving food scraps demonstrated a 0.018 kW wet ton⁻¹ net electrical production, or \$14 wet ton⁻¹ electrical revenue

capability (Banks et al., 2011). Besides the capital and operation cost drawback, there are operational challenges for heterogeneous and inconsistent feedstocks entering the AD system. For example, the conversion of highly biodegradable food scraps and fresh green waste is prone to run-away kinetics during the first stages of AD, resulting in decreased pH and subsequent souring, failing or extended recovery or treatment time. Yet this is similar to what is observed for these wastes during composting, because conversion of organic N to ammonia N—while potentially positive if ammonia recovery is implemented—can be inhibitory to the compost process if allowed to stay within the system.

2.5.2.1.2 Nutrient recovery and water recycling

As noted above, if a slurry digester is preferred for its enhanced biological kinetics, then excessive wastewater production must be addressed. One method to alleviate excessive water use is to utilize digested effluent to dilute incoming feedstock so that fresh water is not needed and a portion of the effluent is maintained within the system. The concern in regard to this approach is the potential for build-up of key chemical inhibitors to the microorganisms that carry out the AD. This build-up can occur through degradation of organic compounds to soluble inorganics that are continually recycled and maintained within the system, particularly ammonia, solids and—to a lesser degree—phosphorus and salts (Yenigun and Demirel, 2013; Chen et al., 2008; Melbinger et al., 1971; McCarty and McKinney, 1961).

Nutrient recovery (NR) refers to the use of solids, liquids, and wastewater purification processes that can use a variety of mechanical, chemical or biological processes in sequential steps to achieve a preferred degree of wastewater cleaning, while also producing value-added fertilizer products (Ma et al., 2013b). In the case of recycled water from AD effluent, the degree of removal needed is low, only requiring the reduction of certain key inhibitors to the AD process. Within an integrated compost biorefinery, only partial recycling should be required, thereby reducing the size of the NR system needed. Only partial recycling is required because, on the one hand, a fraction of the effluent can be incorporated into the compost piles for moisture maintenance, and on the other hand, compost leachate and runoff can be used as dilution water for the AD feedstock.

Capital and operation costs are increased when an NR system is included. The types, form, and value of the nutrient products are therefore of vital importance to overall economics. It is very important that products made are consistent and of high quality. Products may include ammonium sulfate, fibrous solids, fine solids with high macro- and micro-nutrient content, and phosphorus fertilizers.

2.5.2.2 Conversion of stable organic wastes

Numerous thermochemical treatment technologies are available to process stable organic wastes and are of possible consideration for integration within a compost biorefinery. Of interest here is the treatment of dry wood materials entering the compost facility. Wood can be a challenging feedstock for biological microbes to process, but it is the preferred feedstock for thermochemical routes (Meier et al., 2013; Jahirul et al., 2012; Bridgewater, 2012; Garcia-Perez et al., 2012a; Bahng et al., 2009). Potential thermochemical technologies to integrate with composting facilities include combustion, gasification, pyrolysis, and wood-fuel pellets production. The focus of this work is on pyrolysis and wood-fuel pellet production because these are two alternatives that can be readily implemented.

Combustion for power generation and gasification also has intriguing potential. Notably, gasification has unique integration capabilities with AD, particularly in regard to bio-based syngas conversion for enhanced biogas production (Luo et al., 2013; Henstra et al., 2007; Wang et al., 2013). In addition, gasification can be tuned for the production of specialized high-carbon biochars (Suliman et al., *in prep.* [a], *in prep.* [b], *in prep.* [c], *in prep.* [d]; Rodriguez-Reinoso and Molina-Sabio, 1992). Similar economic analysis for gasification and combustion can be conducted; however, they were not considered for this project due to time constraints. Further research efforts for gasification integration and modeling within a biorefinery concept are envisioned for future Waste to Fuels research.

2.5.2.2.1 Pyrolysis-composting systems

Pyrolysis is the thermal degradation of stable organic waste in the absence of oxygen to produce carbonaceous char, oil and combustible gases. The product distribution depends on the process conditions, particularly temperature and feedstock. Relatively low temperatures in the range 400 to 800°C are typically used for pyrolysis (Garcia-Perez et al., 2011, 2012b; Czernik and Bridgewater, 2004). Pyrolysis can treat dry woody feedstock and even deal with a certain degree of moisture by utilizing *in situ* drying made available from the pyrolysis gases produced during the process.

Currently, there are two business models for pyrolysis: (1) fast pyrolysis for the production of bio-oil and biochar, and (2) slow pyrolysis for the production of biochar and heat. Many companies make charcoal for grilling purposes. However, due to existing technical hurdles as well as economic concerns, only a few companies have made profitable businesses: fast wood pyrolysis for oil (e.g., Ensyn and BTG) and wood or grass pyrolysis for agricultural biochar (e.g., CoolPlanet and The Biochar Company) (Knight, 2012). Pyrolysis is a relatively simple business scheme but it is a complex engineering system. It is well suited for a large facility that processes forest residues and is likely only profitable when it is coupled with a separate high-value market for the resultant biochar.

Pyrolysis systems are intriguing in regard to synergies with compost operations, due to their ability to produce value-added products and renewable energy while more optimally treating a specific woody feedstock.

Biochar

Waste wood can undergo pyrolysis and later have the resultant char combined with compost before or after composting. Two particular properties of biochar make it a compelling opportunity for combination with composts: their high sorption capacity and their stability.

- (1) Adsorption: Biochar has the ability to adsorb gases, odors, environmental contaminants, nutrients, and water. Specifically, char can adsorb sulfur dioxide (Lizzio and DeBarr, 1996) and hydrogen sulfide (H₂S) (Cal et al., 2000), along with other odorous compounds. Research has shown that char can be added as a top layer to the composting piles and effectively reduce emitted odors (Prost et al., 2013; Grob et al., 2011). Across the world, biochar has been applied to mitigate odors, gaseous emissions from stacks and engines, heavy metal contamination of soils, and pathogens. In developing countries, people add it in composting toilets for odor reduction (Mohan et al., 2014; De et al., 2013; Grob, 2011; Chen et al., 2009; Liu et al., 2009; Marsh and Reinoso, 2006; Zagorodni, 2006; Bansal and Goyal,

2005; Harland, 1994; Korkisch, 1988; Poduska and Anderson, 1981).

- (2) **Stability:** Carbon content in compost declines rapidly after it is added to soil, especially in hot and humid environments. However, biochar's recalcitrant properties are quite the opposite, with upper stability bounds from hundreds to thousands of years. Addition of biochar to soil provides a longer functional carbon source (Grob et al., 2011; Lehmann, 2007a; 2007b; Lehmann et al., 2006). Production of biochar, in combination with its storage in soils, is considered a method for reducing atmospheric CO₂ because the high recalcitrance of the char significantly slows the rate of carbon's return to the atmosphere (Roberts et al., 2009; Lehmann, 2007a). The biochar surface weathers and oxidizes over time, but the skeleton structure remains intact, having long-term effects on soil bulk density and water holding capacity (Grob et al., 2011). Adding biochar to soils has been practiced for thousands of years to turn dense clay soils into more porous media for improved root growth (Lehmann et al., 2006; Glaser et al., 2002).

Pyrolysis reactors have many different parameters that affect the quality of the biochar. The type of feedstock also affects the resultant biochar's properties. It is important to understand the type of char that is in demand, as well as understanding feedstock preparation needs, so that the pyrolysis reactor and associated facilities can be built and operated accordingly. Uses and property evaluation of the biochar made from specific woody materials has been studied (Lehmann and Joseph, 2009), and biochar businesses processing these materials are popping up around the United States. Several facilities are producing biochar for use as a soil amendment or potting mix (Garcia-Perez et al., 2013; 2012a; Knight, 2012). Undoubtedly, one way to incorporate pyrolysis into a composting facility is to tap into the adsorbent market.

In Japan, the use of biochar production facilities was examined for treating MSW. Although the process operated as anticipated, it was found that there were problems with energy efficiency and char utilization. Possible solutions included (1) optimizing the input waste composition, treatment parameters, and types of unit operations, and (2) securing biochar purchasing contracts with thermal electric power companies, iron manufacturers, and cement production plants (Hwang and Kawamoto, 2010).

Bio-oils and other chemicals

The pyrolysis liquid product contains bio-oils and other compounds. Chemicals have been extracted from pyrolysis oil for hundreds of years, and there are several technologies available for adding value to the oil (Garcia-Perez et al., 2012b). The bio-oil has insecticidal, bactericidal, and fungicidal properties (Bedmutha et al., 2011; Booker et al., 2010). One study found that bio-oil enhanced plant growth (Fernandez-Akarregi et al., 2010). It is possible to extract acetic acid, aldehydes, ketones, and methanol from the oil (Vitasari, 2012; Rasrendra et al., 2011; Patel and Weusthuis, 2006; Emrich, 1985), and useful aromatic compounds can be made (Pham et al., 2014). Technologies to recover these chemicals have rather high capital expenses, but it is conceivable that a niche market can be exploited.

On the other hand, there are much simpler technologies to convert bio-oil to usable products that do not require a high degree of separation. These include wood adhesives (Effendi et al., 2008; Mohan et al., 2006; Czernik and Bridgewater, 2004), asphalt binders (Williams et al., 2011),

pesticides (Bedmutha et al., 2011; Booker et al., 2010), road deicers (Czernik and Bridgewater, 2004), surfactants (Emrich, 1985), and wood preservatives (Mohan et al., 2006). Sugars can also be extracted from the oil (Czernik and Bridgewater, 2004; Radlein, 1999), which could be sprayed into a composting pile to enhance microbial kinetics, or could be added to AD to enhance methane production.

Energy

From an energy perspective, pyrolysis is a well-developed technology for producing heat that could be utilized within the biorefinery, or to obtain more concentrated forms of energy such as the production of electricity with a steam or gas turbine system (Chiaramonti et al., 2007). Fast pyrolysis can produce oil that typically has a heating value of around 15-20 MJ kg⁻¹ (comparable to the 40 MJ kg⁻¹ for petroleum-derived heating oil). This oil can be sold to rural homeowners, or the electricity can be produced on-site using a variety of engines, as studied previously (Lehto et al., 2013; Chiaramonti et al., 2007; Czernik and Bridgewater, 2004). With further downstream processing, bio-oil can be turned into gasoline, diesel, gas-oil residue, or jet fuel (Elliott et al., 2012; Anex et al., 2010). The char fraction can also be burned for heat.

2.5.2.2.2 Wood-fuel pellets production

Pelletization includes the debarking, chipping, drying and grinding of woody biomass to make wood-fuel pellets for pellet stoves. Pelleting is one of the most promising methods to densify the biomass for long-distance transport. The main advantages of this product are its high density, low moisture content, and high calorific value (approx. 17 MJ kg⁻¹) (Heinimo and Jungiger, 2009).

Wood-fuel pellets are one of the most successfully traded biomass commodities (Heinimo and Jungiger, 2009). The three main producers of pellets are Sweden, Canada and the United States. In the US, the total production of pellets in 2011 was 5.4 million tons. The production in Canada was 2.9 million tons in 2011 (Pellets-Mill.com, 2012). There are approximately 150 pellet plants in the US, each producing between 10,000 to 750,000 tons of pellets per year.

The global production of this commodity has shown a dramatic increase in the last 10 years. In 2001 the global production of pellets was 4 million tons, while in 2013 the global production reached 23.6 million tons. The global pellet market is expected to grow to more than 50 million tons by 2025 (Statista Inc., 2015). This increase is mainly due to an increase in demand from Europe, Japan and South Korea. The geographic position of Washington State offers great economic advantages for exporting pellets to Asia's growing market.

2.5.2.3 Summary

Municipal solid waste contains both readily biodegradable and stable organic fractions. Separated fractions can be processed differently to achieve better waste treatment and stabilization, while allowing a compost biorefinery to process more waste efficiently. Energy, heat, and valuable co-products can result from the AD treatment of wet putrescent material and from the pyrolysis and pellet production treatment of woody biomass waste. Anaerobic digestion is adept at treating the readily biodegradable fraction either in a slurry or dry system. Slurry digesters can produce considerable amounts of liquid effluent, which could be problematic for the compost facility; however, the liquid effluent can either be used as water inputs to the compost feedstock, compost piles, or nutrient recovery units. Nutrient recovery units can be installed for simultaneous recovery of saleable fertilizer and recycling of the liquid as dilution

water to the digester. The choice of AD and pyrolysis reactors is important to consider for ultimate co-product characteristics and market value. Gasification and combustion are other thermal options that could be considered for treating woody biomass waste, and—as with all biorefineries—other additional unit operations could be added to the basic ones being studied here, including greenhouses, drying and bagging operations, and the inclusion of solar units to name just a few.

2.5.3 Part 3 – Technical analysis of emerging technologies

Mass, energy flow, and economics analyses were conducted for (1) pyrolysis producing biochar and heat, (2) pyrolysis producing biochar and electricity, (3) wood-fuel pellet production, and (4) anaerobic digestion with compressed natural gas production. The results of the technical analyses are summarized and discussed below.

2.5.3.1 Pyrolysis for biochar and heat

2.5.3.1.1 Model assumptions: Inputs and process conditions

In our analysis it was considered that the feedstock is a wood waste sized between 10 and 100 mm (3/8-4 in) and mostly free of ferrous and non-ferrous metals. The biomass pretreatment step would be carried out by the same system in operation at the composting facility. The idea was to use the same facilities employed for the preparation of bulking agents, so a new grinder did not have to be purchased (Figure 2.8, Table 2.20). The capacity of the pyrolysis unit would be 100 ton day⁻¹. The initial moisture content of the woody biomass feedstock is expected to be 50% by weight.

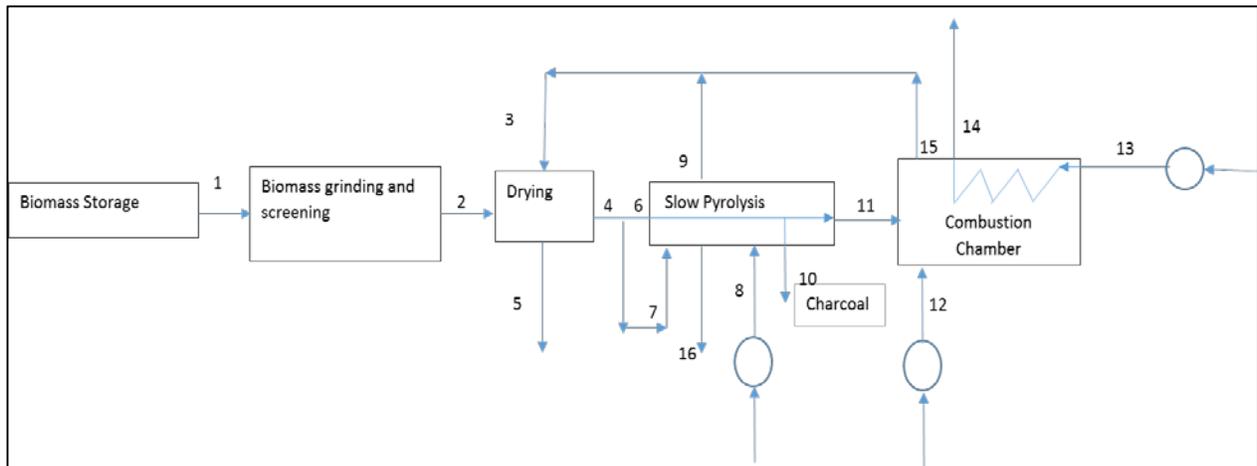


Figure 2.8: Process diagram of the pyrolysis unit with heat recovery. The material properties for each numbered step are listed in Table 2.20.

The woody biomass-rich materials would be received between 4 pm and 6 pm and would be stored in the stockpile that, after grinding (typical size 1-4 inches), would be blended with the stockpile of bulking agents (wood chips). The first processing step was to screen and sort out large materials (greater than 2 inches). The undersized screenings were sent to be mixed while the overs were sent to a secondary screen to remove contaminants. The conveyor would contain a screen that allows the smaller particles to bypass the grinder while the oversize material continues across the screen into the grinder. The product from the grinder would be discharged to

the conveyor that brings the chips into a chips pile. The chips would have 25 x 25 mm size and would be stored in a covered storage system. Two new front-end loaders (20 ton hour⁻¹ capacity each) would process the 100 ton day⁻¹ biomass in three hours. These front-end loaders would need to be purchased to meet the processing demand.

Table 2.20: Properties of main streams.

N°	Description	Flow rate (ton day ⁻¹)	Temperature (°C)	Pressure (atm)	Moisture content (wt.)
1	Biomass	100	25	1	50
2	Biomass	100	25	1	50
3	Combustion gases	-	-	1	-
4	Biomass	-	80	1	10
5	Exhaust gases	-	120	1	-
6	Biomass for pyrolysis	-	80	1	10
7	Biomass for combustion	-	80	1	10
8	Combustion air	30% excess	25	1	-
9	Combustion gases	-	> 600°C	1	-
10	Charcoal	-	80	1	-
11	Pyrolysis gases	-	500	1	-
12	Combustion air	10% excess	25	1	-
13	Air	-	25	1	-
14	Hot air	-	120	1	-
15	Combustion gases	-	Drying temp.	1	-
16	Ash	-	80	1	-

2.5.3.1.2 Mass, energy, and economic calculations

The calculations for the pyrolysis model follow the same format as the compost model described earlier. The following section describes the results from the mass and energy flow and economics calculations for the pyrolysis-compost facility. Detailed calculations can be found in Appendix K.

Mass and energy flow

Fuel consumption in the tub grinder: The grinder energy requirement was estimated at 10.6 kWh ton⁻¹ and the fuel consumption was estimated at 0.25 L kWh⁻¹ (Levis and Barlaz 2013). The amount of diesel needed to run the grinder would be 265 L day⁻¹. This is the largest energy cost of the process.

Fuel consumption by the front-end loader: The front-end loaders use 0.33 kWh ton⁻¹ of energy (Komilis and Ham, 2004; Levis and Barlaz, 2013) and consume 0.26 kWh⁻¹ of fuel (Levis and Barlaz, 2013). The two new front loaders would be consuming 8.58 L day⁻¹ of diesel.

Drier: The drier would be a rotary drum type. The energy requirement for the drier would be 117.4 GJ day⁻¹ (1 GJ = 10⁹ J), with heat losses through the walls of the drier equal to 15% of the energy required for drying. Consequently, the energy that would be required for the drying is 134.9 GJ day⁻¹. This energy would need to be provided by the combustion of gases. In order to obtain enough energy for drying and to make sure that the gases leaving the oven are over 130°C (to avoid condensation of water) it will be necessary to combust gases at 584°C, which is the

result of blending the combustion gases from the pyrolysis reactor and the boiler. The total flow of combustion gases used for drying would therefore be 310.5 ton day⁻¹. These gases would leave the drier at approximately 143°C.

The size of the drier was estimated using information reported online (refer to Competitive Price Sawdust Rotary Drum Dryer in <http://hngxjx.en.alibaba.com/>). This Rotary drum drier was designed for sawdust. In our case, the drum should be able to process 100 ton day⁻¹ (4 ton hour⁻¹). The selected drum has a diameter of 1.2 m and a length of 12 m, a speed of 5.8 rpm, and power of 11 kW. The purchase cost of this oven would be \$45,000.

Pyrolysis: The pyrolysis unit would be fed 44.5 ton day⁻¹ of biomass and 4.94 ton day⁻¹ of water (moisture) (10 wt. %) at 80°C. The pyrolysis unit is expected to operate continuously the whole day. The throughput capacity of the unit would be a maximum of 4.2 ton hour⁻¹. The pyrolysis unit would have a silo with a capacity for 20 tons of chips (more than 4 hours of operation). 66.7 GJ day⁻¹ would be needed to run the reactor. The estimated yield of char is 25% of the dry biomass, so 11 ton day⁻¹ of biochar would be produced. The pyrolysis vapor (which includes the moisture, gases, and condensable materials) would be 38 ton day⁻¹. No carrier gas would be used in the pyrolysis reactor. The elemental composition of the biomass, char, and vapor are shown in Table 2.21.

Table 2.21: Elemental composition of biomass, char, and vapor (Suliman et al., *in prep.* [a]).

Material	C	H	N	O	Ash	Water vapor (ton day ⁻¹)	Total (ton day ⁻¹)
Biomass (% dry wt.)	51	8.2	0.4	40	0.3		
Char (% dry wt.)	80	4.5	0.3	14	1.2		
Vapors	14	3.1	0.14	16	-	4.9	38

The mass balance in the combustion chamber coupled with the pyrolysis reactor was conducted assuming that 11% of the biomass needs to be combusted to provide the energy needs of the pyrolysis reactor. In this case it was considered that 30% excess air is needed to completely combust the biomass. The flow of combustion air needed was 49.67 ton day⁻¹. The flow of combustion gases obtained was 10.3 ton day⁻¹ CO₂, 4.7 ton day⁻¹ H₂O (water), 2.7 ton day⁻¹ O₂ (oxygen), and 38.76 ton day⁻¹ N₂. Combusting gases would give out 47.6 GJ day⁻¹, and this enthalpy (heat) is achieved when the temperature of the combustion gases is 600°C. The enthalpy (heat) of the pyrolysis vapors would be 716.7 GJ day⁻¹.

Air heater: The pyrolysis vapors would be combusted with air. It was assumed that 10% excess air would be sufficient. The flow of air needed for combustion is 216.5 ton day⁻¹. The combustion process would result in the production of 50.7 ton day⁻¹ of CO₂, 33.3 ton day⁻¹ of H₂O, 4.6 ton day⁻¹ of O₂, 166.2 ton day⁻¹ of N₂. The total flow of the combustion air would be 254.8 ton day⁻¹.

In order to have enough heat for the drying process it would be necessary to keep the combustion gases from the air heater relatively hot, at 427°C. This would result in an enthalpy of the gases of 200.7 GJ day⁻¹. Knowing the enthalpy of the pyrolysis vapors, it was possible to estimate the

energy available to produce hot air. In this case, it was considered that 10% of the energy available was lost through the walls of the air heater. Consequently, the amount of energy for the production of hot air would be 464.1 GJ day⁻¹. The air would be heated from 25°C to 120°C. The estimated mass of hot air that could be produced with 461.4 GJ day⁻¹ was estimated at 4,888.6 ton day⁻¹.

Capital cost estimation

This pyrolysis system has the following equipment: drier, pyrolysis reactor, fan for biomass burning, fan for pyrolysis vapor burning, and a combustion chamber for hot air production. Two front-end loaders (20 ton hour⁻¹ capacity each) are also needed for the extra processing. The estimated equipment cost is \$0.5 million (Table 2.22). Total Capital Investment (TCI) costs were \$2.1 million (Table 2.23). The assumed loan interest is 5.12%, which would be paid over 20 years. The capital recovery would be \$0.58M year⁻¹. The yearly payment would then be \$170,932 year⁻¹.

Table 2.22: Equipment cost for the pyrolysis for biochar and heat model (Seider et al., 2009).

Equipment	Estimated cost (\$)
Drier (direct-heat rotary drum) (2015)	45,000
Pyrolysis reactor (2015)	120,724
Fan 1 (biomass burning) (2015)	2,338
Fan 2 (pyrolysis vapor burning) (2015)	3,508
Combustion chamber (2015)	350,770
Total (2015)	522,340

Table 2.23: Calculation for the Total Capital Investment (TCI) for the pyrolysis for biochar and heat system to be added to a composting facility (see Peters et al., 2003, p. 251, for a solids processing plant).

Calculation of FCI	Coefficients	Cost updated 2015 (\$)
Purchased equipment cost (PEC)	100%	522,340
Delivering of Equipment cost	10%	52,234
Delivered Equipment (DPEC)		574,574
Installation % of DPEC	45%	258,558
Instrumentation and controls (installed) % of DPEC	18%	103,423
Piping (installed) % of DPEC	16%	91,931
Electrical System (installed) % of DPEC	10%	57,457
Buildings (including services) % of DPEC	25%	143,643
Yard improvements % of DPEC	15%	86,186
Total direct plant cost		1,315,774
Engineering and supervision % of DPEC	33%	189,609
Construction expenses % of DPEC	39%	224,083
Legal expenses % of DPEC	4%	22,983
Contractors' fee % of DPEC	17%	97,677
Contingency % of DPEC	35%	201,100
Total indirect plant cost		735,454
Fixed capital investment (FCI)		2,051,229
Start up (SU) % of DPEC	10%	57,457
Total Capital Investment (TCI)		2,108,686

Operation and maintenance costs

The total estimated O&M for the pyrolysis system were \$1 million year⁻¹ (Table 2.24). Labor was the most expensive, followed by maintenance, operating overhead, property taxes and insurance, diesel, and electricity.

Table 2.24: Estimated annual cost for operation and maintenance.

Item	Annual cost (\$)
Diesel	52,531
Electricity (2 motor)	24,262
Maintenance (5% of capital cost)	105,434
Labor (12 workers, \$20 h ⁻¹)	594,432
Property taxes and insurance (3% capital cost)	63,261
Operating overhead (22.8% of maint. and labor)	159,569
Total	999,489

Gross earnings

Earnings would come from the sale of biochar and from the tipping fees for the added waste mass that can be processed. The default selling price for the biochar produced was estimated at \$200 ton⁻¹, which assumes mostly bulk sales. The revenue from selling biochar was \$0.66 million year⁻¹. The earnings from tipping fees were expected to be \$1.8 million year⁻¹. The total earnings were therefore \$2.5 million year⁻¹, with gross earnings of \$1.3 million year⁻¹ (Table 2.25). Notably, in the assumptions, price received for biochar was a concern, as markets for biochar are not mature and the assumed price point of \$200 ton⁻¹ cannot be assured with long-term contracts, particularly if the char is not engineered for high-value purposes.

Table 2.25: Summary of factors to calculate the gross earnings.

Cost breakdown	Estimate (\$ year⁻¹)
Capital	170,932
Operation & maintenance	999,489
Annual revenues (total earnings)	2,467,800
Gross earnings (before taxes)	1,295,578

Case 1: If we assume that the money for the capital cost is obtained from the bank at 5.12% interest per year, in order to pay the capital (\$2.1M) and the interest in 20 years we would need to pay \$170,932 year⁻¹. When federal taxes (\$440,496 year⁻¹) are included, the net earning is \$855,081 year⁻¹.

Case 2: If the facility owner provides funds for capital costs, then the gross earnings of the plant (before taxes) would be \$1,468,310 year⁻¹. The federal taxes would be \$499,225 year⁻¹. The net earnings would therefore be \$969,085 year⁻¹. This would result in a ROI of **46%** per year, which is much higher than the ROI of the composting facility alone, which had an ROI of **14%**. Our results were similar to those reported by Miles (2009) for a facility with similar capacity. Mr. Miles estimated a capital cost in 2009 of \$0.5-\$1 million (equivalent to 2015 costs of \$0.57 million to \$1.14 million). The capital cost of the modeled facility was higher (\$2.1 million). Mr. Miles considered that it was possible to obtain revenues from the heat produced for amounts

equivalent to \$320,000 year⁻¹; this was not considered as a source of revenue in this case. The operation and maintenance costs in this study were also higher than the costs estimated by Mr. Miles (\$1.0 million year⁻¹ vs. \$0.4 million year⁻¹). A reduction in the capital cost and O&M costs of the unit, obtaining better selling prices for the biochar, and obtaining revenue for selling the heat produced can improve the economic viability of producing biochar. The tipping fees are currently necessary to make this approach viable, because the revenue for selling the biochar does not cover the O&M costs.

2.5.3.2 Pyrolysis for biochar and electricity

2.5.3.2.1 Model assumptions: Inputs and process conditions

This pyrolysis setup produces steam from a Rankine cycle. Instead of producing hot air, electricity is obtained. The two main pieces of equipment that are added to the previous system are a steam boiler and a turbine (Figure 2.9).

2.5.3.2.2 Mass, energy, and economic calculations

The mass and energy balance of the Rankine cycle is very similar to the previous case. It was assumed that 464.4 GJ day⁻¹ were available to produce steam. The water would enter the boiler at 40°C and would be used to produce super-heated steam at 320°C and 20 atm. The following section describes the results from the mass and energy flows and the economics analysis. Detailed calculations can be found in Appendix K.

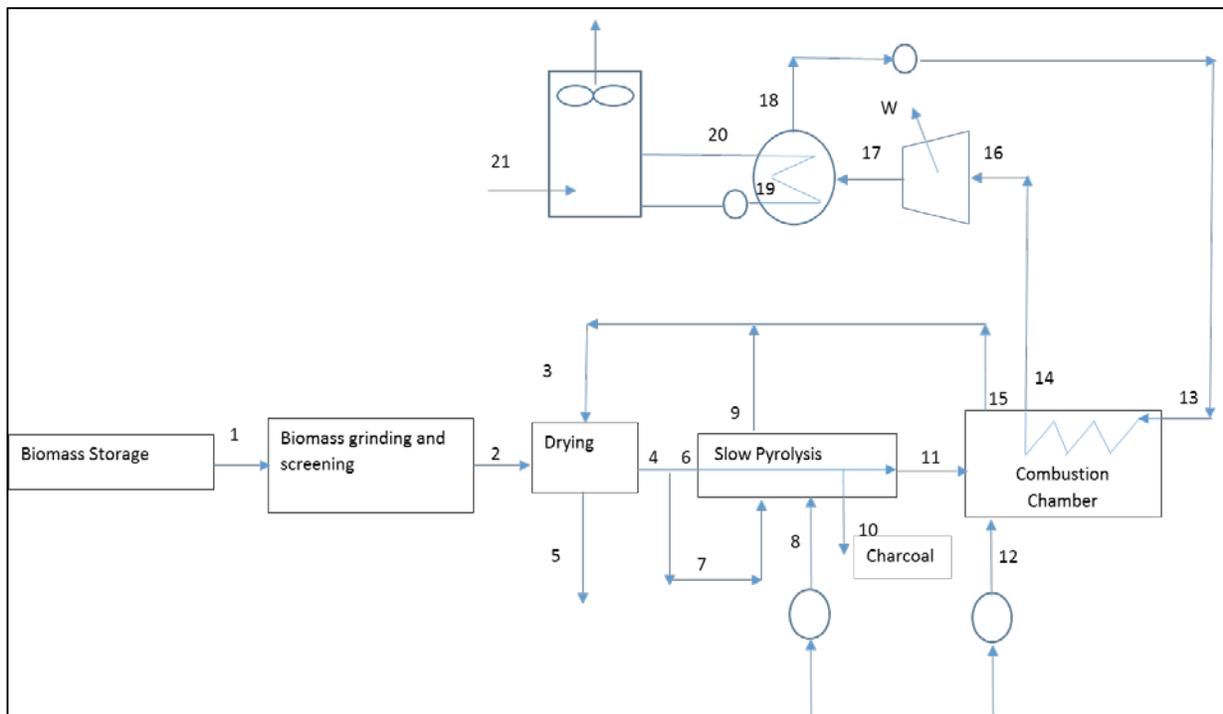


Figure 2.9: Scheme for a pyrolysis unit with a Rankine cycle for the production of electricity and biochar.

Mass and energy flow

The amount of steam that would be produced was equal to 160.1 tons day⁻¹. The power output of the turbine would be 14,741 kWh day⁻¹. The composting facility would consume 9,325 kWh day⁻¹, so the overall production for export would be 5,417 kWh day⁻¹. For a flow of 160.1 tons day⁻¹ of condensed steam, the amount of heat lost would be 383.2 GJ day⁻¹.

Capital cost estimation

Capital cost estimates are similar to the pyrolysis system for biochar and heat, but this system would be more expensive, mostly from the purchase of a turbine (Table 2.26). In summary, the Total Capital Investment cost would be \$4.7 million (Table 2.27). The capital recovery cost would be \$378,123 year⁻¹.

Table 2.26: Equipment cost.

Item	Cost (\$)
Steam boiler (2015)	166,704
Turbine (2015)	454,837
Condenser (2015)	11,600
Other equipment (previous section) (2015)	522,340
Total (2015)	1,155,481

Table 2.27: Calculation for the Total Capital Investment (Peters et al., 2003).

Calculation of FCI	Coefficients	Cost updated 2015 (\$)
Purchased Equipment cost (PEC)	100%	1,155,481
Delivering of Equipment cost	10%	115,548
Delivered Equipment (DPEC)		1,271,029
Installation % of DPEC	45%	571,963
Instrumentation and controls (installed) % of DPEC	18%	228,785
Piping (installed) % of DPEC	16%	203,364
Electrical System (installed) % of DPEC	10%	127,102
Buildings (including services) % of DPEC	25%	317,757
Yard improvements % of DPEC	15%	190,654
Total direct plant cost		2,910,656
Engineering and supervision % of DPEC	33%	419,439
Construction expenses % of DPEC	39%	495,701
Legal expenses % of DPEC	4%	50,841
Contractors' fee % of DPEC	17%	216,074
Contingency % of DPEC	35%	444,860
Total indirect plant cost		1,626,917
Fixed capital investment (FCI)		4,537,574
Start up (SU) % of DPEC	10%	127,103
Total Capital Investment (TCI)		4,664,677

Operation and maintenance costs

The estimated total O&M cost for the pyrolysis system for biochar and electricity would be \$1.2 million (Table 2.28), which is higher than the pyrolysis system for biochar and heat (\$1.0 million).

Table 2.28: Estimated annual cost for operation and maintenance.

Item	Annual cost (\$)
Diesel	52,531
Electricity	24,262
Maintenance	233,233
Labor (12 workers, \$20 h ⁻¹)	594,432
Property taxes and insurance (3% of capital cost)	139,940
Operating overhead (22.8% of maint. and labor)	188,707
Total	1,233,107

Gross earnings

Total earnings would be the same as the previous pyrolysis model (\$2.47 million year⁻¹), but the unit would also sell electricity (\$229,960 year⁻¹). The total earnings would therefore be \$2.7 million year⁻¹, and gross earnings would be \$1.1 million year⁻¹ (Table 2.29).

Table 2.29: Summary of factors to calculate the gross earnings.

Cost breakdown	Estimate (\$ year⁻¹)
Capital	378,123
Operation & maintenance	1,233,107
Annual revenues (total)	2,697,760
Gross earnings (before taxes)	1,086,530

Case 1: If the assumption is that the money for the capital cost is obtained from the bank at 5.12% interest per year, paying the capital (\$4.7 million) and the interest over 20 years would require \$378,123 year⁻¹. When taxes (\$369,420 year⁻¹) are included, the net earning becomes \$717,110 year⁻¹.

Case 2: If the owner of the facility provides all of the capital cost, the gross earnings of the plant (before taxes) would be \$1,464,653 year⁻¹. The federal taxes would be \$497,982 year⁻¹. The net earnings would therefore be \$966,671 year⁻¹. This would result in a ROI of 21% per year. This ROI is considered acceptable and competitive with current commercial interest rates, but it is lower than the ROI of the pyrolysis system for biochar and heat, estimated at 46%.

2.5.3.3 Wood-fuel pellet production

2.5.3.3.1 Model assumptions: Inputs and process conditions

In this scenario, a pellet mill system would be used to make wood-based fuel for pellet stoves. The capacity of the pellet mill system is 100 tons day⁻¹, processing woody biomass with 50% moisture content. The facility would be operated 24 hours per day. The lifespan of the project would be 25 years. First, the woody biomass would be placed in a rotary cutter to reduce the size of the original woody biomass, and then it would be transported by a belt conveyor to a hot air stove to reduce the moisture content down to 10% (Figure 2.10). Then, another belt conveyor would deliver the dry biomass to a hammer mill where the final size would be less than 3 mm.

The dried pieces of woody biomass would then be carried up into a material bin in which it would be stored. From the material bin, a feeder would feed the biomass into two parallel pellet mill units, where the pellets would be made. From there a belt conveyor and a bucket elevator would transport the pellets to a counter flow cooler. Another belt conveyor and bucket elevator would then carry the cold pellets to a vibrating screener before going on to a finished product silo. The pellets would finally be packaged by a packing machine (Figure 2.10).

Economic calculations

The purchasing information for each of the equipment units was obtained from a quotation generated by Jinan Biomass Machinery Equipment Co., Ltd (<http://www.bio-machinery.com/>, retrieved 4/14/2015). The following section describes results from the economics analysis. Detailed calculations can be found in Appendix K.

Capital cost estimation

Equipment needs and cost for the pre-treatment step (Table 2.30) is more than the pellet production step (Table 2.31) for making wood-fuel pellets. After taking into consideration the reduction of moisture content from 50 to 10% by weight, the specific equipment for pellets would have a capacity of 2.31 tons hour⁻¹. Parameters with a lifespan equal or greater to the project selected time (25 years) were discounted in year zero (0) in the cash flow. Other parameters with a lifespan less than 25 years were discounted as an annual equivalent cost. The purchase cost of all the equipment is estimated to be \$666,921.

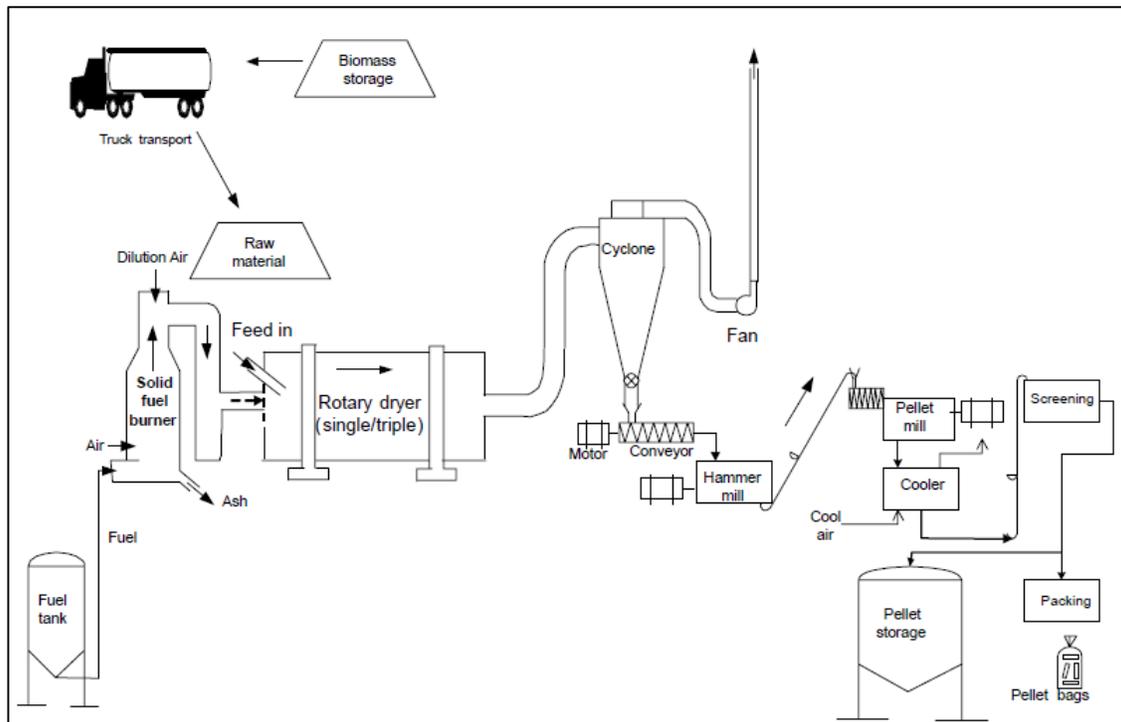


Figure 2.10: Schematic layout of typical biomass pelleting plant (Mani et al., 2006).

The TCI costs are estimated at \$2.7 million (Table 2.32). In this case the interest of the bank was assumed to be 5.12%, and the number of years 25. The yearly payment would then be \$193,334 year⁻¹.

Table 2.30: Equipment needed for woody biomass pretreatment (Quote from: Jinan Biomass Machinery Equipment; <http://www.bio-machinery.com/>, retrieved 4/14/2015).

Equipment	Total price with scaling factor (\$)
Rotary Cutter	199,450
Belt Conveyor	6,205
Rotatory Drum	141,968
Fan blower	6,538
Cyclone	5,873
Air lock	1,662
Belt Conveyor	6,205
Hammer Mill	64,637
Fan blower	5,540
Cyclone	5,430
Air lock	4,986
Total	448,494

Table 2.31: Equipment needed for woody biomass pellet production (Quote from: Jinan Biomass Machinery Equipment; <http://www.bio-machinery.com/>, retrieved 4/14/2015).

Equipment	Quantity (Set)	Total price with scaling factor (\$)
Biomass level meter	2	433
Biomass bin	1	6,395
Feeder	2	3,816
Conditioner	2	3,610
Pellet mill	2	82,517
Belt conveyor	1	1,186
Bucket elevator	1	1,908
Air lock	1	1,289
Counter flower cooler	1	4,951
Fan blower	1	1,599
Cyclone	1	908
Air lock	1	567
Belt conveyor	1	1,496
Bucket elevator	1	2,166
Vibrating Screener	1	2,940
Air lock	1	774
Transporting pipes	2	1,341
Cyclone	1	516
Silo	1	2,837
Packing machine	1	5,014
Bag dust collector	2	9,902
Electronic control	1	11,862
Control cabinet	1	14,956
Total		218,427

Table 2.32: Fixed capital investment (FCI) calculations for pretreatment and pellet production for 5 tons hour⁻¹ capacity and with a scaling factor of 1.65 (Peters et al., 2003).

Calculation of FCI	Coefficients	Cost updated 2015 (\$)
Purchased Equipment cost (PEC)	100%	666,921
Delivering of Equipment cost (of PEC)	10%	66,692
Delivered Equipment (DPEC)		733,613
Installation % of DPEC	45%	330,126
Instrumentation and controls (installed) % of DPEC	18%	132,050
Piping (installed) % of DPEC	16%	117,378
Electrical System (installed) % of DPEC	10%	73,361
Buildings (including services) % of DPEC	25%	183,403
Yard improvements % of DPEC	15%	110,042
Total direct plant cost		1,679,974
Engineering and supervision % of DPEC	33%	242,092
Construction expenses % of DPEC	39%	286,109
Legal expenses % of DPEC	4%	29,344
Contractors' fee % of DPEC	17%	124,714
Contingency % of DPEC	35%	256,765
Total indirect plant cost		939,025
Fixed capital investment (FCI)		2,618,999
Start up (SU) % of DPEC	10%	73,361
Total Capital Investment (TCI)		2,692,360

Operation and maintenance costs

The total O&M cost for pellet production was estimated at \$1.1 million, with the majority of the costs incurred as a result of labor (Table 2.33).

Table 2.33: Estimated annual cost for operation and maintenance.

Item	Annual cost (\$)
Diesel	52,531
Electricity	173,160
Maintenance	91,156
Labor (12 workers, \$20 h ⁻¹)	594,432
Property taxes and insurance (3% of the capital cost)	80,771
Operating overhead (22.8% of maintenance and labor)	156,314
Total	1,148,364

Gross earnings

Earnings would come from the sale of wood-fuel pellets and from the increased earnings from tipping fees for the added waste mass that can be processed. The default selling price for the pellet produced was estimated at \$230 ton⁻¹, which assumes mostly bulk sales (EEA, 2015; Pirraglia et al., 2015; Mani et al., 2006). The cost of making the pellets would be \$44.7 ton⁻¹. This number is very close to the production cost of \$51 ton⁻¹ reported by Mani et al. (2006), but it is lower than those reported by Samson and Duxburty (2000) (\$72 to \$102 per ton). The revenue for selling pellets would be \$3.0 million year⁻¹. The earnings from tipping fees would be

\$1.8 million year⁻¹. The total earnings would then be \$4.8M year⁻¹, and gross earnings would be \$3.5 million year⁻¹ (Table 2.34).

Table 2.34: Summary of factors to calculate the gross earnings.

Cost breakdown	Estimate (\$ year⁻¹)
Capital	193,334
Operation & maintenance	1,148,364
Annual revenues (total)	4,800,000
Gross earnings (before taxes)	3,458,303

Case 1: If the assumption is that the money for the capital cost is obtained from the bank at 5.12% interest per year, paying the capital (\$2.7 million) and the interest over 25 years would require \$193,334 year⁻¹. Total gross earnings would be \$3.46 million year⁻¹, and federal taxes would be \$1.17 million year⁻¹. The net earnings of the unit would then be \$2.28 million year⁻¹.

Case 2: If the owner of the facility provides all of the capital cost, then the federal taxes would be \$1,241,556 year⁻¹. The gross earnings of the plant (before taxes) would be the same as in Case 1: \$3.46 million year⁻¹. The net earnings would then be \$2.41 million year⁻¹. This would result in an ROI of 88% per year. This is much higher than composting (14%), pyrolysis for biochar and heat (46%), and pyrolysis for biochar and electricity production (21%). This ROI is acceptable and competitive with current commercial interest rates.

2.5.3.4 Anaerobic digestion with Compressed Natural Gas production

2.5.3.4.1 Model assumptions: Inputs and process conditions

The development of the anaerobic digestion process model was based on the data from an AD receiving food scraps (Angelidaki et al., 1999). A flow rate of 120 tons day⁻¹ of source-separated food scraps from commercial venues (e.g., grocery stores) was assumed, producing 100 tons day⁻¹ of compost leachate. The AD system would operate 8,000 hours year⁻¹, with a daily production capacity of 220 tons of feedstock per day. A slurry digester was chosen for this first modeling effort.

The AD process was constructed in the Aspen PlusTM process engineering software (Aspen Technologies, Inc.). In this program, several types of processes can be linked to create a unique system based on input and process conditions assumptions. A process consists of components being mixed, separated, heated, cooled, and converted by unit operations. These components can be transferred from unit to unit through process streams. Aspen Plus process simulation models can be used to predict process behavior. The user can interactively change specifications, such as operating conditions, and feed compositions, to run new scenarios and analyze alternatives.

Systems can be set up in Aspen Plus by following these steps:

- Define the process flowsheet configuration.
- Define the unit operations in the process. Select unit operation models from the Aspen Plus model library to describe each unit operation.
- Define the process streams that flow between these unit operations.
- Specify the chemical components in the process. Use components from the Aspen Plus databanks, or define them.

- Choose appropriate thermodynamic models from those available in Aspen Plus, to represent the physical properties of the components and mixtures in the process.
- Specify the component flow rates and the thermodynamic conditions (e.g., temperature and pressure) of feed streams to the process.
- Specify the operating conditions for the unit operations in the flowsheet.

Thermodynamic calculations: The biochemical conversion of lignocellulosic biomass to ethanol model (Non-Random Two-Liquid model) was used to calculate liquid activity coefficients for the thermodynamic property method. Vapor enthalpy, entropy, Gibbs energy and density are computed from an equation of state, which can be related to other properties through fundamental thermodynamic equations.

Anaerobic digestion: The anaerobic digestion process was modeled using 14 types of decomposition reactions as supplied by Banks et al. (2011). The temperature was set at 37°C.

Feedstock: The flow of feedstock to the anaerobic digester was 120 tons day⁻¹ of food scraps and 100 tons day⁻¹ of compost leachate. It was assumed that the food scraps had a total solids (TS) content of 27.7% (Banks et al., 2011). The assumed composition of food scraps was mainly carbohydrates, protein, and lipids (Table 2.35). It was assumed that the compost leachate was 2.6% sugar, and the rest was water (estimated from practical experience).

Table 2.35: Assumed composition of food scraps used in the anaerobic digester.

Composition	Food scraps (Buffiere et al., 2006)	Inputs in ASPEN plus
Carbohydrate (mg g ⁻¹ DM)	302 – 735	399
Hemicellulose (mg g ⁻¹ DM)	85 – 295	85
Lignin (mg g ⁻¹ DM)	19 – 96	19
Crude protein (mg g ⁻¹ DM)	90 – 208	308
Lipid (mg g ⁻¹ DM)	35 – 81	181
Ash from calcium	0-10	8

Process description for AD-CNG: A block flow diagram of anaerobic digestion with food scraps was setup in ASPEN Plus to model the system (Figure 2.11). Food scraps, including mostly biodegradable organics (carbohydrates, proteins and lipids) would be fed to a mixer and diluted with compost leachate. The slurry stream would be pumped to a heat exchanger and then into an anaerobic digester. After anaerobic digestion, the slurry would be sent to a buffer tank to separate the biogas. The slurry would be continually sent to a solid-liquid separator. After separation, the effluent would be pumped out of the system and the residuals would also be removed. The residuals would be used as organic fertilizer. The biogas would be sent to gas purification. N-methyl-2-pyrrolidone (NMP) is one of the popular physical solvent methods to remove acid gas such as CO₂ and H₂S (Burr and Lyddon, 2008). Higher pressure favors the absorption of CO₂. Thus the biogas stream would first use a compressor to increase pressure, and then use a heat exchanger to decrease the temperature. After purification, more than 96% CH₄ in biogas would be sent out the system as CNG to be used in vehicles.

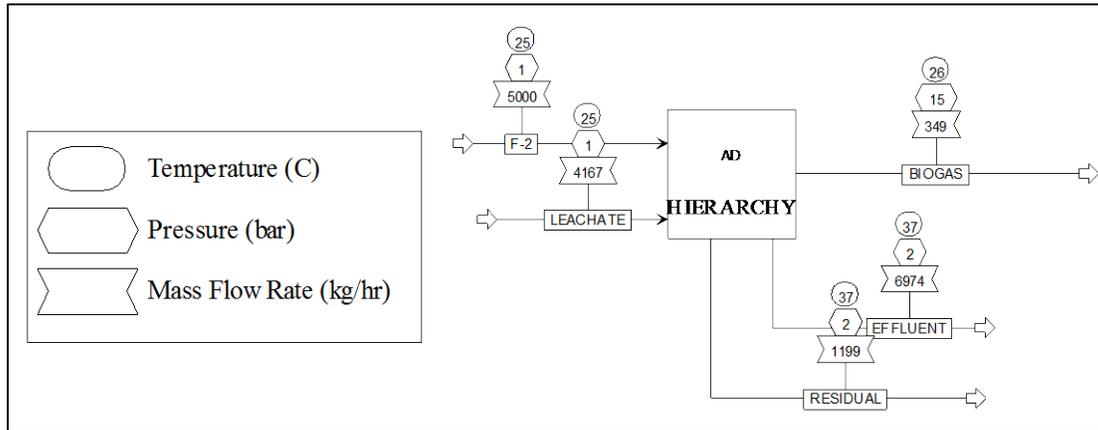


Figure 2.11: Block flow diagram of anaerobic digestion with food scraps.

2.5.3.4.2 Mass, energy, and economic calculations

A summary of the model results are discussed below. More information can be found in Appendix L.

Mass and energy balances

The products from the AD-CNG system are biogas and organic fertilizer (Figure 2.12). The amount of CNG produced (96% CH₄) was estimated at 12,690 m³ day⁻¹ (4,230,000 m³ year⁻¹). The amount of effluent generated was estimated at 196 tons day⁻¹, which would produce 29 tons day⁻¹ of organic fertilizer.

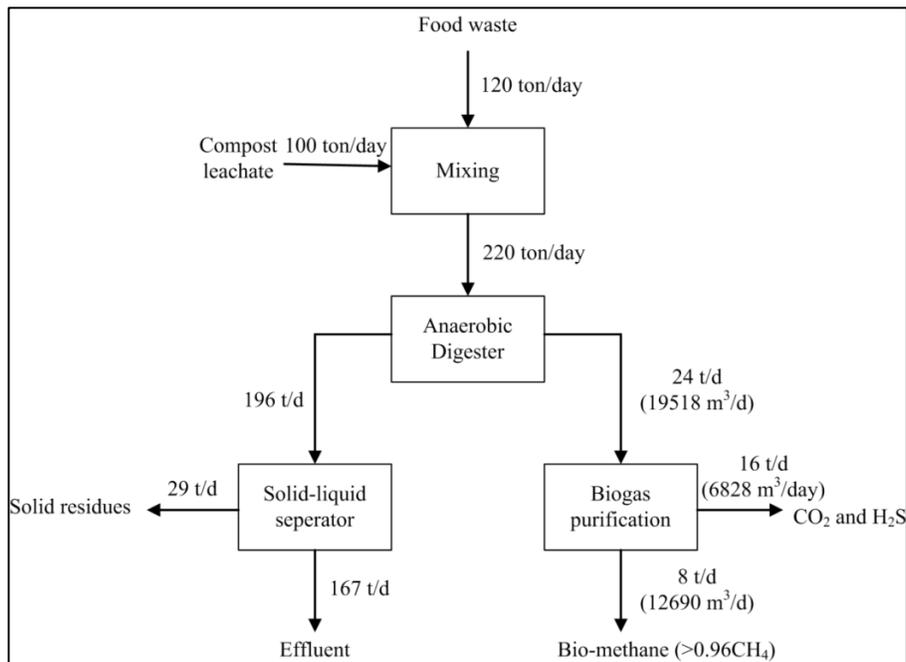


Figure 2.12: AD-CNG mass flow diagram.

Cost estimation

The ASPEN software calculated capital costs associated with initially building and starting the system, as well as operating costs associated with processing the material. The model is capable of calculating these costs for the user, or the user may directly enter the capital and operating cost coefficients, if these costs are known. The ASPEN Capital Cost Estimator was used, which uses the equipment models contained in the Icarus Evaluation Engine—a knowledge base of design, cost, and scheduling data, methods, and models—to generate preliminary equipment designs and to simulate vendor-costing procedures to develop detailed Engineering-Procurement-Construction estimates.

Capital cost

The estimated capital cost was \$15.0 million (Table 2.36). The adjusted total project cost was \$14.8 million year⁻¹ based on ASPEN output and adjustments from experience reported from the industry.

Table 2.36: Estimation of capital costs.

Account	Total Cost (\$)
Equipment	7,048,255
(Above Ground) AG Pipe	382,579
Piling	35,201
Concrete	77,793
Grout	4,719
Steel	57,346
Instrumentation	650,124
(Under Ground) UG Electrical	22,532
(Above Ground) AG Electrical	512,462
Pipe Insulation	26,505
Equip Insulation	4,827
Paint	31,643
Direct Total Cost	8,853,986
Const Equip & Indirect	395,600
Const Mgt, Staff, Sup	301,600
Freight	337,300
Taxes and Permits	527,000
Engineering	1,550,400
Other Project Costs	720,914
Contingency	2,283,624
Indirect Total Cost	6,116,438
Total Project Capital Cost	14,970,424
Adjusted Total Project Cost	14,800,271

Operation and maintenance costs

Total O&M was estimated at \$1.39 million year⁻¹. The largest cost was maintenance, followed by plant overhead, labor, utility, general and administrative, and operating charges (Table 2.37).

Table 2.37: Estimation of operation and maintenance costs.

Account	Estimated annual cost (\$)
Raw materials	0
Utility ¹	122,256
Labor ²	240,000
Maintenance (3.3% of total project cost)	498,000
Operating charges (25% of labor)	60,000
Plant overhead (50% of labor and maintenance)	369,000
General and administrative (8%) ³	103,140
Total	1,392,397

¹ The electricity price is \$0.078 kWh⁻¹ and the total electricity cost is \$98,694. The water price is \$0.0317 m⁻³ and the total water heat and cooling cost is \$23,561.

² Labor costs include 3 operators per shift and no supervisory costs (\$10 h⁻¹, Levis and Barlaz, 2013).

³ Includes administrative salaries/expenses, R&D, product distribution and sales cost.

Revenues

Revenues were calculated from expected sales of the products (CNG and fertilizer), tipping fees, and credits. It was assumed that the price of natural gas was \$0.52 m⁻³ (provided by vendor quotes from DVO Inc.). Anaerobic digestion fertilizer was expected to sell at \$20 ton⁻¹ (Levis and Barlaz, 2013). Tipping fees were set at \$60 ton⁻¹. Approximately 70% of the food scraps received would be eligible for carbon credits (\$5 ton⁻¹). RINS (renewable identification numbers) are currently 0.5 credits ton⁻¹ of food scraps (\$0.73 GGE⁻¹, gasoline gallon equivalent). The total earnings were therefore estimated at \$5.0 million year⁻¹ (Table 2.38).

Table 2.38: Estimation of revenue.

Name	Estimated annual cost (\$)
Biogas (96% CH ₄)	2,035,268
Organic Fertilizer	70,017
Carbon credits	140,035
RINS	348,562
Tipping fee	2,400,000
Total	5,046,354

Gross earnings and net earnings

In this scenario, the investment could be paid back in 5.31 years at the return rate of 10%. The profitability index (PI) was calculated at 1.52. When PI > 1, the project is considered acceptable. The estimated ROI (assuming ROI is the total revenue divided by the total project cost × 100) was 34%.

The effect of plant capacity on AD-CNG profitability was estimated. The facility started to be profitable (PI = 1) when the daily methane production capacity reached 5,000 m³ (Figure 2.13). Profit increased as capacity grew from 5,000 to 30,000 m³; after that, the facility would require larger equipment. In summary, results suggest that using the maximum capacity of the AD reactor provides a higher profitability index.

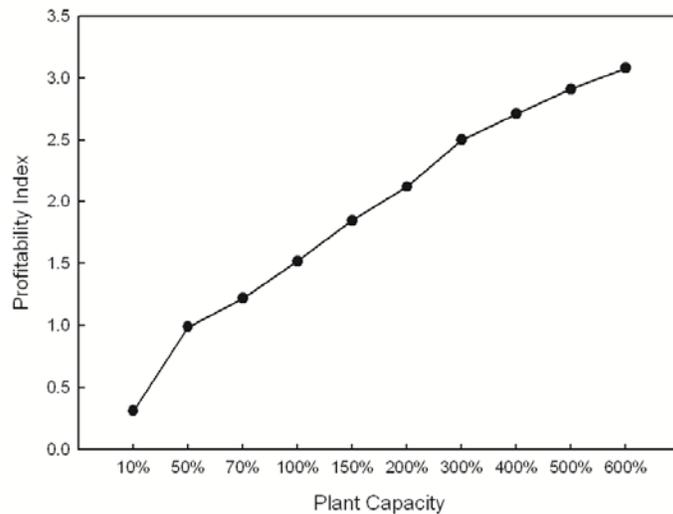


Figure 2.13: Effect of plant capacity on AD-CNG profitability.

2.5.3.5 Summary

This section detailed the design and economics of potential add-on technologies to the baseline compost model. Specifically, these were an AD process for production of CNG so as to treat a specialized flow of industrial food scraps. The use of a slurry digester was modeled, assuming that dilution water could be obtained from compost leachate. The resulting liquid effluent could either be used for wetting the compost feedstock, compost pile hydration if needed, or recycled back to the AD unit as dilution water after being processed through nutrient recovery units. These are viable options, although modeling these scenarios were not part of this initial study. Meanwhile, a separate flow of stable wood-based organics would be treated either through pyrolysis or wood-fuel pellet formation. Products would be heat and biochar, biochar and electricity, or wood-fuel pellets. Economics at these proposed larger scales were promising, with estimated ROI values being particularly encouraging for wood-fuel pellets and AD-CNG as the respective treatments for separate stable and readily biodegradable organics, respectively. It is worth noting that economic models are dependent upon assumed markets and market price points for products, with many of the product markets and business plans not being mature, and therefore prone to volatility and lower-than-expected pricing. Future modeling efforts will build off of these models to complete lifecycle assessments so as to evaluate the quantitative and economic impact of the environmental savings that could be achieved via integration. Also future studies can incorporate additional unit operations such as nutrient recovery units and greenhouses.

2.6 Conclusions

The use of composting, anaerobic digestion, pyrolysis, and pellet production to recycle organic waste—including the organic waste fraction of MSW—can provide many benefits, such as recycling waste efficiently and producing multiple value-added products and energy. This study demonstrates that tipping fees are providing incentives for composting facilities to process more waste to gain more revenue, although environmental and human health concerns arise when

facilities accept high quantities of putrescible material relative to their facility’s capabilities. Literature shows that AD lowers odor emissions of such green waste, when an AD-composting treatment is compared to composting alone. In addition, capitalizing on the woody waste for biochar or wood-fuel pellet production can offer diverse revenue streams. The integration of different systems with composting could lead to biorefineries with better performance than the existing, sole-purpose composting facilities. This study’s results showed that such integration can also achieve higher rates of return on investment than a composting facility.

Comparing models of pyrolysis for char production, pyrolysis for char and electricity production, and pellet production from 100 tons of woody waste revealed that pellet production had the higher return on investment (88%), followed by pyrolysis producing biochar and heat (46%) and pyrolysis producing biochar and electricity (21%) (Table 2.39). This ROI for the pyrolysis systems may be optimistic, because the highest biochar market price for all char produced was assumed. Anaerobic digestion processing 120 tons of food scraps had a competitive ROI of 34%, although this does not include taxes and operations and maintenance costs (Table 2.39). Estimates from this AD model are also liberal, due to assumed sale value for all fertilizer and CNG products, and that the cheapest system components were chosen. Even in this optimum case, the capital cost for the AD system is \$14.8 million, which is significantly higher than those of pyrolysis and pellet production (\$2.1 million and \$4.7 million, respectively). A less expensive AD system may be needed to more economically treat putrescible material, to initially stabilize the waste and capture energy prior to composting.

Table 2.39: Summary of economic analysis for composting, pyrolysis, pellet production, and AD.

	Composting	Pyrolysis for char	Pyrolysis for char and electricity	Pellet production	AD-CNG
Processing capacity (wet ton day ⁻¹)	667	100	100	100	120
Waste type	Mixed yard and food scraps	Wood waste	Wood waste	Wood waste	Food scraps
Capital cost (\$, total)	28,409,444	2,108,686	4,664,677	2,692,360	14,800,271
Land purchase	Yes	No	No	No	No
O&M (\$ year ⁻¹)	4,756,311	999,489	1,233,107	1,148,364	1,392,397
Revenue (\$ year ⁻¹)	11,024,538	2,467,800	2,697,760	4,800,000	5,046,354
ROI, 0% financed	14%	46%	21%	88%	34%*

*This ROI was calculated differently; taxes were set at zero and O&M costs were not included.

2.7 References

- Amlinger, F., Peyr, S., Cuhls, C. 2008. Greenhouse Gas Emissions from Composting and Mechanical Biological Treatment. *Waste Management Research* 26, 47–60.
- Anex, R.P., Aden, A., Kazi, F.K., Fortman, J., Swanson, R.M., Wright, M.M., Satrio, J.A., Brown, R.C., Daugaard, D.E., Platon, A. 2010. Techno-economic Comparison of Biomass-To-Transportation Fuels via Pyrolysis, Gasification, and Biochemical Pathways. *Fuel* 89, S29–S35.
- Angelidaki, I., Ellegaard, L., Ahring, B.K. 1999. A Comprehensive Model of Anaerobic Bioconversion of Complex Substrates to Biogas. *Biotechnology and Bioengineering* 63(3), 363–372.
- Bahng, M.-K., Mukarakate, C., Robichaud, D.J., Nimlos, M.R. 2009. Current Technologies for Analysis of Biomass Thermochemical Processing: A Review. *Analytica Chimica Acta* 651(2), 117–138.
- Banks, C.J., Chesshire, M., Heaven, S., Arnold, R. 2011. Anaerobic Digestion of Source-Segregated Domestic Food Waste: Performance Assessment by Mass and Energy Balance. *Bioresource Technology* 102, 612–620.
- Bansal, R.C., Goyal, M. 2005. *Activated Carbon Adsorption*, Taylor & Francis.
- Barrows, B. 2011. Fact Sheet: Food Waste for Delivery to Oregon Composting Facilities. 11-LQ-011. State of Oregon Department of Environmental Quality. Portland, OR.
- Beck-Friis, B., Smars, S., Jonsson, H., Kirchmann, H. 2001. Gaseous Emissions of Carbon Dioxide, Ammonia, and Nitrous Oxide from Organic Household Waste in a Compost Reactor under Different Temperature Regimes. *Journal of Agricultural Engineering Research* 78(4), 423–430.
- Bedmutha, R., Booker, C.J., Ferrante, L., Briens, C., Berruti, F., Yeung, K.K.-C., Scott, I.M., Conn, K.L. 2011. Insecticidal and Bactericidal Characteristics of the Bio-Oil from the Fast Pyrolysis of Coffee Grounds. *Journal of Analytical and Applied Pyrolysis* 90(2), 224–231. <http://dx.doi.org/10.1016/j.jaap.2010.12.011>
- BioCycle. 2005. Plastics Separation in Compost. *BioCycle* 46(9), 58–59. Available online at <http://www.biocycle.net/2005/09/22/plastics-separation-in-compost/>.
- Boldrin, A., Andersen, J.K., Moller, J., Christensen, T.H., Favoino, E. 2009. Composting and Compost Utilization: Accounting of Greenhouse Gases and Global Warming Contributions. *Waste Management Research* 27(8), 800–812.
- Booker, C.J., Bedmutha, R., Vogel, T., Gloor, A., Xu, R., Ferrante, L., Yeung, K.K.-C., Scott, I.M., Conn, K.L., Berruti, F., Briens, C. 2010. Experimental Investigations into the Insecticidal, Fungicidal, and Bactericidal Properties of Pyrolysis Bio-Oil from Tobacco Leaves Using a Fluidized Bed Pilot Plant. *Industrial and Engineering Chemical Research* 49(20), 10074–10079.
- Bridgwater, A.V. 2012. Review of Fast Pyrolysis of Biomass and Product Upgrading. *Biomass Bioenergy* 38, 68–94.
- Buffiere, P., Loisel, D., Bernet, N., Delgenes, J.P. 2006. Towards New Indicators for the Prediction of Solid Waste Anaerobic Digestion Properties. *Water Science and Technology* 53(8), 233–241.
- Burr, B., Lyddon, L. 2008. A Comparison of Physical Solvents for Acid Gas Removal. 87th Annual Gas Processors Association Convention, Grapevine, TX, March. pp. 2–5.

- Cadena, E., Colon, J., Sanchez, A., Font, X., Artola, A. 2009. A Methodology to Determine Gaseous Emissions in a Composting Plant. *Waste Management* 100, 2799–807.
- Cal, M., Strickler, B., Lizzio, A. 2000. High Temperature Hydrogen Sulfide Adsorption on Activated Carbon: Effects of Gas Composition and Metal Addition. *Carbon* 38, 1757–1765.
- Card, T.R., Schmidt, C.E. 2012. Air Emissions Control for Composting Operations. *BioCycle* 53(3), 27–32.
- Chen, L., Hoff, S., Cai, L., Koziel, J., Zelle, B. 2009. Evaluation of Wood Chip-Based Biofilters to Reduce Odor, Hydrogen Sulfide and Ammonia from Swine Barn Ventilation Air. *Journal of the Air and Waste Management Association* 59(5), 520-530.
- Chen, Y., Cheng, J.J., Creamer, K.S. 2008. Inhibition of Anaerobic Digestion Process: A Review. *Bioresource Technology* 99(10), 4044–4064.
- Chiaromonti, D., Oasmaa, A., Solantausta, Y. 2007. Power Generation using Fast Pyrolysis Liquids from Biomass. *Renew. Sustainable Energy Reviews* 11(6), 1056–1086.
- Czernik, S., Bridgewater, A.V. 2004. Overview of Applications of Biomass Fast Pyrolysis Oil. *Energy & Fuels* 18, 590–598.
- de Bertoldi, M., Vallini, G., Pera, A. 1983. The Biology of Composting: A Review. *Waste Management Research* 1(3), 157–176.
- De, M., Azargohar, R., Dalai, A.K., Shewchuk, S.R. 2013. Mercury Removal by Bio-char Based Modified Activated Carbons. *Fuel* 103, 570–578.
- Diaz, L.F., Golueke, C.G., Savage, G.M., Eggerth, L.L. 1993. *Composting and Recycling Municipal Solid Waste*. CRC Press.
- Drennan, M., Distefano, D.T. 2010. Characterization of the Curing Process from High-Solids Anaerobic Digestion. *Bioresource Technology* 101(2), 537–544.
- Ecology. 2010a. Solid Waste in Washington State 19th Annual Status Report, p. 174. Washington State Department of Ecology, Olympia, WA.
- Ecology. 2010b. Washington Statewide Waste Characterization Study. Area, p. 135. Washington State Department of Ecology, Olympia, WA.
- Ecology. 2011. Siting and Operating Composting Facilities in Washington State. Good Management Practices. Washington State Department of Ecology, Olympia, WA.
- Ecology. 2013. Washington State Composted Materials for 2013. Washington State Department of Ecology, Olympia, WA. Updated April 30, 2015.
<http://www.ecy.wa.gov/programs/swfa/organics/pdf/2013CompostedMaterials.pdf>
 Retrieved from <http://www.ecy.wa.gov/programs/swfa/organics/soil.html> on June 9, 2015.
- Effendi, H., Gerhauser, H., Bridgewater, A.V. 2008. Production of Renewable Phenolic Resins by Thermochemical Conversion of Biomass: A Review. *Renewable and Sustainable Energy Reviews* 12(8), 2092–2116.
- Elliott, D.C., Hart, T.R., Neuenschwander, G.G., Rotness, L.J., Olarte, M.V., Zacher, A.H., Solantausta, Y. 2012. Catalytic Hydroprocessing of Fast Pyrolysis Bio-Oil from Pine Sawdust. *Energy & Fuels* 26(6), 3891–3896.
- Emrich, W. 1985. *Handbook of Charcoal Making*, Springer.
- Energy and Environmental Affairs (EEA). 2015. Wood Pellet Price Survey. Retrieved from <http://www.mass.gov/eea/energy-utilities-clean-tech/home-heating/wood/wood-dealers-and-prices.html> on June 17, 2015.

- EPA. 2011. Municipal Solid Waste Generation, Recycling, and Disposal in the United States: Facts and Figures for 2010. EPA-530-F-11-005. US Environmental Protection Agency, Solid Waste and Emergency Response, Washington, DC.
- EPA. 2013. Non-Hazardous Waste Management Hierarchy. Retrieved June 9, 2015, from <http://www.epa.gov/wastes/nonhaz/municipal/hierarchy.htm>.
- Fernandez-Akarregi, A.R., Makibar, J., Cueva, F., Brañas, J., del Campo, P., Piskorz, J., Miranda-Apodaca, J., Robredo, A., Pérez López, U., Lacuesta, M., Muñoz-Rueda, A., Mena-Petite, A. 2010. High Quality Fertilizers Based on Biomass Pyrolysis Bio-Oil and Char. 18th European Biomass Conference and Exhibition, ETA-Florence Renewable Energies, Florence, Italy.
- Frear, C., Ewing, T., Yu, L., Ma, J., Chen, S. 2012. Two Novel Floor-Scale Anaerobic Digester Systems for Processing Food Waste. Part 1: Multi-Reactor, Liquid Recycle System for High Solids. Part 2: Moderate Solids Digester System. Department of Biological Systems Engineering and the Center for Sustaining Agriculture and Natural Resources, 142.
- Garcia-Perez, M., Garcia-Nunez, J.A., Lewis, T., Kruger, C., Fuchs, M.R., Flora, G., Newman, G., Kantor, S. 2013. Methods for Producing Bio-char and Advanced Biofuels in Washington State. Part 4: Literature Review. Sustainability Issues, Business Models and Financial Analysis. Department of Biological Systems Engineering and the Center for Sustaining Agriculture and Natural Resources.
- Garcia-Perez, M., Garcia-Nunez, J.A., Lewis, T., Kruger, C.E., Kantor, S. 2012b. Methods for Producing Bio-char and Advanced Bio-fuels in Washington State. Part 3: Literature Review of Technologies for Product Collection and Refining. Department of Biological Systems Engineering and the Center for Sustaining Agriculture and Natural Resources, 129.
- Garcia-Perez, M., Kruger, C., Fuchs, M., Sokhansanj, S., Badger, P. C., Garcia-Nunez, J. A., Lewis, T., Kantor, S. 2012a. Methods for Producing Bio-char and Advanced Bio-fuels in Washington State. Part 2: Literature Review of Biomass Supply Chain and Processing Technologies (From Field to Pyrolysis Reactor). Second Project Report. (p. 79). Pullman, WA. Retrieved from <http://www.ecy.wa.gov/biblio/1207033.html>
- Garcia-Perez, M., Lewis, T., Kruger, C.E. 2011. Methods for Producing Bio-char and Advanced Biofuels in Washington State. Part 1: Literature Review of Pyrolysis Reactors. Department of Biological Systems Engineering and the Center for Sustaining Agriculture and Natural Resources, 87.
- Glaser, B, Lehmann, J., and Zech, W. 2002. Ameliorating Physical and Chemical Properties of Highly Weathered Soils in the Tropics with Charcoal – A Review. *Biology and Fertility of Soils* 35(4), 219–230.
- Grob, J., Donnelly, A., Flora, G., Miles, T. 2011. Bio-char and the Biomass Recycling Industry. *BioCycle* 50–52.
- Harland, C.E. 1994. *Ion Exchange: Theory and Practice*, Royal Society of Chemistry.
- Haug, R.T. 1993. *The Practical Handbook of Compost Engineering*. CRC Press.
- Heinimo, J., Jungiger, M. 2009. Production and Trading of Biomass for Energy – An Overview of the Global Status. *Biomass Bioenergy* 33, 1310–1320.
- Henstra, A.M., Sipma, J., Rinzema, A., Stams, A.J.M. 2007. Microbiology of Synthesis Gas Fermentation for Biofuel Production. *Current Opinion in Biotechnology* 18, 200–206.
- Holm-Nielsen, J. B., Al Seadi, T., Oleskowicz-Popiel, P. 2009. The future of anaerobic digestion and biogas utilization. *Bioresource Technology* 100 (22), 5478-5484.

- Hwang, K., Kawamoto, K. 2010. Survey of Carbonization Facilities for Municipal Solid Waste Treatment in Japan. *Waste Management* 30 (7), 1423–1429.
- Integrated Waste Management Board (IWMB). 2007. Comprehensive Compost Odor Response Project. Publication # 442-07-001. California IWMB.
- Jahirul, M.I., Rasul, M.G., Chowdhury, A.A., Ashwath, N. 2012. Biofuels Production through Biomass Pyrolysis – A Technological Review. *Energies* 5(12), 4952–5001.
- Knight, E. 2012. Bio-char Companies & Organizations (compiled September 2012 by Erich Knight). Retrieved from http://www.bio-char-international.org/company_list on June 9, 2015.
- Komilis, D.P., Ham, R.K. 2004. Life-Cycle Inventory of Municipal Solid Waste and Yard Waste Composting in the United States. *Journal of Environmental Engineering* 130 (11), 1390–1400.
- Komilis, D.P., Ham, R.K., Park, J.K. 2004. Emission of Volatile Organic Compounds during Composting of Municipal Solid Wastes. *Water Research* 38 (7), 1707–1714.
- Korkisch, J. 1988. *CRC Handbook of Ion Exchange Resins*, Taylor & Francis.
- Kreith, F. 1994. *Handbook of Solid Waste Management*. New York, McGraw-Hill.
- Krogmann, U., Woyzechowski, H. 2000. Selected Characteristics of Leachate, Condensate and Runoff Release during Composting of Bio-Genic Waste. *Waste Management Research* 18, 235–248
- Lehmann, J. 2007a. Bio-energy in the Black. *Frontiers in Ecology and the Environment* 5(7), 381–387.
- Lehmann, J. 2007b. A Handful of Carbon. *Nature* 447, 143–144.
- Lehmann, J., and Joseph, S. 2009. *Bio-char for Environmental Management: Science and Technology*, Earthscan.
- Lehmann, J., Gaunt, J., Rondon, M. 2006. Bio-char Sequestration in Terrestrial Ecosystems – A Review. *Mitig. Adapt. Strat. Global Change* 11(2), 395–419.
- Lehto, J., Oasmaa, A., Solantausta, Y., Kytö, M., Chiaramonti, D. 2013. Fuel Oil Quality and Combustion of Fast Pyrolysis Bio-oils. *VTT Technology* 87, 79.
- Levis, J.W., Barlaz, M.A. 2013. *Composting Process Model Documentation*. North Carolina State University. NC 27695-7908.
- Liu, Z., Zhang, F.-S. 2009. Removal of Lead from Water using Bio-chars Prepared from Hydrothermal Liquefaction of Biomass. *Journal of Hazardous Materials* 167(1), 933–939.
- Lizzio, A.A., DeBarr, J.A. 1996. Effect of Surface Area and Chemisorbed Oxygen on the SO₂ Adsorption Capacity of Activated Char. *Fuel* 75(13), 1515–1522.
- Luo, G., Wang, W., Angelidaki, I. 2013. Anaerobic Digestion for Simultaneous Sewage Sludge Treatment and CO Biomethanation: Process Performance and Microbial Ecology. *Environmental Science and Technology* 47, 10685–10693.
- Ma, J., Wilson, K., Zhao, Q., Frear, C. 2013b. Review of Emerging Nutrient Recovery Technologies for Farm-based Anaerobic Digesters and Other Renewable Energy Systems. Prepared for Innovation Center for US Dairy.
- Ma, M., Wilson, K., Zhao, Q., Yorgey, G., Frear, C. 2013a. *Odor in Commercial Scale Compost: Literature Review and Critical Analysis*. Olympia, WA.
- Mani, S., Sokhansanj, S., Bi, X., Turhollow, A. 2006. Economics of the Producing Fuel Pellets from Biomass. *Applied Engineering in Agriculture* 22(3), 421–426.
- Manser, A.G.R., Keeling, A.A. 1996. *Practical Handbook of Processing and Recycling Municipal Waste*. CRC Lewis Publishers.

- Marsh, H., Reinoso, F.R. 2006. Activated Carbon, Elsevier Science.
- Mata-Alvarez, J., Mace, S., Llabres, P. 2000. Anaerobic Digestion of Organic Solid Wastes. An Overview of Research Achievements and Perspectives. *Bioresource Technology* 74(1), 3–16.
- McCarty, P.L. McKinney, R.E. Salt Toxicity in Anaerobic Treatment. *Journal Water Pollution Control Federation* 33, 399-415 (1961).
- McDonald, D. 2011. How to Make Organics Recycling "Business as Usual". *BioCycle* 52(3), 27–31.
- Meier, D., van de Beld, B., Bridgwater, A.V., Elliott, D.C., Oasmaa, A., Preto, F. 2013. State-of-the-Art of Fast Pyrolysis in IEA Bioenergy Member Countries. *Renewable and Sustainable Energy Reviews* 20, 619–641.
- Melbinger, N.R., Donnellon, J., Zablatzky, H.R. 1971. Toxic Effects of Ammonia Nitrogen in High-Rate Digestion [with Discussion]. *Journal of the Water Pollution Control Federation* 43(8), 1658–1670.
- Miles, T.R. 2009. The Economics of Biochar Production. PNW Biochar Group Meeting, Richland, WA.
- Mohan, D., Pittman, C.U., Jr., Steele, P.H. 2006. Pyrolysis of Wood/Biomass for Bio-oil: Critical Review. *Energy & Fuels* 20(3), 848–889.
- Mohan, D., Sarswat, A., Ok, Y.S., Pittman, C.U. 2014. Organic and Inorganic Contaminants Removal from Water with Bio-char, a Renewable, Low Cost and Sustainable Adsorbent – A Critical Review. *Bioresource Technology* 160, 191–202.
- Nunnally, S.W. 2007. Construction Methods and Management. 7th Ed. Pearson Prentice Hall, Columbus, OH.
- Pagans, E., Barrena, R., Font, X., Sánchez, A. 2006. Ammonia Emissions from the Composting of Different Organic Wastes – Dependency on Process Temperature. *Chemosphere* 62(9), 1534–1542.
- Patel, M., Weusthuis, R.A. 2006. Medium and Long-term Opportunities and Risks of the Biotechnological Production of Bulk Chemicals from Renewable Resources – The Potential of White Biotechnology: The BREW Project. Utrecht University. Final Report. 474.
- Pellets-Mill.com. 2012. Analysis of Global Wood Pellets Market. Retrieved from <http://www.pellets-mill.com/htm/PelletsNews-cn/wood-pellets-global-market166.html> on June 16, 2015.
- Peters, M.S., Timmerhaus, K.D., West, R.E. 2003. Plant Design and Economics for Chemical Engineers, Fifth Edition. McGraw-Hill, 1008 pp.
- Pham, T.N., Shi, D., Resasco, D.E. 2014. Evaluating Strategies for Catalytic Upgrading of Pyrolysis Oil in Liquid Phase. *Applied Catalysis B: Environmental* 145, 10–23.
- Pirraglia, A., Gonzalez, R., Saloni, D. 2015. Wood Pellets: An Expanding Market Opportunity. *Biomass Magazine*. Retrieved from <http://biomassmagazine.com/articles/3853/wood-pellets-an-expanding-market-opportunity> on June 17, 2015.
- Poduska, R.A., Anderson, B.D. 1981. Successful Storage Lagoon Odor Control. *Journal of the Water Pollution Control Federation* 53(3), 299–310.
- Prost, K., Borchard, N., Siemens, J., Kautz, T., Sequaris, J.-M., Moller, A., Amelung, W. 2013. Bio-char Affected by Composting with Farmyard Manure. *Journal of Environmental Quality* 42(1), 164–172.

- Radlein, D. 1999. The Production of Chemicals from Fast Pyrolysis Bio-Oils. CPL Press: Newbury, UK.
- Rasrendra, C.B., Girisuta, B., van de Bovenkamp, H.H., Winkelman, J.G.M, Leijenhors, E.J., Venderbosch, R.H., Windt, M., Meier, D., Heeres, H.J. 2011. Recovery of Acetic Acid from an Aqueous Pyrolysis Oil Phase by Reactive Extraction using Tri-n-octylamine. *Chemical Engineering Journal* 176–177, 244–252.
- Roberts, K.G., Gloy, B.A., Joseph, S., Scott, N.R., Lehmann, J. 2009. Life Cycle Assessment of Bio-char Systems: Estimating the Energetic, Economic, and Climate Change Potential. *Environmental Science and Technology* 44(2), 827–833.
- Rodríguez-Reinoso, F., Molina-Sabio, M. 1992. Activated Carbons from Lignocellulosic Materials by Chemical and/or Physical Activation: An Overview. *Carbon* 30(7), 1111–1118.
- Samson, R., Duxburty, P. 2000. Assessment of Pelletized Biofuels. Resource Efficient Agricultural Production-Canada.
- Seider, W.D., Seader, J.D., Lewin, D.R., Widagdo, S. 2009. Product and Process Design Principles. Synthesis, Analysis, and Evaluation. Third Edition. John Wiley & Sons, Inc.
- Sherman, R. 1999. Large-Scale Organic Material Composting. NC State University. North Carolina Cooperative Extension Service.
- Statista Inc. 2015. Global Wood Pellet Market in 2010 and 2012 with Projections through 2025, by Major Region (in million metric tons). Retrieved from <http://www.statista.com/statistics/243910/global-wood-pellet-consumption-outlook/> on June 16, 2015.
- Suliman, W., Harsh, J., Abu-Lail, N., Fortuna, A. Garcia-Perez, M. *In preparation*. [d]. Understanding the Role of Bio-char Porous Structure and Surface Chemistry in Augmenting Hydrologic Properties of a Sandy Soil. For submission to *Geoderma*.
- Suliman, W., Harsh, J., Abu-Lail, N., Fortuna, A., Dallmeyer, I. Garcia-Perez, M. *In preparation*. [a]. Understanding the Effect of Pyrolysis Conditions and Feedstock Composition on the Bulk and Surface Properties of Bio-chars. For submission to *Biomass and Bioenergy*.
- Suliman, W., Harsh, J., Abu-Lail, N., Fortuna, A., Dallmeyer, I. Garcia-Perez, M. *In preparation*. [b]. Modification of Bio-char Surface by Air Oxidation: Role of Pyrolysis Temperature. For submission to *Biomass and Bioenergy*.
- Suliman, W., Harsh, J., Fortuna, A., Garcia-Perez, M., Abu-Lail, N. *In preparation*. [c]. Towards the quantification of the effects of bio-char oxidation and pyrolysis temperature on the transport of pathogenic and nonpathogenic *E. coli* in bio-char-amended sand columns. For submission to *Environmental Science and Technology*.
- Thorneloe, S.A., Weitz, K.A. 2003. Holistic Approach to Environmental Management of Municipal Solid Waste. Proceedings Sardinia 2003, Ninth International Waste Management and Landfill Symposium, CISA publisher, Cagliari.
- Thorneloe, S.A., Weitz, K.A. 2004. Sustainability and Waste Management. Proceedings from Sustainable Waste Management, Waste Management Association of Australia, November 24-26, 2004, Melbourne, Australia.
- Thorneloe, S.A., Weitz, K.A., Jambeck, J. 2005. Moving from Solid Waste Disposal to Materials Management in the United States. Waste Management and Landfill Symposium, p. 11.

- Thorneloe, S.A., Weitz, K.A., Nishtala, S.R. 2001. US Case Studies using Municipal Solid Waste Decision Support Tool. US Environmental Protection Agency, Office of Research and Development, Air Pollution Prevention and Control Division, Washington, DC.
- US DOE. 2003. Commercial Building Energy Consumption and Expenditure. Energy Information Administration, US Department of Energy.
- Vitasari, C.R., Meindersma, G.M., de Haan, A.B. 2012. Glycoldehyde Co-extraction during the Reactive Extraction of Acetic Acid with Tri-n-octylamine/2-ethyl-1-hexanol from Wood-based Pyrolysis Oil-derived Aqueous Phase. *Separation and Purification Technology* 95, 39–43.
- Wang, W., Xie, L., Luo, G., Zhou, Q., Angelidaki, I. 2013. Performance and Microbial Community Analysis of the Anaerobic Reactor with Coke Oven Gas Biomethanation and In Situ Biogas Upgrading. *Bioresource Technology* 146, 234–239.
- Williams, R.C., Metwally, M.A.R.M., Brown, R.C. 2011. Bio-oil Formulation as an Asphalt Substitute. In: Google Patents.
- Yenigün, O., Demirel, B. 2013. Ammonia Inhibition in Anaerobic Digestion: A Review. *Process Biochemistry* 48(5), 901–911.
- Zagorodni, A.A. 2006. *Ion Exchange Materials: Properties and Applications*, Elsevier Science.
- Zhang, H., Matsuto, T. 2011. Comparison of Mass Balance, Energy Consumption and Cost of Composting Facilities for Different Types of Organic Waste. *Waste Management* 31, 416–422.

3. Extension and Outreach

Chad Kruger, Craig Frear, Georgine Yorgey, Nick Kennedy, Shannon Mitchell, Jim Jensen, Jingwei Ma, Quanbao Zhao, and Greg Astill

3.1 Abstract

The applied nature of the research funded by the Department of Ecology's Waste 2 Resources Program, particularly those projects that directly target new and improved technologies, will only lead to improving the economics and the environmental footprint of processing organic wastes in Washington if these technologies are adopted and applied by commercial producers, processors, and industry.

The extension team therefore carried out multiple outreach activities to support adoption and application of emerging technologies for waste management:

- Giving 36 presentations at national and regional conferences;
- Providing technical support to nine stakeholder groups, ranging from literature reviews contracted by Ecology, the EPA and the Innovation Center for US Dairy, to federal advisory panels focused on furthering the adoption of technologies to recover nutrients and to control the production of greenhouse gases;
- Training four young professionals who have now transitioned to academia and industry;
- Disseminating an AD curriculum for training AD technicians to a supplier of farm-based and municipal digester systems; and
- Developing six formal extension publications, and 13 other durable extension products including webpages, blog posts, and published conference proceedings.

Through these outreach activities, the team reached an estimated 12,000 scientists, producers, industry professionals, regulators, policy-makers, and other interested parties across the country, increasing awareness of the potential and opportunities surrounding biorefinery technologies, and sharing tools, resources and successful experiences that can help diverse groups further develop and implement these technologies in their line of work. Such awareness and resources are critical early steps that contribute to improving the economics and the environmental footprint of facilities processing organic wastes in Washington State.

3.2 Outreach and extension activities

The applied nature of the research funded by the Department of Ecology's Waste 2 Resources Program, particularly those projects that directly target new and improved technologies, will only lead to improving the economics and the environmental footprint of processing organic wastes in Washington if these technologies are adopted and applied by commercial producers, processors, and industry. Outreach and extension are therefore critical to achieving the Waste 2 Resources Program's objectives.

Mr. Chad Kruger (Director, Center for Sustaining Agriculture and Natural Resources [CSANR]), Ms. Georgine Yorgey (Associate in Research, CSANR), and Dr. Craig Frear (Assistant Professor, Department of Biological Systems Engineering), with support from several other individuals, were responsible for the delivery of outreach and extension for the biennium. Outreach was in the form of conference presentations, technical support to multiple stakeholders, training of future professionals in the field, development of formal extension publications, and development of other durable extension products.

3.2.1 Conference presentations

The extension team—which in addition to Kruger, Yorgey and Frear included Drs. Jingwei Ma, Shannon Mitchell, and Quanbao Zhao (Research Associates, Department of Biological Systems Engineering), Mr. Jim Jensen (Senior Specialist, Energy Extension Program), and Mr. Greg Astill (PhD Candidate, Department of Biological Systems Engineering)—made numerous presentations during the biennium related to anaerobic digestion, pyrolysis, and nutrient recovery, both regionally and nationally. These presentations included:

- A total of 13 presentations at the “Waste to Worth” conference, a national manure management conference, which was hosted in Seattle, WA from March 30 to April 2, 2015. While the focus was on animal-based systems, there was good representation of concepts important to Waste to Fuels Technology Transfer, such as:
 - “Renewable Natural Gas: Biogas Cleaning & Upgrading 101” (Frear).
 - “Co-digestion: A Primer on Substrates and Project Considerations” (Frear).
 - “Digested Solids: Forms, Markets, & Trends” (Jensen).
 - “A Primer on Available and Emerging N, P and Salt Recovery: Performance and Cost” (Ma).
 - “Anaerobic Digestion Projects: Environmental Credits 101” (Astill).
 - “Expanding Markets for Manure Treatment Technologies: Making Innovations Economically Viable and Reaching Underserved Users” (Frear, invited panelist).
 - “Tours of two farm-based anaerobic digesters and nutrient recovery systems in Whatcom County” (Frear, lead tour presenter, follow-up newspaper article).
 - One of the tours to a farm with an anaerobic digester was filmed, and a video on Animal Agriculture in a Changing Climate was produced and released (<https://youtu.be/ei-RGHt-xqw>).
- Ma, J., Yu, L., Zhao, Q., Chen, S., and Frear, C. (2015) Kinetic and microbial community analysis for enhanced food waste hydrolysis: an investigation on pH. ASABE Annual International Meeting. 2015, New Orleans, LA.
- Zeb, I., Ma, J., Zhao, Q., Yu, L., Frear, C. (2015) Recycling AD effluent as dilution water for AD process: effects of TAN and salinity. ASABE Annual International Meeting. 2015, New Orleans, LA.
- Ma, J., Zhao, Q., Frear, C., Laurens, L., Jarvis, E., and Nagle, N. (2014) Anaerobic digestion of whole and lipid-extracted algal biomass. Algae Biomass Summit. 2014, San Diego, CA.
- Ma, J., Zhao, Q., Frear, C., Laurens, L., Jarvis, E., and Nagle, N. (2014) The effect of calcium on the kinetics of methane production and LCFA degradation from algal biomass. Algae Biomass Summit. 2014, San Diego, CA.
- Frear, C., Ma, J., Zhao, Q. (2014) Nutrient recovery technologies on CAFOs and implications to reactive nitrogen management, presentation to the EPA/USDA/USGS

Working Group on Management Strategies for Reactive Nitrogen and Co-Pollutants, Washington DC, June 24-26, 2014.

- Ullman, J.L., Baar, E.L., Mitchell, S.M., Frear, C. (2014) Manure and bio-solid management practices to remove antibiotics and limit the promotion of antibiotic-resistance, Institute of Biological Engineering Annual Conference, Lexington, KY, March 6-8. IBE 2014 Conference Proceedings, p 35-36.
- Frear, C. (2014) Review of emerging nutrient recovery technologies, EPA Region 9 Webinar, February 5, 2014
- Frear, C. (2013) Review of emerging nutrient recovery technologies, EPA Region 10 AFO/CAFO Workshop, Portland OR, December 3, 2013
- Frear, C. (2013) Compost odor literature review, a report to Washington State Department of Ecology, Washington Organics Recycling Conference, Vancouver WA, November 20, 2013
- Frear, C. (2013) Review of emerging nutrient recovery technologies, USDA NRCS/EPA Region 10 Nutrient Recovery Conference, Portland OR, November 19, 2013
- Zhao, Q., Kennedy, N., Chen, S., Frear, C. (2013) Commercialization of anaerobic digestion, ammonia, phosphorus and hydrogen sulfide scrubbing system, Washington Clean Technology Alliance Ag Tech Conference, Seattle WA, July 31, 2013
- Frear, C. (2013) Review of emerging nutrient recovery technologies, EPA Region 10 Nutrient Recovery Conference, Seattle WA, July 30, 2013
- Frear, C., Zhao, Q., Ma, J., Zhao, Q. (2013) Anaerobic Digestion of Whole and Lipid-Extracted Algal Biomass from Four Industrial Strains--Determination of Important Methane and Nutrient Information, ASABE National Conference (2013), Kansas City, MO, July 22-25, 2013
- Ma, J., Yu, L., Zhao, Q., Frear, C., and Chen, S. (2013) Enhance volatile fatty acid (VFA) and bio-methane productivity by pretreatment of lawn grass, ASABE National Conference (2013), Kansas City, MO, July 22-25, 2013
- Mitchell, SM, Ullman, J., Teel, AL., Watts, RJ, and Frear, C. (2013) Ampicillin, florfenicol, sulfamethazine and tylosin effect on biogas production and their degradation efficiency during anaerobic digestion, ASABE National Conference (2013), Kansas City, MO, July 22-25, 2013
- Frear, C. Yorgey, G., Kantor, S., Benedict, C., Kruger, C. (2013) WSU NIFA Anaerobic Digestion Systems Field Day, Lynden WA, July 10, 2013
- Kennedy, N. and Frear, C. (2013) Next generation food scraps/green waste organics recycle, Biocycle National Conference (2013), San Diego, CA, April 8-11, 2013
- Frear, C. (2013) Biomass/bioenergy in the PNW, WSU ANR Extension Meeting Invited Speaker, Ellensburg WA, February 14, 2013.
- “Outputs of Organics Recycling as Inputs for Resilient Communities”, delivered by Chad Kruger at the BioCycle West Coast Conference, April 13-16, 2015 in Portland, Oregon.
- Kruger, C.E. (2014). Waste to Fuels Technology Research Update. Washington Organics Recycling Conference.
- Kruger, C.E. (2013). Saving the Planet with Soil Amendments? Northwest Biosolids Management Association. September 10, Chelan, WA.
- Kruger, C.E., (2013). Building Biocarbon in Pacific Northwest Agricultural Systems. Northwest Biocarbon Summit, June 10, Seattle, WA.

- Kruger, C.E., and G.G. Yorgey, (2013). Capturing carbon in our farms: The biocarbon potential of Pacific Northwest agriculture. Invited keynote. Sustainable Path: Enlisting Nature to Stem Climate Change, February 28, Seattle, WA.

3.2.2 Technical support

Dr. Frear supplied considerable technical support to industry, government, non-governmental organizations, producers, and third-party project developers. Dr. Frear contributed as a:

- Core panelist for EPA's Nutrient Technology Challenge. Dr. Frear is part of a team of experts providing guidance to the EPA as they develop a challenge program looking to catalyze development of manure nutrient recovery technologies (anticipated launch in late 2015). The expert team's efforts are focused on detailing the scope, goals, rules, evaluation and awards.
- Participant in multiple meetings with the California non-governmental organization Sustainable Conservation on coordinating policy, research, and extension activities related to organic management at the urban/agricultural interface, including AD, compost, vermicompost, nutrient recovery, and other technologies.
- Technical expert for project and policy development related to compost, AD, bioplastics, and CNG. Consulting entities included EPA, EPA Regions 9 and 10, USDA NRCS, USDA Rural Energy, US DOE, Dairy Management Incorporated, Walmart, Vermont Bio-methane Project Team, and various third party developers.
- Regular teleconference attendee to working groups on anaerobic digestion, nutrient recovery, pyrolysis, and other biorefinery-related topics. These working groups were convened by Washington State, EPA National Office, EPA Agstar, and the American Biogas Council.
- Technical contributor to the US government Biogas Roadmap, a collaboration between EPA, US DOE, USDA, and the President's Office to further the adoption of anaerobic digesters on farms, municipalities, and industries for control of harmful greenhouse gases as well as production of valuable energy, fuel and other coproducts.

Dr. Frear and his team also completed or conducted three important and contracted literature reviews related to AD systems and biorefining:

- Ma, J., Frear, C. (2015). Dairy manure management and anaerobic digestion: review of gaseous emissions, Report to SRA and EPA, March 11, 2015.
- Ma, J., Wilson, K., Zhao, Q., Yorgey, G., Frear, C. (2013). Odor in commercial scale compost: Literature review and critical analysis, Report to the Washington State Department of Ecology. Available at <https://fortress.wa.gov/ecy/publications/SummaryPages/1307066.html> (review was carried out in the 2011-13 biennium, and report finalized in the 2013-15 biennium).
- Ma, J., Kennedy, N., Yorgey, G., Frear, C. (2013). Review of emerging nutrient recovery technologies for farm-based anaerobic digesters and other renewable energy systems, Report to the Innovation Center for US Dairy, November 6, 2013. Available at <http://csanr.wsu.edu/wp-content/uploads/2014/07/ICUSD-Emerging-NR-Technology-Report-Final.121113B.pdf>.

Finally, Dr. Frear also provided technical support during the design of a compost facility (PacifiClean), an industrial solids digester (in Quincy, WA), and a municipal digester (in Yakima, WA).

3.2.3 Training of future professionals

The biennium was successful in the training of four young professionals who transitioned to the academic and industry world, focused on resource management, sustainability and the biorefinery concept:

- Nick Kennedy, M.Sc., WSU Associate in Research,
- Shannon Mitchell, Ph.D., postdoctoral researcher, and now future Assistant Professor at the University of South Alabama,
- Raul Pelaez-Samaniego, Ph.D., postdoctoral researcher, and now future Assistant Professor at the University of Cuenca, Ecuador,
- Jingwei Ma, Ph.D., postdoctoral researcher and now future Assistant Professor at Hunan University, China.

In addition, Dr. Frear coordinated with Bellingham Technical College to disseminate the already-developed joint AD Technician curriculum to Quasar, supplier of farm-based and municipal digester systems. Quasar will use the curriculum to train its own staff as well as regional municipal AD Technicians.

3.2.4 Extension products

In addition to aiding in the preparation of this final report, the extension team completed work on several durable products.

3.2.4.1 Formal extension publications

The extension team spent a considerable amount of time during this biennium working on a number of linked fact sheets covering biorefinery topics. These fact sheets were formally peer reviewed by subject matter experts through the WSU Extension Publications system:

- Mitchell, S.M., Kennedy, N., Ma, J., Yorgey, G.G., Kruger, C.E., Ullman, J.L., Frear, C.S. *In press*. Anaerobic digestion effluents and processes: the basics. WSU Extension Fact Sheet FS171E.
- Kennedy, N., Yorgey, G., Frear, C., Evans, D., Jensen, J., Kruger, C. *In press*. Biogas upgrading on dairy digesters. WSU Extension Publication, Pullman, WA.
- Kennedy, N.P., Yorgey, G.G., Frear, C.S., Kruger, C.E. *In press*. On-farm co-digestion of dairy manure with high-energy organics. WSU Extension Manual. Pullman, WA.
- Kennedy, N.P., Yorgey, G.G., Frear, C.S., Kruger, C.E. *In press*. Project considerations for on-farm co-digestion of dairy manure. WSU Extension Manual. Pullman, WA.
- Gallinato, S., Kruger, C., Frear, C. (in review). Economic feasibility of post-digester nutrient recovery using struvite crystallization and WSU Air Trap system. WSU Extension Factsheet, Pullman, WA.
- Yorgey, G.G., Ma, J., Kennedy, N.P., Frear, C.S. *In preparation*. Approaches to recovery of phosphorus and nitrogen from dairy manure. WSU Extension Publication, Pullman, WA.

3.2.4.2 Other durable extension products

In addition to formal Extension Publications, the team produced a number of articles and non-reviewed extension materials, including:

- Several webpages with connections to a database of relevant publications on the WSU Center for Sustaining Agriculture and Natural Resources' webpage (<http://csanr.wsu.edu/publications>): [Waste Management](#), [Compost](#), [Anaerobic Digestion](#), [Biochar](#), [Biofuels](#), [Energy](#), and [Farm Energy](#) webpages.
- A University Partnership Research Project web profile page, developed in coordination with EPA Agstar (http://www.epa.gov/agstar/projects/profiles/WSU_AgSTAR_Site_Profile_508_030514.pdf).
- A one-day symposium on AD Systems and AD biorefinery modeling: Frear, C., Kruger, C. (2014) Modeling anaerobic digestion systems symposium, Washington State University sponsored symposium as part of US Dairy Innovation Center Sustainability National Meeting, Seattle WA, November 20, 2014.
- Blog posts on the WSU Center for Sustaining Agriculture and Natural Resources "Perspectives on Sustainability" Blog:
 - Frear, C. 2014. The reactive nitrogen "wicked problem" – critical nutrient, disastrous pollutant. August 4, 2014. Available at <http://csanr.wsu.edu/the-reactive-nitrogen-wicked-problem/>.
 - Yorgey, G.G. 2014. Closing the nutrient loop. July 2, 2014. Available at <http://csanr.wsu.edu/closing-the-nutrient-loop/>.
 - Frear, C. 2014. The 'rest' of the food system January 22, 2014. Available at <http://csanr.wsu.edu/the-rest-of-the-food-system/>.
 - Kruger, C. 2013. Safety first, please! Even renewable fuels can be hazardous. June 18, 2013. Available at <http://csanr.wsu.edu/renewablefuelsafety/>.
- Proceedings published in association with the Waste to Worth Conference. Proceedings and, in the near future, presentation materials and recordings, are available at <http://www.extension.org/pages/72719/agenda-for-waste-to-worth-2015-.VVLf1fVikq>:
 - Renewable natural gas: Biogas cleaning and upgrading 101,
 - Co-digestion: A primer on substrates and project considerations,
 - Digested solids: forms, markets, and trends,
 - Panel discussion: Expanding markets for manure treatment technologies, and
 - A primer on available and emerging N, P and salt recovery: Performance and cost.
- A one-page summary of the organic waste biorefinery concept, and an accompanying graphic, available at <http://csanr.wsu.edu/wp-content/uploads/2013/11/Biorefinery-Concept-Handout-FINAL.pdf>.

3.3 Impacts of outreach and extension activities

Through these four core outreach activities—conference presentations, technical support, training of future professionals, and development of formal and other extension publications—the extension team shared the results described in other chapters of this report, as well as the results of related research on biorefinery technologies. The team estimates that close to 12,000

scientists, producers, industry, regulators, policy-makers, and other interested parties across the country were reached, including:

- The 280 participants at the Waste to Worth conference, where the extension team gave 13 different presentations. The associated farm tour video has already accumulated 43 views, even though it has not yet been released.
- An estimated average of 20 professionals at each of the other 23 national and regional conference presentations.
- The dozens of scientists, students and colleagues that interacted and collaborated with the four professionals during their training at WSU, a number that will grow significantly as these professionals take on new positions in academia and industry.
- The curriculum disseminated through Quasar has the potential to reach dozens if not hundreds of current and future AD technicians, including those in Quasar's employment working at their AD facilities, as well as the regional municipal AD technicians they train.
- The WSU extension publications, articles, blog posts, and resources on WSU's webpages have been viewed almost 11,000 times cumulatively.

These statistics are considered conservative, as they do not include views or downloads of the additional research products posted on EPA's, eXtension's, or Ecology's webpages, nor do they include the numbers of stakeholders and professionals involved in the working groups that Dr. Frear has advised throughout this biennium.

In addition to these educational impacts, Dr. Frear's technical support contributed directly to the adoption of these technologies in commercial composting and anaerobic digestion operations across Washington State.

Through these outreach and technical support activities, the team has increased the awareness of the potential and opportunities surrounding biorefinery technologies, and has shared tools, resources and successful experiences that can help diverse groups further develop and implement these technologies in their line of work. Such awareness and resources are critical early steps that contribute to improving the economics and the environmental footprint of facilities processing organic wastes in Washington State.

4. Improving Understanding of Biochar Physico-Chemical Properties and its Behavior as a Soil Amendment

Waled Suliman, James B. Harsh, Nehal I. Abu-Lail, Ann-Marie Fortuna, Ian Dallmeyer, Hamid Iqbal, Matt Smith, Manuel Garcia-Pérez, and Markus Flury

4.1 Abstract

Fundamental studies were conducted to better understand the relationship between the biochar production conditions—pyrolysis temperature and post-pyrolysis oxidation—and the resulting physico-chemical properties—bulk and surface properties—of the biochar. Results showed that the surface area of the biochar started to develop at very low temperature with the formation of very small pores. As the pyrolysis temperature increased, the surface lost oxygenated functional groups and became less negatively charged. The surface of the char was re-oxidized with oxygen during the post-pyrolysis oxidation process. The addition of biochars to soils dramatically improved their water holding capacity, as these purposefully oxidized biochars retained more water. These studies showed that the surface charge is a critical parameter controlling the adsorption of *Escherichia coli*, as oxidized biochars—which have more negative charge on the surface—enhanced *E. coli* movement in the soil. A commercial biochar produced in a boiler was studied in a separate set of experiments. Very limited adsorption of nitrogen and phosphorus was observed when the commercial biochar was put in contact with rainwater, either as a pure medium or when it was blended with a sandy soil. This result points to the importance of surface chemistry on the capacity of these chars to adsorb nutrients, and to the need to develop specially designed, engineered biochars for each particular purpose. More studies are needed to develop such engineered biochars for environmental purposes.

4.2 Background

4.2.1 Potential value of biochar

The 1.5 million tons of manure currently generated in the state of Washington contain more than 19,000 tons of phosphorus (P) and more than 75,000 tons of nitrogen (N). These nutrients tend to accumulate in lagoons prior to application of lagoon water to agricultural lands. Direct application of these waters to adjacent fields can result in rates of more than 600 kg N ha⁻¹ yr⁻¹ and 160 kg P ha⁻¹ yr⁻¹, much more than typically required. This over-application results in significant runoff of both nitrogen and phosphorus into rivers and streams, and leaching into groundwater. The accumulation of nutrients in these aquatic systems can lead to eutrophication, posing a serious risk to the environment in the Pacific Northwest.

Biochar is a carbon-rich, porous material prepared via thermochemical decomposition of organic materials in an oxygen-limited environment (Ronsse et al., 2013; Crombie et al., 2013). Biochar is receiving growing attention as a soil amendment due to its potential to enhance soil fertility,

retain soil moisture, and sequester carbon (Song and Guo, 2012). The use of biochar as a soil amendment dates back to the Amazonian Dark Earths (known as Terra Preta) in the Amazon Basin, where charred organic materials appear to have been added purposefully to the soil to enhance its fertility. Some of these anthropogenically modified soils date back 7,000 years, and have long-lasting fertility resulting from the biochar's presence and stability (Maia et al., 2011; Lehmann and Joseph, 2009).

The addition of biochars enriched with N and P is an attractive agricultural management strategy to enhance soil fertility. The use of biochar in compost and in the recovery of N and P from AD processes can mitigate environmental issues such as GHG emissions and nutrient and pathogen leaching in soils—a serious and persistent problem in agriculture. Washington State University's (WSU) biochar program is advancing the design and use of biochars to adsorb and retain nutrients both at the source—nutrient retention from AD effluents—and in the soils—through compost and biochar amendment. Producing engineered biochars that can improve the viability of amended soils offers a path to increasing productivity in regions of the state dominated by marginal soils, such as the low-grade, sandy Quincy series soils found in Adams, Benton, Douglas, Franklin, Klickitat, Walla Walla, and Yakima counties (Hipple, 2012).

Washington State University's biochar program aims to engineer biochars for use as soil amendments or for other environmental applications. To produce biochar with the capacity to effectively reduce nutrient leaching and transport of pathogens such as *Escherichia coli*, a critical first step is to fully understand what factors control the physical and chemical characteristics of biochar, which in turn will determine the biochar's effect when added to marginal soils or to composting piles. The Waste 2 Resources funding provided by the Department of Ecology supported bench-scale studies to evaluate the bulk and surface properties of biochar engineered under different conditions. These evaluations provided the basis for a study on the effectiveness of a commercial biochar on nutrient retention. The study of the properties of engineered biochar also provided foundational research that informed additional studies, supported in part by Waste 2 Resources funding, on applied uses of biochar as soil amendments.

4.2.2 Factors affecting biochar properties

4.2.2.1 Feedstock and pyrolysis temperature

A wide range of biomass feedstocks are available for use in the manufacturing of biochar. These include wood materials, agricultural residues, forest residues, and wastes from food, sugar, or juice processing (McKay, 2002; Novak et al., 2009), as well as potentially aquatic plants, sewage sludge, and animal farm wastes (Verheijen et al., 2010). However, lignocellulosic materials are overwhelmingly the most common form of biomass and the most important source for charcoal-making worldwide. Woody biomass contains varying amounts of hemicellulose, cellulose, lignin, and slight quantities of other organics extractives (e.g. fats, phytosterols, and phenolics) and inorganic compounds (such as nitrogen, phosphorus, potassium, sulfur, silicon, alkaline metals, and various trace minerals). The structure of the resultant biochar can vary significantly depending on the plant species, the plant tissue, the soil type, the climate conditions, and the time of harvest of the feedstock used (Maia et al., 2011; McKendry, 2002; Collison et al., 2009).

Biomass pyrolysis is the major anaerobic thermochemical conversion method used to convert biomass into liquid fuel, gases, and charcoal (Fu, 2009). The reaction mechanisms of biomass

pyrolysis are complex, due to the large variation of biomass components and the thermochemical reactions that occur (Maia et al., 2011; Demirbas, 2004). In general, pyrolysis conditions play a vital role in the heterogeneity of the resultant biochar's chemical and physical properties (Fu, 2009). Therefore, controlling pyrolysis conditions is one means of maximizing biochar yield and adapting biomass pyrolysis to site-specific applications.

The feedstock properties and the pyrolysis temperature are considered the main factors affecting biochar characteristics (Zhao et al., 2013). Higher biochar yield, for instance, is characteristic of biochar produced from high lignin content and high mineral content parent materials (Collison et al., 2009; Antal and Grønli, 2003). Likewise, selecting the raw material and production conditions can control the carbon content of biochar. At high pyrolysis temperatures, woody and herbaceous biomass usually provides a more carbon-rich biochar compared to other feedstocks such as sewage sludge and animal manures (Verheijen et al., 2010; Bruun et al., 2011). Several studies have reported that yield, aliphatic carbons, surface functionality, and the nitrogen, oxygen and hydrogen content of biochar decreased when reaction temperatures increased (Song and Guo, 2012; Bruun et al., 2011; Spokas et al., 2012; Mašek et al., 2013). According to a recent study published by Zhao et al. (2013), the peak temperature may be the most important parameter affecting surface area, pH, volatile matter, and the recalcitrance of the biochar, while the cation exchange capacity (CEC), ash content, total carbon, fixed carbon, and mineral concentrations were mainly affected by feedstock properties.

Despite the fact that the number of papers reporting on the physico-chemical characteristics of biochar is growing, there are still uncertainties surrounding the effect that varying the pyrolysis temperature and feedstock source has on the yield and on the properties of the finished biochar (Zhao et al., 2013; Wang et al., 2009). The level of uncertainty is particularly high when considering the use of pyrolysis temperature to engineer physico-chemical properties in biochar that enhance their performance as soil amendments, which have rarely been reported in the literature. Thus, the main objective of this seed research was to examine how feedstock source and pyrolysis temperature affects the yield and properties of biochar, and to thereby clarify these biochar-feedstock-pyrolysis temperature relationships.

4.2.2.2 Surface functional groups

While biochar has significant potential as a soil amendment, studies with freshly produced biochars have not been able to reproduce the effectiveness of the centuries-old Terra Preta soils in the Amazon Basin (Granatstein et al., 2009). One possible reason is that when the char is left in the soil for long periods of time the surface is slowly oxidized (Liang et al., 2006); that is, certain molecules on the biochar's carbonaceous surface react with oxygen in the air within soil pores, creating oxygenated complexes on the biochar's surface, such as hydroxyl, carbonyl, and carboxyl groups. Surface complexes—including the acidic functional groups—are responsible for many of the biochar's physico-chemical properties, and these properties in turn determine the biochar's behavior when added to the soil.

The carboxyl groups (also known as carboxylic acid groups because of their acidic nature) are essential for improving the biochar's nutrient holding capacity, as well as polarizing the surface, which should also increase the material's water retention. A high proportion of carboxyl and other oxygen-rich groups should also provide biochar with many of the desirable properties of humic acid, an important product of soil organic matter decomposition that contains a high

proportion of carboxylic acid functional groups—on the order of 2-5 milliequivalents per gram (meq g^{-1}), with total acidic groups—including hydroxyl and carbonyl groups—as high as 9 meq g^{-1} (Mbagwa and Piccolo, 1997). Numerous studies have found that these acidic functional groups can be formed on the surface of activated carbons in quantities similar to those found in various humic materials. For example, Valdés et al. (2002) indicated that total acidic functional groups on activated carbons can reach at least 2 meq g^{-1} , with half the acidic functional groups being carboxyl groups.

Oxidized biochar is biochar that has been exposed to an oxidizing agent, such as oxygen itself—either as a treatment of simply in the surrounding air—and therefore has a high proportion of acidic functional groups on its surface. The acidic nature of the oxidized biochar means that they are particularly well suited for the retention of basic ions such as ammonia or other cation compounds (Kastner et al., 2009). The effectiveness of oxidized biochar in removing ammonia from gas streams and ammonium from liquid streams has received considerable attention. Chiang et al. (2002a) showed a strong correlation between the quantity of ammonia adsorbed by the carbon and the concentration of acidic functional groups on the surface. A relatively high concentration of acidic functional groups can also favor the formation of chelates with metal ions, which helps to bind these positively charged ions to the surface of the carbon. When the surface density of carboxyl groups is very high, chelates with metal ions can almost completely immobilize potentially toxic metal compounds (Fuchs et al., 2012).

These acidic functional groups can be formed when oxidizing agents attack the carbonaceous surfaces. Such oxidation processes have been shown to lead to significant increases in the number of acidic functional groups on the carbonaceous surfaces, including carboxyl groups (Valdés et al., 2002; Park and Jin, 2004; Chiang et al., 2002b). However, most of the biochar oxidation tests reported in the literature were conducted using very aggressive reagents such as nitric acid (HNO_3), hydrogen peroxide (H_2O_2), ammonium persulfate ($(\text{NH}_4)_2\text{S}_2\text{O}_8$) and ozone (O_3) (Valdés et al., 2002; Pradhan and Sandle, 1999).

Although the oxidation of coal and activated materials in air in the range of temperature between 120 and 250°C has been extensively studied (Nordon et al., 1979; Oda et al., 1981; Koch, 1998), it was not possible to find any study on the effect of the pyrolysis conditions when producing the biochar on the structure and the oxidability of the resulting carbonaceous materials. This low temperature, air oxidation method is of great interest to the biomass pyrolysis community because it can be easily and cheaply integrated during the biochar cooling step. Thus, the second objective of this research was to study the effect of pyrolysis temperature on the oxidability of biochar, and the effect of the oxidation process on the bulk and surface properties of the resulting oxidized biochars.

4.2.3 Effect of biochar and co-composted biochar on the retention of nutrients from composting materials

Thanks to its high surface area, biochar can serve as a soil amendment to enhance soil aggregation, water holding capacity, and organic carbon content (Smith et al., 2010; Lehmann et al., 2011). It can also serve for the remediation of contaminants (Beesley et al., 2010) such as heavy metals, pesticides, and organics, whose adsorption on biochar has been documented (Chen et al., 2008; Cao et al., 2009; Uchimiya et al., 2010; Paz-Ferreiro et al., 2014). Biochar can also

be added to compost piles, where the biochar promotes microbial growth (Jindo et al., 2012), increases aeration (Zhang et al., 2014), and reduces NH₃ and N₂O emissions during the composting process (Steiner et al., 2010; Wang et al., 2013). The cation exchange capacity and the proportion of functional groups on the biochar itself may increase due to such co-composting (Prost et al., 2013).

Biochar mixed into mature compost and co-composted biochar may be useful amendments to reduce leaching of nutrients and contaminants from the compost itself. Biochar can potentially prevent the leaching of pollutants that may already be part of the compost, can reduce the leaching of nitrate from soil (Knowles et al., 2011; Clough et al., 2013), and can reduce pore water concentrations of metals (Brennan et al., 2014; Meng et al., 2014). However, it is not known whether biochar or co-composted biochar, when added to mature compost, would improve the amendment's retention capabilities for nutrients. The aim of this study was therefore to test whether amendments using a commercially available biochar could reduce the leaching of dissolved organic carbon (DOC) and nutrients from mature compost. The hypothesis being tested was that when biochar was mixed with compost, there would be a reduction in the leaching of DOC and nutrients. A second hypothesis states that co-composted biochar—biochar added to the feedstock during composting, producing co-composted biochar that can then be mixed with mature compost as well—would be less effective in reducing the leaching of DOC and nutrients because the biochar could become saturated with DOC and nutrients during the composting. Column leaching experiments in simulated bioretention mixes made with compost, biochar, and sand were carried out to test these hypotheses.

Authors' note: This study's results have been published in *Science of the Total Environment*:

Iqbal, H., Garcia-Perez, M., Flury, M. 2015. Effect of biochar on leaching of organic carbon, nitrogen, and phosphorus from compost in bioretention systems. *Science of the Total Environment* 521-522: 37-45.

Portions of this section and of the associated *Methods* and *Results and discussion* sections were taken directly—with modest modifications—from this publication.

4.2.4 Additional applications of biochar in soil amendments

The seed research funded by the Department of Ecology's Waste 2 Resources Program focused on the effect that feedstock, pyrolysis temperature, and post-pyrolysis oxidation had on the resultant biochar's physical and chemical properties, as well as a bench-scale study to evaluate the effectiveness of a commercial biochar on nutrient retention. Those biochars showing the most promise for application as soil amendments to improve moisture retention, to reduce leaching of nutrients, and to reduce the transport of bacteria were then used in a series of applied soil amendment studies funded by the Washington State Department of Agriculture, with additional support from the Department of Ecology's Waste 2 Resources Program. The findings of two of those studies are summarized in this report, to provide examples of the applications of this seed research.

4.3 Methods

4.3.1 Effects of feedstock source and pyrolysis temperature on biochar yield and properties

Three feedstocks were selected that (1) were appropriate for bioenergy production, (2) could be obtained in large quantities, and (3) were native to the Pacific Northwest. These feedstocks were pine wood (PW), pine bark (PB), and hybrid poplar wood (HP). Biochar samples were produced from the pyrolysis of each of these three feedstocks at six different pyrolysis temperatures (350, 400, 450, 500, 550, 600°C) in a laboratory-scale spoon reactor.

Changes in the bulk composition of the eighteen different biochar samples produced (3 feedstocks x 6 pyrolysis temperatures) were examined via elemental and proximate analyses. The elemental analysis was performed using a TRUSPEC-CHN® (LECO, US) elemental analyzer, which determined the total carbon (C), nitrogen (N), and hydrogen (H) of the sample. Oxygen (O) content was determined by subtracting the ash, C, N, and H contents from the total mass of the sample. These results were used to calculate atomic H:C, O:C, N:C, and O+N:C ratios, which are indicative of the bonding arrangement (Brendova et al., 2012) and polarity (Cantrell et al., 2012) of the material. In the proximate analysis, fixed carbon, volatiles, and ash content were determined by using a high temperature muffle furnace, Isotemp® (Fishe Scientific, US) and a thermo-gravimetric analyzer (TGA), SDTA851e (Mettler Toledo, US), following methods described elsewhere (Crombie et al., 2013; Mitchell et al., 2013).

The surface properties of each biochar sample were investigated using a series of analyses:

- Scanning electron microscopy (SEM) to determine surface topography.
- Nitrogen (N₂) and CO₂ adsorption isotherms to determine the apparent surface area, the total pore volume, the pore size distribution, and the micropore volume.
- X-ray photoelectron spectroscopy (XPS) measurements were obtained to determine the surface composition.
- Boehm titration was carried out to quantify the acidic groups covering the biochar surface.
- The Cation Exchange Capacity (CEC) of the samples was determined according to the method of passive barium exchanged with forced magnesium exchange (Lee et al., 2010).
- The Zeta potential (ζ) of biochar suspensions was determined using the method described by Julien et al. (1998).

The composition of the ash and associated properties such as pH and electrical conductivity (EC) were also measured.

4.3.2 Effects of pyrolysis temperature on biochar oxidability and its resultant properties

The same set of eighteen biochar samples described above (3 feedstocks x 6 pyrolysis temperatures) were subjected to post-pyrolysis oxidation. Air was used as the oxidizing agent to modify the surface of the biochar samples during the oxidation step. Oxidation of about 50 mg of each biochar sample was carried out in a spoon reactor operated at 250°C for 30 minutes, with an air stream flowing at 2 L min⁻¹. The bulk composition and surface properties of the resulting oxidized biochar samples were analyzed using the same methods described above. The

properties of oxidized biochar samples were compared to those of their unoxidized counterparts using descriptive statistics (standard deviations, means, correlation coefficients (*r*)) and statistical *t* test analyses.

4.3.3 Effect of biochar and co-composted biochar on the retention of nutrients from composting materials

Column leaching experiments in simulated bioretention mixes made with compost, biochar, and sand were carried out to evaluate the effects of biochar, co-composted biochar, and their blends with composting materials on the retention of nutrients. These experiments were carried out on eight different media: four pure media—compost, biochar, co-composted biochar, and sand—and four media mixes—compost+biochar, compost+co-composted biochar, fully mixed compost+sand, and layered compost+sand (Table 4.1).

Table 4.1: Composition of soil amendments tested in this study. See full details on the methodology in Iqbal et al. (2015) (see *Authors' note* on page 93).

Amendment material	Pure Media				Media Mixes		
	Compost	Biochar	CC-Bio*	Sand	Comp+Bio*	Comp+CC-Bio	Comp+Sand (Mixed or Layered)
Compost	100%	-	-	-	75%	75%	70%
Biochar	-	100%	-	-	25%	-	-
Co-Composted Biochar	-	-	100%	-	-	25%	-
Sand	-	-	-	100%	-	-	30%

* CC: co-composted; Bio: biochar.

PVC columns were packed with each of the media or mixes being evaluated, and then irrigated with a flow rate of 77 mm hr⁻¹. This rate is equivalent to 33.5 mm day⁻¹, representative of a 6-month, 24-hour storm in the Puget Sound area (Ecology, 2012), where the ratio of catchment area to bioretention areas is 50 to 1. The experiment lasted 36 hours, resulting in a cumulative water flux of 2800 mm.

The leachate from each column was sampled at three hour intervals, and analyzed for pH, electrical conductivity, dissolved organic carbon, nitrogen and phosphorus. Full details on the methodology are described in the peer-reviewed publication of this study (Iqbal et al. 2015; see *Authors' note* on page 93).

4.3.4 Additional studies on the effects of biochar soil amendments on relevant soil properties

Four of the eighteen biochar samples were used in further studies looking at the effect of the biochar's porous structure and surface chemistry on the hydrological, nutrient retention, and *Escherichia coli* transport properties of blends of biochar with Quincy sandy soils. The four biochars selected for these studies were produced from Pine Wood and Pine Bark, at temperatures of 350°C and 600°C, and oxidized to generate oxygenated functional groups on the surface.

4.4 Results and discussion

4.4.1 Effects of feedstock source and pyrolysis temperature on biochar yield and properties

The biochar yield decreased sharply as pyrolysis temperature increased from 350°C to 600°C (Figure 4.1), which corresponds to the temperature range at which most of the thermal decomposition of lignocellulosic materials occurs (Paris et al., 2005). Between 500°C and 600°C, the biochar yield did not change much, indicating that most of the volatile fraction had been removed (Novak et al., 2009). The yields of char were also dependent on the original feedstock source. Pine bark (PB) resulted in the largest biochar yield. This may be due to the high ash and lignin content of PB, which is known to contribute to char formation (Song and Guo, 2012). The differences in char yields between pine (PW) and poplar (HP) woods were relatively small and most likely due to the differences in their lignin content (Paris et al., 2005). Char yields were generally more sensitive to feedstock source. Our findings are generally consistent with other reports in the literature for other feedstocks (Crombie et al., 2013; Al-Wabel et al., 2013; Kim et al., 2012).

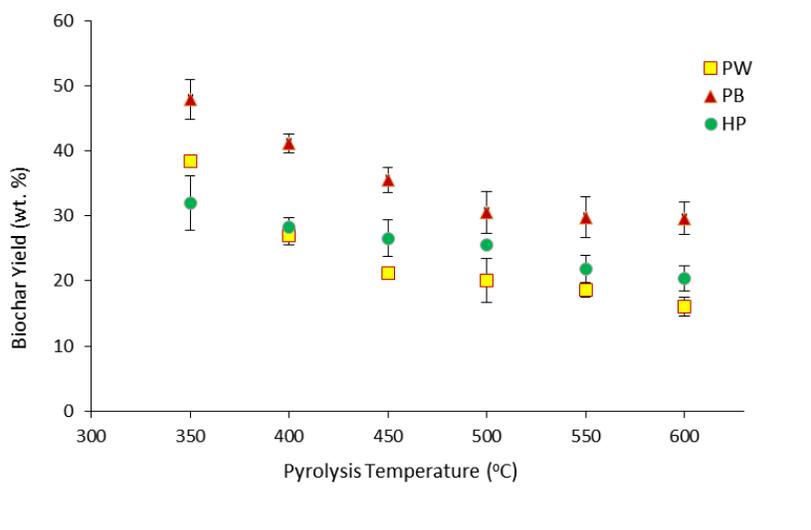


Figure 4.1: Biochar yields as a function of temperature for Pine wood (PW), Pine bark (PB), and Hybrid poplar wood (HP).

The oxygen to carbon (O:C) and hydrogen to carbon (H:C) ratios decreased linearly with pyrolysis temperature (Figure 4.2a), as did the content of oxygen (Figure 4.2b) and volatiles (Figure 4.3), suggesting a gradual increase in the number of aromatic structures and the thermal recalcitrance of the biochar. The removal of volatiles at temperatures over 450°C creates cavities that result in greater surface area of the biochars produced. The biochar produced from pine wood pyrolyzed at 600°C had the greatest surface area: approximately 400 m² g⁻¹ (Figure 4.4a). The XPS and Boehm titration confirmed that most oxygenated surface functional groups are gradually removed as pyrolysis temperatures increased (Figure 4.5). Consequently, biochar surfaces became more hydrophobic and the negative charge induced by the oxygenated functional groups decreased. The concentration of the mineral matter increased with increases in pyrolysis temperature (Figure 4.6), leading to an increase in the content of leachable alkalines.

The pyrolysis temperature had the greatest influence on biochar properties, although the biomass source affected some of the measured properties.

Overall, this study's results indicate that it is possible to design a biochar with desirable physico-chemical properties—properties that would benefit specific agricultural or environmental applications—by using an appropriate combination of pyrolysis temperature and feedstock source.

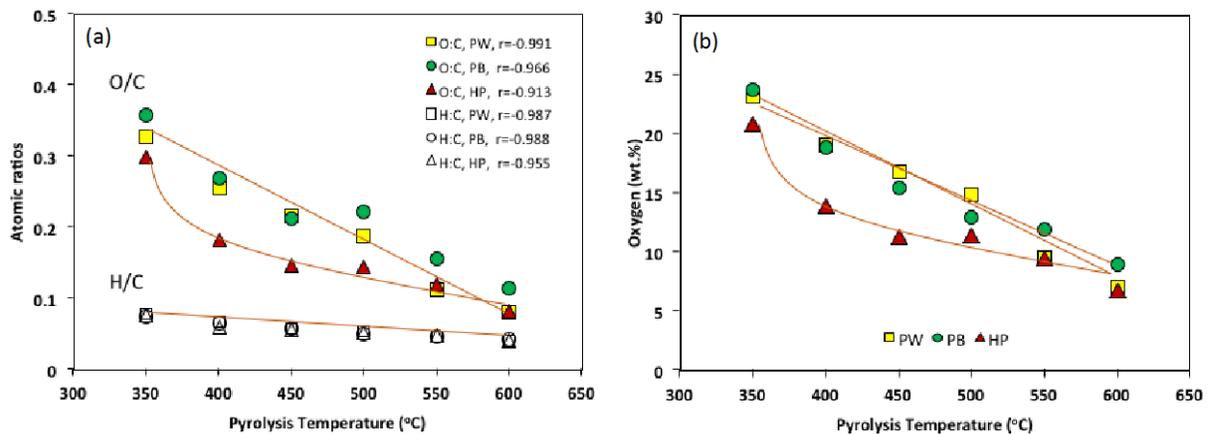


Figure 4.2: Bulk composition parameters as a function of pyrolysis temperature for Pine wood (PW), Pine bark (PB), and Hybrid poplar wood (HP): (a) atomic ratios and (b) total oxygen of PW, PB, and HP biochars.

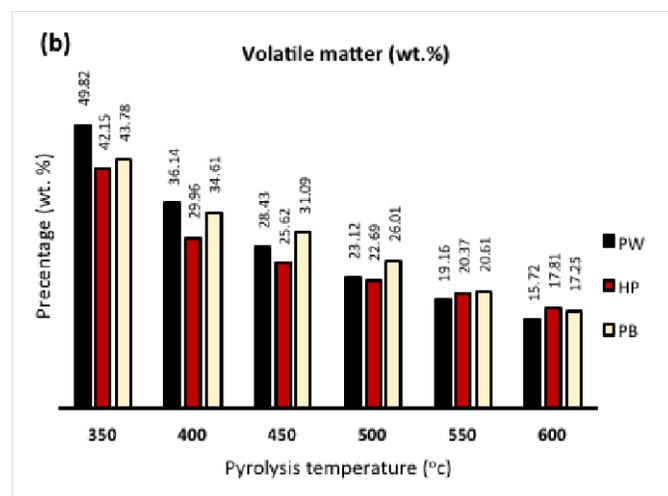


Figure 4.3: Percentage of volatile matter as a function of pyrolysis temperature for Pine wood (PW), Pine bark (PB), and Hybrid poplar wood (HP) biochar.

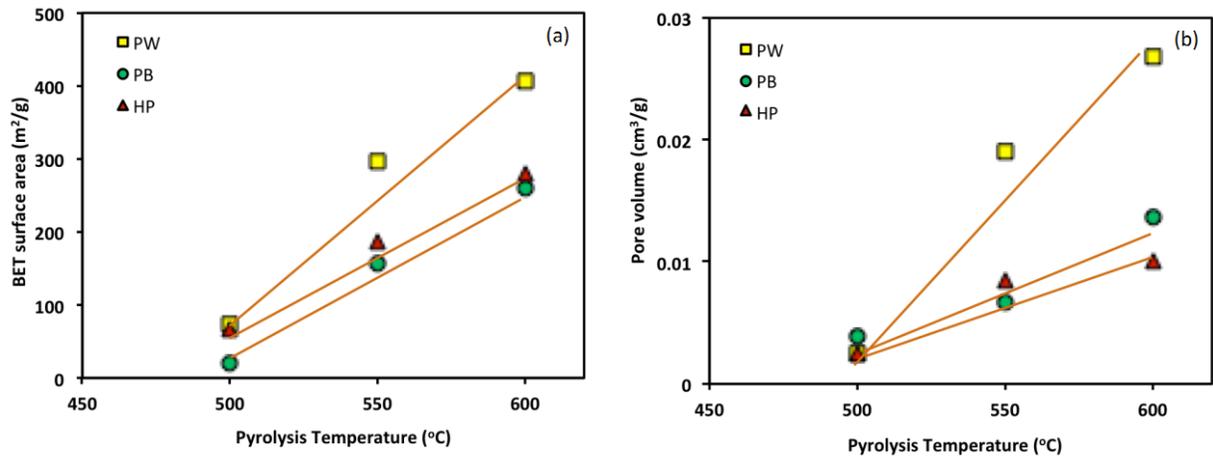


Figure 4.4: Influence of pyrolysis temperature and feedstock source on (a) surface area and (b) pore volume of prepared biochars.

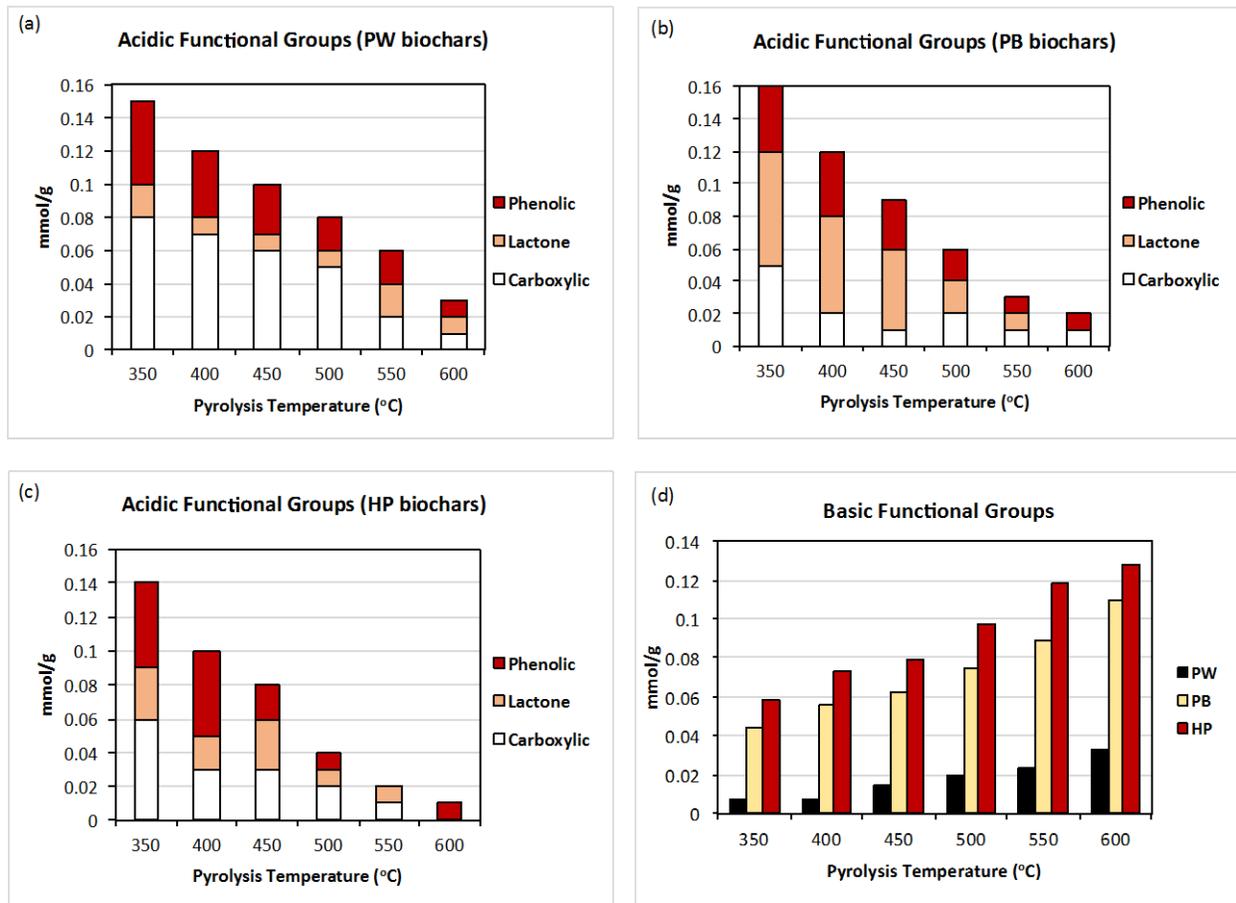


Figure 4.5: Variation in surface acidic and total basic functional group as a function of pyrolysis temperature.

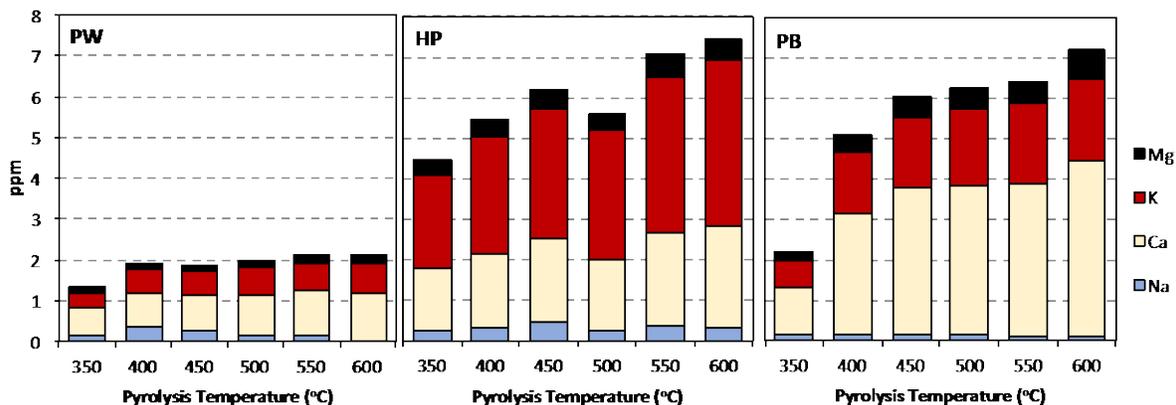


Figure 4.6: Mineral content of PW, HP, and PB biochars made at six pyrolysis temperatures.

4.4.2 Effects of pyrolysis temperature on biochar oxidability and its resultant properties

The elemental and proximate analyses of all the oxidized and unoxidized chars suggest that the carbonaceous materials produced at low temperatures were more susceptible to oxidation than those obtained at high temperatures. A number of surface properties of the resultant biochars were examined to better understand how pyrolysis temperatures and feedstock sources relate to the development of surface characteristics.

The removal of volatiles during the pyrolysis step resulted in the gradual creation of microporosity detectable by CO₂ adsorption but which was difficult to detect with N₂ adsorption, suggesting that the chars contain micropores mostly less than 1 nm in entrance dimension. A side-by-side comparison of unoxidized and oxidized samples shows that microporous structure, in general, was not significantly altered until the pyrolysis temperature reached 600°C. For example, CO₂ adsorption detected surface area increases from 500 to 570, 424 to 550, and 417 to 557 m² g⁻¹ in PW, PB, and HP biochars, respectively, when produced at 600°C. On the other hand, slight increases and slight decreases in microporous characteristics were observed (Table 4.2). The increase in area can be explained by the oxidation and removal of some of the walls of the carbonaceous material, while the decrease in microporous volume can be attributed to the partial blockage of micropores by oxygen-containing functional groups, which limit CO₂ diffusion and adsorption (Parra et al., 1995; Harry et al., 2006).

Low temperature biochars appeared to be more suitable for oxidation by air than those produced at high temperatures. The surface composition, determined by XPS and Boehm titration, confirmed that the formation of carbonyl and carboxyl groups is easier for biochars produced at low temperature (Figure 4.7). The results clearly showed that the oxidation with air increased the number of acidic functional groups, especially through the formation of carboxyl on the biochar surfaces. Air oxidation of pine wood biochars introduced a large number of carboxylic functional groups; the pine wood biochar functionalities therefore rapidly improved, likely due to their greater surface area. These findings are consistent with Salame and Bandosz (2001). Slight

increases in the number of carboxylic groups were observed in pine bark and poplar wood biochars, regardless of pyrolysis temperature. The data obtained from the Boehm analysis clearly showed that the total acidic functional group content is very dependent on the pyrolysis temperature (Figure 4.7). The amount of oxygen surface groups formed during oxidation decreased as the structure of the biochar formed gained stability due to being produced at higher temperatures.

Table 4.2: Characteristics of microporous structure of unoxidized (UO) and oxidized (AO) PW, PB, and HP biochars as a function of pyrolysis temperature.

Sample ID	PV _{mic} ^a (cm ³ g ⁻¹)		PV _{tot} ^b (cm ³ g ⁻¹)		P _{cap.} ^c (cm ³ g ⁻¹)		SA _{CO₂} ^d (m ² g ⁻¹)		Pore volume distribution of oxidized biochar (%)			
	UO	AO	UO	AO	UO	AO	UO	AO	<0.5 (nm)	0.5-0.7 (nm)	0.7-0.9 (nm)	>0.9 (nm)
PW-350	0.06	0.08	0.14	0.23	32	42	146	190	1.80	26.06	35.25	36.9
PW-400	0.10	0.11	0.28	0.43	57	61	262	277	2.35	27.12	34.79	35.74
PW-450	0.13	0.13	0.44	0.48	73	69	333	317	2.56	27.55	34.57	35.32
PW-500	0.16	0.15	0.43	0.54	88	85	404	386	2.45	27.24	34.81	35.5
PW-550	0.18	0.20	0.44	0.59	98	107	446	488	2.03	26.34	35.08	36.56
PW-600	0.20	0.23	0.57	0.75	110	125	500	570	2.02	25.98	35.00	37.00
PB-350	0.07	0.07	0.20	0.24	38	41	172	187	2.29	26.58	35.04	36.09
PB-400	0.08	0.09	0.20	0.29	46	50	211	227	2.47	26.9	28.34	29.00
PB-450	0.12	0.11	0.39	0.38	64	61	291	280	2.52	27.00	28.04	28.69
PB-500	0.13	0.14	0.36	0.47	70	78	318	355	2.59	27.33	32.15	32.88
PB-550	0.16	0.15	0.54	0.45	87	80	395	367	2.61	27.23	28.61	29.17
PB-600	0.17	0.22	0.43	0.81	93	120	424	550	2.50	26.8	36.28	37.62
HP-350	0.08	0.07	0.27	0.20	46	37	208	171	2.02	26.26	35.34	36.38
HP-400	0.10	0.10	0.31	0.35	57	56	259	257	2.49	27.13	31.63	32.15
HP-450	0.11	0.10	0.38	0.48	61	54	277	245	2.71	27.18	26.18	26.98
HP-500	0.14	0.13	0.50	0.91	79	68	361	313	2.56	26.77	29.29	30.54
HP-550	0.15	0.15	0.57	0.43	84	80	382	367	2.75	27.05	29.19	29.92
HP-600	0.17	0.22	0.65	0.87	91	122	417	557	2.65	26.8	37.43	38.57

a = Micropore volume, b = total pore volume, c = pore capacity, d = surface area-CO₂.

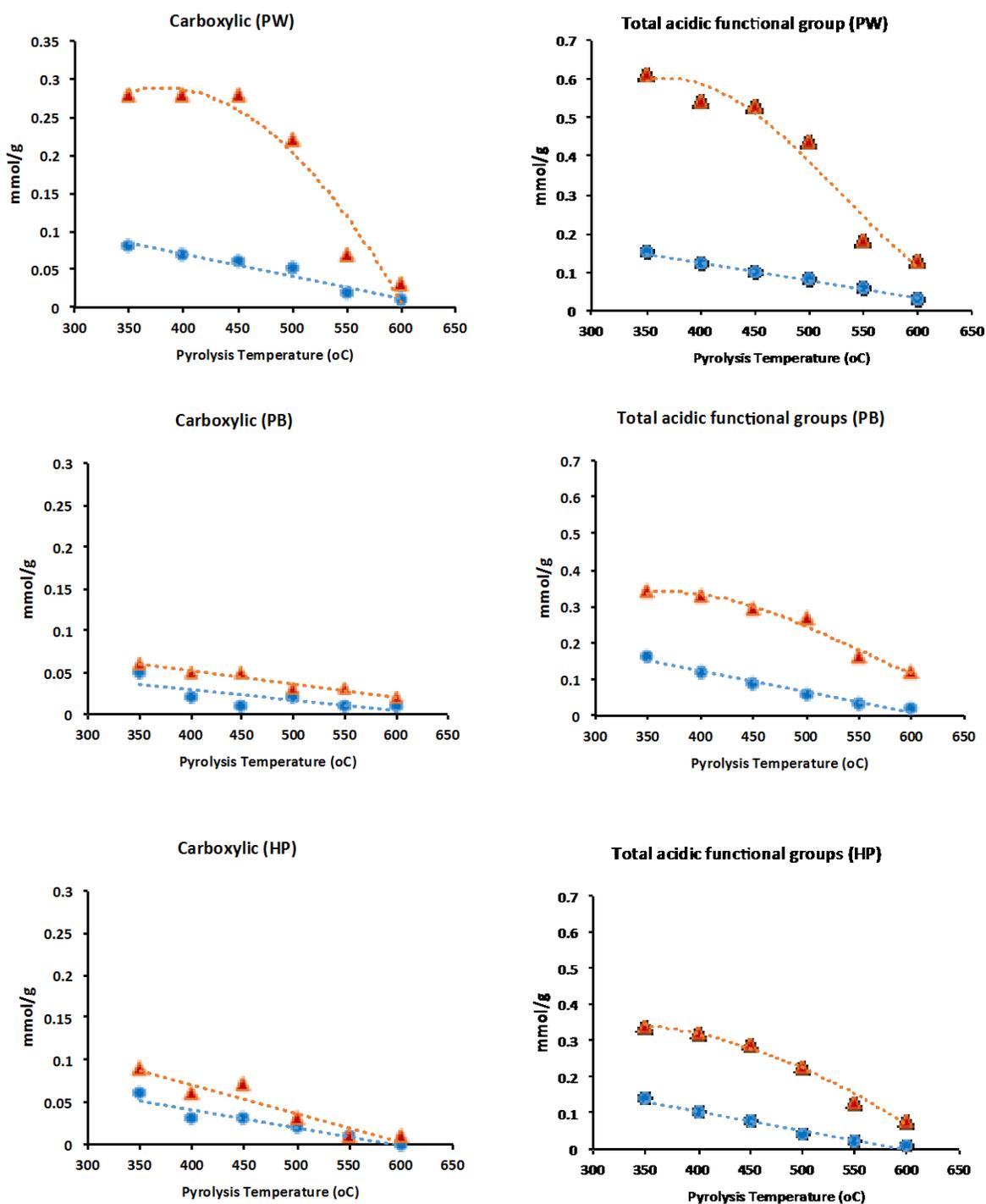


Figure 4.7: Carboxylic (left panels) and total acidic functional groups (right panels) of oxidized (red symbols) and unoxidized (blue symbols) PW (top), HP (middle) and PB biochars (bottom panels), measured via the Boehm analysis.

Biochar is amphoteric in nature due to the wide variety of functional groups localized on its surface. Therefore, determination of its potential at zero charge (PZC)—the point at which the biochar surface becomes uncharged ($\zeta=0$)— is an important parameter required to understand its electro-kinetic behavior (Qian and Chen, 2014). The formation of oxygenated functional groups added negative charges on the biochar surface, which led to the pH at the point of zero charge being always higher for unoxidized biochars (Figure 4.8). For example, in the PW-350 biochar, which had a pH PZC of 3 when unoxidized, oxidation lowered the pH PZC by about 1.8 pH units (Figure 4.8).

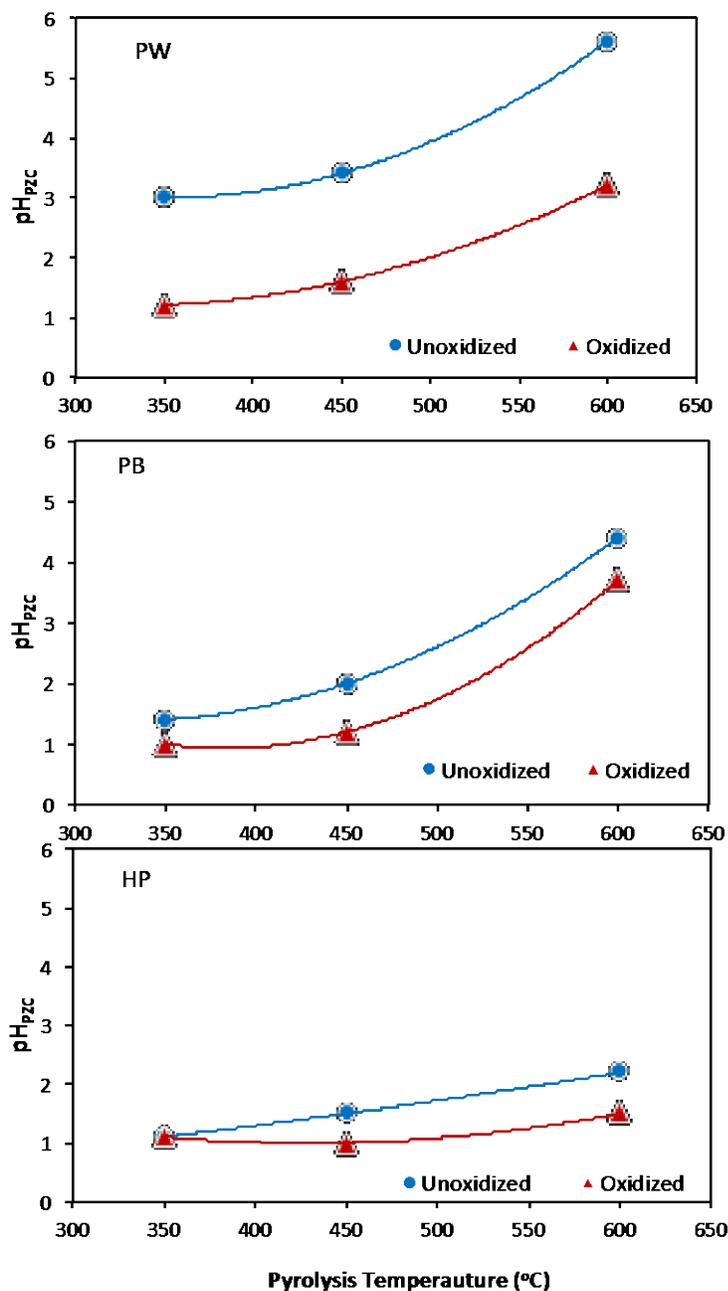


Figure 4.8: pH at which the charge on the surface of oxidized and unoxidized biochars becomes zero (pH_{PZC}), as a function of pyrolysis temperatures for different feedstocks.

The differences in the pH at the point of zero charge (pH_{PZC}) between unoxidized and oxidized samples increased as a function of pyrolysis temperature (Figure 4.8). For example, oxidation of the pine wood (PW) biochar led to the pH_{PZC} values dropping by approximately 2 pH units when produced at 450°C (PW-450), compared to a 2.4 pH unit drop when produced at 600°C (PW-600) (Figure 4.8). The same pH_{PZC} trend as a function of pyrolysis temperature was observed in the biochars produced from pine bark and poplar wood, though the relationship was feedstock dependent (Figure 4.8). In contrast to the differences exemplified above for pine wood, the pH_{PZC} of pine bark (PB-600) and hybrid poplar (HP-600) decreased only slightly with oxidation: 0.7 and 0.8 pH points, respectively. These results are consistent with what would be expected due to the formation of oxygenated functional groups on the surface of the char. The study's pH_{PZC} results are generally in agreement with the results reported by Cheng et al. (2008), Qian and Chen (2014), and Qiu et al., (2006). The charge on the surface of the catalyst controls the retention of charged objects. For example, *E. coli*—which is typically negatively charged—will be more likely to be retained by a char whose surface is positively charged.

Overall, this study's results suggest that low temperature, air oxidation of biochar is a feasible process for increasing the amount of oxygenated functional groups on the surface of biochar. However, trade-offs exist between the pyrolysis temperature that maximizes desirable physico-chemical properties that would benefit agricultural and environmental applications—600°C—and the temperature that produces biochars that are more suitable for oxidation by air, and therefore for increasing the amount of oxygenated functional groups via post-pyrolysis treatment. These results confirm that the production and post-treatment of the biochar should be designed with the final application in mind. For example, biochars for high water retention could be produced at either low or high temperature, but the biochar produced at high temperature has to be oxidized. The selection of the feedstock seems to be critical. Low-density (high-porosity) softwood woody biomass is likely to result in better biochar material for most applications. Materials for the removal of *E. coli* should be positively charged and the size of the pores should facilitate the diffusion of these microorganisms. The pH_{PZC} results described above can also inform efforts to design engineered biochars specifically for use in soils with particular pH values. Further study will help refine the development of engineered biochars for a broader range of targeted environmental applications. It will also be interesting to assess changes in biochar characteristics through time, possibly through weathering experiments, to determine how surface oxidation may change as biochars persist in an oxidized environment in the soil.

4.4.3 Effect of biochar and co-composted biochar on the retention of nutrients from composting materials

Analysis of the chemical and physical properties of the pure media—compost, biochar, co-composted biochar, and sand (see Table 4.1)—showed that the compost contained the highest amounts of nutrients, and that the co-composted biochar adsorbed nitrogen and other nutrients, as has been observed by others (Prost et al., 2013). The biochar and the co-composted biochar had by far the highest surface area. These and other, more detailed results are presented in the peer-reviewed publication of this study (Table 2 in Iqbal et al. 2015; see *Authors' note* on page 93).

The leachate from the compost had the most nitrogen, though the co-composted biochar had adsorbed some nitrogen during composting, leading to some leaching (Figure 4.9a). Adding biochar, co-composted biochar or sand to compost reduced—but did not eliminate—the leaching of total nitrogen and nitrate/nitrite (Figure 4.9b). The mixing of biochar or co-composted biochar with compost did not decrease the phosphorus leaching, most of which leached as ortho-phosphorus (Figure 4.9e and f), nor did it decrease the outflow concentrations of dissolved organic carbon (Figure 4.9g and h).

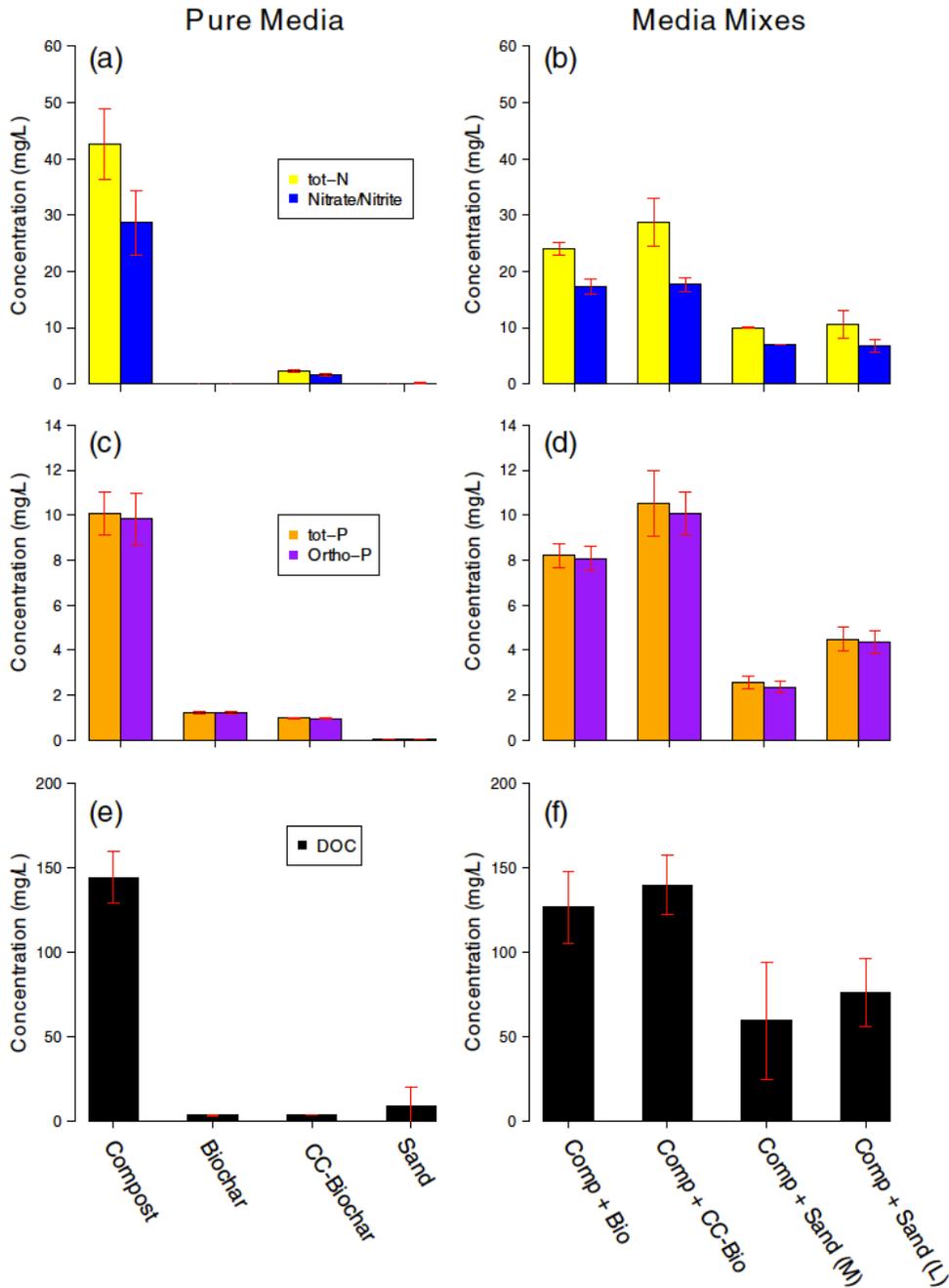


Figure 4.9: Nitrogen, phosphorus, and dissolved organic carbon (DOC) leached from pure media and media mixes. Data represent averages of three replicates from composite samples, and error bars are \pm one standard deviation (Figure 5 in Iqbal et al. 2015).

As the compost was the major source of nutrients, the amount of each nutrient in the leachate was dependent on the total amount of compost in the column. The concentration of nutrients in the leachate was therefore normalized by the mass of compost used in each treatment. The biochar and co-composted biochar amendments did not reduce total N and nitrate/nitrite leaching compared to the pure compost (Figure 4.10a). The sand amendments, however, significantly reduced both total nitrogen and nitrate/nitrite leaching. The amounts of total N leached from the compost and compost–biochar treatments—most of which was nitrate/nitrite—were 7 to 8% compared to 4 to 5% for the compost–sand mixes (Figure 4.10a).

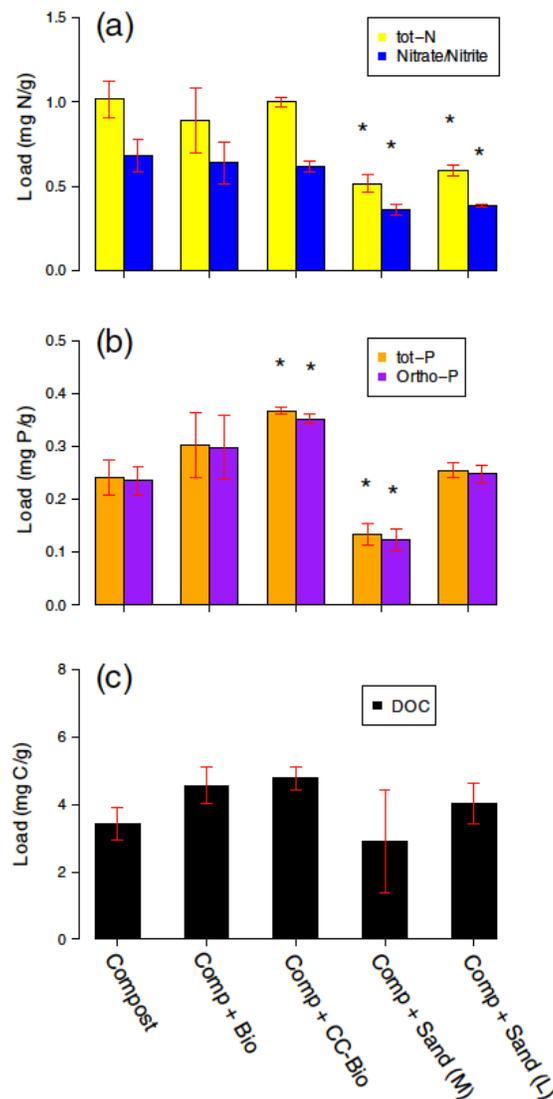


Figure 4.10: Nitrogen, phosphorus, and dissolved organic carbon (DOC) loads in the leachate, normalized by the mass of compost used in each treatment. Data represent averages of three replicates from composite samples, and error bars are ± one standard deviation. Asterisks indicate significant differences (p=0.05) compared to pure compost (Figure 6 in Iqbal et al. 2015).

There was no significant difference in the leaching of phosphorus from compost–biochar and compost–sand (layered) compared with the pure compost (Figure 4.10b). However, more phosphorus leached from the compost–co-composted-biochar mix, and less phosphorus leached from the compost–sand (mixed). In soils, phosphorus leaching is generally limited by the presence of aluminium and iron oxides (Sposito, 2008). Iron concentrations were almost seven times higher in sand (2.2 g kg^{-1}) than in the biochar or co-composted biochar (0.3 g kg^{-1}); therefore, the sand had a higher capacity to suppress phosphorus leaching. Biochar itself leached a substantial fraction of its initial phosphorus, though that initial amount was an order of magnitude smaller than that of the phosphorus in the compost, so that leaching of phosphorus from biochar was negligible.

There were no significant differences between the leaching of DOC among the different treatments (Figure 4.10c), indicating that neither biochar, co-composted biochar, nor sand adsorbed significant amounts of DOC. Estimates of the amount of DOC that the biochar and co-composted biochar could adsorb were an order of magnitude greater than the total amount of DOC leached from our compost-only column, suggesting that the biochar either did not sorb DOC as expected, or, more likely, that the DOC in the leachate did not make thorough contact with the biochar surfaces during the leaching process, thereby making the biochar less effective as a sorbent. Flow in unsaturated porous media, such as occurred in these experiments, provides less contact between fluid and sorbent than in a batch reactor such as those used in the published studies. Sorption determined from a batch sorption test may therefore overestimate sorption under unsaturated flow conditions.

In summary, adding commercial biochar to mature compost had a limited effect on the leaching of nitrate/nitrite, orthophosphorus, and dissolved organic carbon under unsaturated flow conditions. While not effective in preventing leaching of nitrate/nitrite and orthophosphorus, biochar applied to bioretention systems may retain metal contaminants. However, as many metals will readily form soluble complexes with dissolved organic carbon, the presence of excess dissolved organic carbon may circumvent the sorption capacity of biochars for metals.

4.4.4 Additional studies on the effects of biochar soil amendments on relevant soil properties

Below are summaries of two additional studies that applied the results of the seed research presented above to study the effect of biochar as a soil amendment on soil properties important for agricultural production and environmental functions.

4.4.4.1 Effects of biochar quantity and surface characteristics on the hydro-physical properties of soil-biochar blends

This study, currently in preparation for submission to the *Journal of the Total Environment* (Suliman et al., *in prep.* [a]), reports results on the effect of biochar's porous structure and surface chemistry on the hydrological properties of these materials and their blends with sandy soils. The biochars studied were produced from Pine Wood and Pine Bark at temperatures of 350°C and 600°C . The resulting materials were then oxidized under air at 250°C to generate oxygenated functional groups on the surface. All these biochars were thoroughly characterized (surface and bulk properties) and their hydrological properties measured in blends with Quincy sandy soils. The sandy soil was collected, air-dried, and sieved through a 2 mm mesh. The bulk

density, porosity, pH, electrical conductivity (EC), cation exchange capacity (CEC), and particle size distribution were determined. Twenty seven microcosms were prepared for this study, to examine the effect of biochar on the hydro-physical properties of Quincy sandy soils. Each biochar was thoroughly mixed with the soil at a rate of 20 g kg⁻¹. Bulk density, porosity, organic matter, pH, and EC were determined for each biochar-soil mixture. The field capacity, wilting point, and total available soil moisture of the biochar-Quincy sandy soil mixtures were measured for both dry and wet ranges. The soil water potentials and soil water contents were fitted using the model of Van Genuchten. Pearson’s correlation analyses were conducted to identify potential relationships between selected biochar properties and soil water retention characteristics. The biochar produced from PW was more hydrophilic than the biochar produced from PB. The biochars got more hydrophobic as the pyrolysis temperature increased; this is mostly due to the reduction of oxygenated functional groups on the surface. The oxidation increased the content of oxygenated functional groups on the surface, and consequently reduced its hydrophobicity. Oxidized biochars exhibited better wettability in comparison with unoxidized biochars. The biochars also have an impact on soil water content at field capacity (θ_{FC}); the θ_{FC} of sandy soil increased from 16.9% to over 26.1% on average after biochar addition (Table 4.3), with higher soil water contents achieved by soil samples amended with oxidized biochars. This represents an increase of over 50% in soil moisture at field capacity. The majority of the total water potentially stored was available for plant growth (Table 4.3), while in the case of soil without biochar additions, most of this water was easily lost by gravity. Over a wide range of soil water potentials, oxidized biochar-soil mixtures held significantly more water than the unoxidized biochar-soil mixtures, except within the saturation region, with soil water potentials between -0.1 and -5 kPa. The magnitude of the effect of pyrolysis temperature and feedstock source of biochar was found to vary over the range of soil water potentials. The impact of low pyrolysis temperature biochar was somewhat lower on water retention than the impact of biochar produced at high temperature, but the difference was not significant. Soil water contents at different matric potentials were significantly inter-correlated ($P < 0.01$), and were correlated with bulk densities of biochar-amended soil samples. The bulk density is controlled by the volume occupied by the internal cavities in the biochar. There were significant correlations observed between total acidic functional groups on the biochar surface and the water contents at different matric potentials.

Table 4.3: Effect of biochar application to sandy soil on bulk density, pH, electrical conductivity (EC), and soil water contents (θ).

Property	QS	QS-PW350		QS-PW600		QS-PB350		QS-PB600	
		UO	AO	UO	AO	UO	AO	UO	AO
Bulk density (g cm ⁻³)	1.49	1.27	1.28	1.26	1.27	1.28	1.27	1.29	1.27
pH _{H2O} (1:5)	7.5	8.1	7.8	8.12	7.9	8.1	7.5	8.7	8.2
EC _{H2O} (ds m ⁻¹)	0.08	0.01	0.01	0.02	0.04	0.02	0.03	0.06	0.06
θ_{FC} * (%)	16.91	26.55	27.09	25.70	27.50	23.68	25.87	25.43	27.18
θ_{PWP} * (%)	5.32	6.15	6.69	6.56	6.56	6.41	6.60	6.41	5.89
θ_{AWC} * (%)	11.59	20.40	20.40	19.15	20.94	17.27	19.27	19.02	21.29

* θ_{FC} : water content at Field Capacity; θ_{AWC} : Available Water Content; θ_{PWP} : water content at Permanent Wilting Point (-1.5 MPa).

4.4.4.2 Effects of biochar additions on *Escherichia coli* transport

This study is currently in preparation for submission to the journal Environmental Science and Technology (Suliman et al., *in prep.* [b]). A detailed understanding of the transport of *Escherichia coli* O157:H7 within the soil-groundwater system is critical for the protection of public health. Although incorporation of biochar—a carbon-rich porous material—into soils has the potential to reduce the leaching of manure-borne pathogens such as *E. coli*, knowledge concerning the impact of biochar surface functionality on the retention and transport of *E. coli* O157:H7 is still nonexistent. The main objective of this research was to evaluate whether the addition of unoxidized and oxidized biochar to a sandy soil affects the transport of *E. coli* strains through water-saturated soil columns. The researchers hypothesized that the transport of *E. coli* through biochar-amended soils would vary depending on the biochar's surface chemistry. The transport behavior of *E. coli* O157:H7 and *E. coli* K12 was studied using water-saturated column experiments for Quincy sandy soils amended with 20% pine wood or pine bark biochars, produced at 350 and 600°C using lab scale spoon pyrolysis reactor.

Results showed that:

- Oxidized biochar could enhance the transport of *E. coli* O157:H7 cells due to the surface charge;
- *E. coli* O157:H7 displayed higher retention than *E. coli* K12 in biochar-amended soil under experimental pH conditions;
- Increased biochar application rates (from 0 to 20%) led to an attenuation of the transport of both bacterial strains (from 95 to 40%);
- Increased transport was observed for the pine bark biochar produced at 600°C, whereas reduced transport was observed for the pine wood biochar produced at the same pyrolysis temperature.

These results suggest that pine wood biochar produced at 350°C can effectively reduce the transport of *E. coli* in the studied soil.

4.5 Conclusions

The intent of the biochar program at WSU was to carry out bench-scale studies to evaluate the bulk and surface properties of biochar engineered under different conditions, and to evaluate the effectiveness of a commercial biochar—blended with mature compost or co-composted with composting material and then blended with mature compost—on nutrient retention.

Study results indicate that it is possible to design a biochar with desirable physico-chemical properties that would benefit specific agricultural and environmental applications by using an appropriate combination of pyrolysis temperature and feedstock source. However, the high pyrolysis temperatures needed to produce a biochar with such properties makes the resultant biochar less suitable for oxidation by air than those produced at low pyrolysis temperatures. Low temperature, air oxidation of biochar appears to be a feasible process for increasing the amount of oxygenated functional groups on the surface of biochar. However, trade-offs exist between the pyrolysis temperature that maximizes desirable physico-chemical properties that would benefit agricultural and environmental applications—600°C—and the temperature that produces

biochars that are more suitable for oxidation by air, and therefore for increasing the amount of oxygenated functional groups via post-pyrolysis treatment.

The capacity of biochars to retain water, *E. coli*, and nutrients depended on the biochar's surface area, morphology and the composition of the surface. More studies are needed to develop engineered biochar for particular environmental applications.

4.6 References

- Al-Wabel M.I., Al-Omran A., El-Naggar A.H., Nadeem M., Usman A.R. 2013. Pyrolysis temperature induced changes in characteristics and chemical composition of biochar produced from conocarpus wastes. *Bioresource Technology* 131, 374–379. doi:10.1016/j.biortech.2012.12.165.
- Antal M.J., Grønli M. 2003. The Art, Science, and Technology of Charcoal Production. *Industrial and Engineering Chemistry Research* 42, 1619–40. doi:10.1021/ie0207919.
- Beesley, L., Moreno-Jimenez, E., Gomez-Eyles, J.L. 2010. Effects of biochar and greenwaste compost amendments on mobility, bioavailability and toxicity of inorganic and organic contaminants in a multi-element polluted soil. *Environmental Pollution* 158, 2282–2287.
- Brendova, K., Tlustos, P., Szakova, J., Habart, J. 2012. Biochar properties from different materials of plant origin. *European Chemical Bulletin* 1, 535–539.
- Brennan, A., Jimnez, E.M., Puschenreiter, M., Alburquerque, J.A., Switzer, C., 2014. Effects of biochar amendment on root traits and contaminant availability of maize plants in a copper and arsenic impacted soil. *Plant Soil* 379, 351–360.
- Bruun, E.W., Müller-Stöver, D., Ambus, P., Hauggaard-Nielsen, H. 2011. Application of biochar to soil and N₂O emissions: potential effects of blending fast-pyrolysis biochar with anaerobically digested slurry. *European Journal of Soil Science* 62, 581–589. doi:10.1111/j.1365-2389.2011.01377.x.
- Cantrell, K.B., Hunt, P.G., Uchimiya, M., Novak, J.M., Ro, K.S. 2012. Impact of pyrolysis temperature and manure source on physicochemical characteristics of biochar. *Bioresource Technology* 107, 419–428. doi:10.1016/j.biortech.2011.11.084.
- Cao, X., Ma, L., Gao, B., Harris, W., 2009. Dairy-manure derived biochar effectively sorbs lead and atrazine. *Environmental Science and Technology* 43, 3285–3291.
- Chen, B., Zhou, D., Zhu, L., 2008. Transitional adsorption and partition of nonpolar and polar aromatic contaminants by biochars of pine needles with different pyrolytic temperatures. *Environmental Science and Technology* 42, 5137–5143.
- Cheng, C.-H., Lehmann, J., Engelhard, M.H. 2008. Natural oxidation of black carbon in soils: Changes in molecular form and surface charge along a climosequence. *Geochimica et Cosmochimica Acta* 72, 1598–1610. doi:10.1016/j.gca.2008.01.010.
- Chiang, H.-L., Chiang, P.C., Huang, C.P. 2002. Ozonation of activated carbon and its effects on the adsorption of VOCs exemplified by methylethylketone and benzene. *Chemosphere* 47, 267–275.
- Chiang, H.-L., Huang, C.P., Chiang, P.C. 2002. The surface characteristics of activated carbon as affected by ozone and alkaline treatment. *Chemosphere* 47, 257–265. doi:10.1016/S0045-6535(01)00215-6.

- Clough, T.J., Condrón, L.M., Kammann, C., Müller, C., 2013. A review of biochar and soil nitrogen dynamics. *Agronomy* 3, 275–293.
- Collison, M., Collison, L., Sakrabani, R., Tofield, B., Wallage, Z. 2009. Biochar and Carbon Sequestration : A Regional Perspective A report prepared for East of England Development Agency (EEDA) Biochar and Carbon Sequestration: A Regional Perspective A report prepared for East of England Development Agency (EEDA).
- Crombie, K., Mašek, O., Sohi, S.P., Brownsort, P., Cross, A. 2013. The effect of pyrolysis conditions on biochar stability as determined by three methods. *GCB Bioenergy* 5, 122–31. doi:10.1111/gcbb.12030.
- Demirbas, A. 2004. Effects of temperature and particle size on bio-char yield from pyrolysis of agricultural residues. *Journal of Analytical and Applied Pyrolysis* 72, 243–248. doi:10.1016/j.jaap.2004.07.003.
- Ecology, 2012. Stormwater Management Manual for Western Washington. Washington State Department of Ecology, Olympia, WA (Publication Number 12-10-030).
- Fu, P., Hu, S., Xinag, J., Sun, L., Yang, T., Zhang, A., Wang, Y., Chen, G. 2009. Effects of Pyrolysis Temperature on Characteristics of Porosity in Biomass Chars. In *Energy and Environment Technology*, ICEET'09. International Conference, Vol. 1, pp. 109-112. doi:10.1109/ICEET.2009.33.
- Fuchs, M., Garcia-Perez, M., Sjöding, D. 2012. Biochar: Background & Early Steps to Market Development. Olympia, Washington.
- Granatstein, D., Kruger, C., Collins, H., Garcia-Perez, M., Yoder, J. 2009. Use of Biochar from the Pyrolysis of Waste Organic Material as a Soil Amendment. Final Project Report, Vol. 09-07-062, Center for Sustaining Agriculture and Natural Resources, Washington State University. Wenatchee, pp. 168.
- Harry, I.D., Saha, B., Cumming, I.W. 2006. Effect of electrochemical oxidation of activated carbon fiber on competitive and noncompetitive sorption of trace toxic metal ions from aqueous solution. *Journal of Colloid Interface Science* 304, 9–20. doi:10.1016/j.jcis.2006.08.012.
- Hipple, K.W. 2012. Washington Soil Atlas. National Resource Conservation Service, U.S. Department of Agriculture. 121 pp. Available at http://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcs144p2_034094.pdf.
- Iqbal, H., Garcia-Perez, M., Flury, M. 2015. Effect of biochar on leaching of organic carbon, nitrogen, and phosphorus from compost in bioretention systems. *Science of the Total Environment* 521-522, 37-45.
- Jindo, K., Sanchez-Monedero, M.A., Hernandez, T., Garcia, C., Furukawa, T., Matsumoto, K., Sonoki, T., Bastida, F., 2012. Biochar influences the microbial community structure during manure composting with agricultural wastes. *Science of the Total Environment* 416, 476–481.
- Julien, F., Baudu, M., Mazet, M. 1998. Relationship between chemical and physical surface properties of activated carbon. *Water Research* 32, 3414–3424. doi:10.1016/S0043-1354(98)00109-2.
- Kastner, J.R., Miller, J., Das, K.C. 2008. Pyrolysis conditions and ozone oxidation effects on ammonia adsorption in biomass generated chars. *Journal of Hazardous Materials* 164, 1420–1427. doi:10.1016/j.jhazmat.2008.09.051.
- Kim, P., Johnson, A.M., Essington, M.E., Radosevich, M., Kwon, W.-T., Lee, S.-H., Rials, T.G., Labbé, N. 2012. Effect of pH on surface characteristics of switchgrass-derived biochars

- produced by fast pyrolysis. *Chemosphere* 90, 2623–30.
doi:10.1016/j.chemosphere.2012.11.021.
- Knowles, O.A., Robinson, B.H., Contangelo, A., Clucas, L., 2011. Biochar for the mitigation of nitrate leaching from soil amended with biosolids. *Science of the Total Environment* 409, 3206–3210.
- Koch, A. 1998. A study of carbonaceous char oxidation in air by semi-quantitative FTIR spectroscopy. *Fuel* 77, 563–569. doi:10.1016/S0016-2361(97)00157-9.
- Lee, J.W., Kidder, M., Evans, B.R., Paik, S., Buchanan, A.C., Garten, C.T., Brown, R.C. 2010. Characterization of biochars produced from cornstovers for soil amendment. *Environmental Science and Technology* 44, 7970–7974. doi:10.1021/es101337x.
- Lehmann, J., Joseph, S. 2009. *Biochar for Environmental Management: Science and Technology International Biochar Initiative*. Earthscan, London, UK.
- Lehmann, J., Rillig, M.C., Thies, J., Masiello, C.A., Hockaday, W.C., Crowley, D., 2011. Biochar effects on soil biota — a review. *Soil Biology and Biochemistry* 43, 1812–1836.
- Liang, B., Lehmann, J., Solomon, D., Kinyangi, J., Grossman, J., O’Neill, B., Skjemstad, J.O., Thies, J., Luizao, F.J., Petersen, J., Neves, E.G. 2006. Black Carbon Increases Cation Exchange Capacity in Soils. *Soil Science Society of America Journal* 70, 1719-1730. doi:10.2136/sssaj2005.0383.
- Maia, C.M.B.F, Madari, B.E., Novotny, E.H. 2011. Advances in Biochar Research in Brazil. *Dynamic Soil, Dynamic Plant* 5, 53-58.
<http://www.alice.cnptia.embrapa.br/bitstream/doc/915016/1/AdvancesinBiocharResearchinBrazil.pdf>
- Mašek O., Brownsort, P., Cross, A., Sohi, S. 2013. Influence of production conditions on the yield and environmental stability of biochar. *Fuel* 103, 151–155.
doi:10.1016/j.fuel.2011.08.044.
- Mbagwu, J.S.C., Piccolo, A. 1997. Effects of humic substances from oxidized coal on soil chemical properties and maize yield. In: Drozd, J., Gonet, S.S., Senesi, N. (Eds.) *The role of humic substances in the ecosystems and in environmental protection*. IHSS, Polish Society of Humic Substances, Wroclaw, Poland, 921-925.
- McKay, G. 2002. Dioxin characterisation, formation and minimisation during municipal solid waste (MSW) incineration: review. *Chemical Engineering Journal* 86, 343–368.
doi:10.1016/S1385-8947(01)00228-5.
- McKendry, P. 2002. Energy production from biomass (part 1): overview of biomass. *Bioresource Technology* 83, 37–46. doi:10.1016/S0960-8524(01)00118-3.
- Meng, J., Feng, X., Dai, Z., Liu, X., Wu, J., Xu, J. 2014. Adsorption characteristics of Cu(II) from aqueous solution onto biochar derived from swine manure. *Environmental Science and Pollution Research* 21, 7035–7046.
- Mitchell, P.J., Dalley, T.S.L., Helleur, R.J. 2013. Preliminary laboratory production and characterization of biochars from lignocellulosic municipal waste. *Journal of Analytical and Applied Pyrolysis* 99, 71–78. doi:10.1016/j.jaap.2012.10.025.
- Nordon, P., Young, B.C., Bainbridge, N.W. 1979. The rate of oxidation of char and coal in relation to their tendency to self-heat. *Fuel* 58, 443–449. doi:10.1016/0016-2361(79)90086-3.
- Novak, J.M., Busscher, W.J., Laird, D.L., Ahmedna, M., Watts, D.W., Niandou, M.A. 2009. Impact of Biochar Amendment on Fertility of a Southeastern Coastal Plain Soil. *Soil Science* 174, 105–112. doi:10.1097/SS.0b013e3181981d9a.

- Oda, H., Takeuchi, M., Yokokawa, C. 1981. Effect of air-oxidation on the pore-structure of coals and cokes or chars obtained from oxidized coals. *Fuel* 60, 390–396. doi:10.1016/0016-2361(81)90275-1.
- Paris, O., Zollfrank, C., Zickler, G.A. 2005. Decomposition and carbonisation of wood biopolymers—a microstructural study of softwood pyrolysis. *Carbon* 43, 53–66. doi:10.1016/j.carbon.2004.08.034.
- Park, S.-J., Jin, S.-Y. 2004. HCl removal using activated carbon fibers electroplated with silver. *Carbon* 42, 2113–2115. doi:10.1016/j.carbon.2004.03.033.
- Parra, J., de Sousa, J., Pis, J., Pajares, J.A., Bansal, R.C. 1995. Effect of gasification on the porous characteristics of activated carbons from a semianthracite. *Carbon* 33, 801–807. doi:10.1016/0008-6223(95)00004-W.
- Paz-Ferreiro, J., Lu, H., Fu, S., Mendez, A., Gasco, G. 2014. Use of phytoremediation and biochar to remediate heavy metal polluted soils: a review. *Solid Earth* 5, 65–75.
- Pradhan, B.K., Sandle, N.K. 1999. Effect of different oxidizing agent treatments on the surface properties of activated carbons. *Carbon* 37, 1323–1332. doi:10.1016/S0008-6223(98)00328-5.
- Prost, K., Borchard, N., Siemens, J., Kautz, T., Sequaris, J.-M., Möller, A., Amelung, W. 2013. Biochar affected by composting with farmyard manure. *Journal of Environmental Quality* 42, 164–172.
- Qian, L., Chen, B. 2014. Interactions of aluminum with biochars and oxidized biochars: implications for the biochar aging process. *Journal of Agricultural and Food Chemistry* 62, 373–380. doi:10.1021/jf404624h.
- Qiu, Y., Ling, F. 2006. Role of surface functionality in the adsorption of anionic dyes on modified polymeric sorbents. *Chemosphere* 64, 963–971. doi:10.1016/j.chemosphere.2006.01.003.
- Ronsse, F., van Hecke, S., Dickinson, D., Prins, W. 2013. Production and characterization of slow pyrolysis biochar: influence of feedstock type and pyrolysis conditions. *GCB Bioenergy* 5, 104–115. doi:10.1111/gcbb.12018.
- Salame, I.I., Bandosz, T.J. 2001. Surface Chemistry of Activated Carbons: Combining the Results of Temperature-Programmed Desorption, Boehm, and Potentiometric Titrations. *Journal of Colloid and Interface Science* 240, 252–258. doi:10.1006/jcis.2001.7596.
- Smith, J.L., Collins, H.P., Bailey, V.L., 2010. The effect of young biochar on soil respiration. *Soil Biology and Biochemistry* 42, 2345–2347.
- Song, W., Guo, M. 2012. Quality variations of poultry litter biochar generated at different pyrolysis temperatures. *Journal of Analytical and Applied Pyrolysis* 94, 138–145. doi:10.1016/j.jaap.2011.11.018.
- Spokas, K.A., Cantrell, K.B., Novak, J.M., Archer, D.W., Ippolito, J.A., Collins, H.P., Boateng, A.A., Lima, I.M., Lamb, M.C., McAloon, A.J., Lentz, R.D., Nichols, K.A. 2012. Biochar: a synthesis of its agronomic impact beyond carbon sequestration. *Journal of Environmental Quality* 41, 973–989. doi:10.2134/jeq2011.0069.
- Sposito, G. 2008. *The Chemistry of Soils*. 2nd Ed. Oxford University Press, New York, NY.
- Steiner, C., Das, K.C., Melear, N., Lakly, D. 2010. Reducing nitrogen loss during poultry litter composting using biochar. *Journal of Environmental Quality* 39, 1236–1242.
- Suliman, W., Harsh, J.B., Abu-Lail, N.I., Fortuna, A.M., Dallmeyer, I., Garcia-Pérez, M. *In preparation*. [a] Understanding the role of biochar porous structure and surface chemistry

- in augmenting hydrologic properties of a sandy soil. For submission to the Journal of the Total Environment.
- Suliman, W., Harsh, J.B., Fortuna, A.M., Garcia-Pérez, M., Abu-Lail, N.I. *In preparation*. [b] Towards the quantification of the effects of biochar oxidation and pyrolysis temperature on the transport of pathogenic and nonpathogenic *E. coli* in biochar-amended sand columns . For submission to Environmental Science and Technology.
- Uchimiya, M., Lima, I.M., Klasson, K.T., Wartelle, L.H. 2010. Contaminant immobilization and nutrient release by biochar soil amendment: roles of natural organic matter. *Chemosphere* 80, 935–940.
- Valdés, H., Sánchez-Polo, M., Rivera-Utrilla, J., Zaror, C.A. 2002. Effect of Ozone Treatment on Surface Properties of Activated Carbon. *Langmuir* 18, 2111–2116. doi:10.1021/la010920a.
- Verheijen, F.G., Jeffery, S., Bastos, A.C., van der Velde, M., Diafas, I. 2010. Biochar Application to Soils. EUR 24099 EN, Office for the Official Publications of the European Communities, Luxembourg. doi:10.2788/472.
- Wang, Z., Cao, J., Wang, J. 2009. Pyrolytic characteristics of pine wood in a slowly heating and gas sweeping fixed-bed reactor. *Journal of Analytical and Applied Pyrolysis* 84, 179–184. doi:10.1016/j.jaap.2009.02.001.
- Wang, C., Lu, H., Dong, D., Deng, H., Strong, P.J., Wang, H., Wu, W. 2013. Insight into the effects of biochar on manure composting: evidence supporting the relationship between N₂O emission and denitrifying community. *Environmental Science and Technology* 47, 7341–7349.
- Zhang, J., Lü, F., Shao, L., He, P. 2014. The use of biochar-amended composting to improve the humification and degradation of sewage sludge. *Bioresource Technology* 168, 252–258.
- Zhao, L., Cao, X., Mašek, O., Zimmerman, A. 2013. Heterogeneity of biochar properties as a function of feedstock sources and production temperatures. *Journal of Hazardous Materials* 256-257C, 1–9. doi:10.1016/j.jhazmat.2013.04.015.

5. Separating Polyphenolic Compounds from Fruit Pomace for Use as a High Value Food Additive

Ayca Seker, Tao Dong, and Shulin Chen

5.1 Abstract

During wine and grape juice making, high quantities of waste products including grape pulp, seeds, and skins remain unused. However, these waste products, called grape pomace, are a good and cheap source of high-quality polyphenolic compounds. Due to the important role of these compounds in preventing obesity, coronary heart disease, and cancer, the interest in obtaining them from natural sources has grown. Cost-effective extraction and purification methods, however, are essential for producing polyphenols, a high-value food additive, from grape pomace. In this study, a combined polyphenol extraction and purification process based on magnetic polymeric particles with hydrogen bonding affinity ligands was investigated. Polyphenolic compounds were extracted from grape seeds with sonication-assisted solvent extraction by using an aqueous ethanol solution. The purification of crude grape pomace extract was performed with magnetic particles grafted with PEG-600.

The adsorption capacity of these magnetic particles reached 38 mg g⁻¹ dry adsorbent, whereas the commercially available polymeric macroporous resin, XAD-4, only reached 7 mg g⁻¹ dry adsorbent. Also, it took 12-fold less time for the magnetic particles to desorb the same amount of adsorbed polyphenols compared to the XAD-4 resins. Moreover, polyphenols separated with magnetic particles had 1.3- and 1.7-fold higher antioxidant activity than those separated with XAD-4 polymeric resins and the crude polyphenol extract, respectively. These experimental results are encouraging, and could be used as a starting point to scale up this separation process to develop high-value-added food additives from byproducts of the wine and grape juice industries in Washington State and beyond.

5.2 Background

Consumption of polyphenols has been found to have significant health benefits. In recent years, this understanding has led to growing interest in finding such bioactive compounds from natural sources, to be used as food additives. During wine and grape juice making, high quantities of waste products, including grape pulp, seeds, and skins, remain unused. However, these waste products of wine and grape juice in the food processing industry, called grape pomace, are a good and cheap source of high quality polyphenolic compounds. Cost-effective extraction and purification methods, however, are essential for transforming grape pomace—currently seen as a waste byproduct—into a raw material for the production of polyphenols, a high-value food additive.

Phenolic compounds are secondary plant metabolites. Phenolic compounds have an aromatic ring bearing one or more hydroxyl groups and their structures may range from that of a simple phenolic molecule to that of a complex, high molecular mass polymer (Balasundram et al., 2006). Phenolic compounds consist of a wide variety of molecules that have the polyphenol structure: several hydroxyl groups on aromatic rings. Molecules with one phenol ring, such as phenolic acids and phenolic alcohols, are the simpler kind of phenolic compounds. Polyphenols are classified according to the number of phenol rings that the molecules contain and the structural elements that bind these rings to each other. The main groups of polyphenols are flavonoids, phenolic acids, stilbenes, and lignans, though there are others (D'Archivio et al., 2007).

For decades plant polyphenols have attracted scientists since they are necessary for plant physiological functions, they contribute to plant morphology, growth and reproduction, and they provide a protective role against pathogens and predators. The sensory and nutritional quality of fruits, vegetables and other plants are determined by polyphenols (Lapornik et al., 2005; Tomás-Barberan et al., 2000).

The content and composition of polyphenol compounds in fruits is highly variable. Even for the same species the concentrations of specific polyphenols can vary significantly from one fruit to another. As a result, the content of polyphenols in fruits or other plant foods is commonly expressed as its total polyphenol content (Table 5.1). In addition, the total polyphenol concentration in fruits can be influenced by many different factors, such as genetics, environmental conditions, variety, storage, and degree of ripeness (Table 5.1).

In industry, polyphenols have been widely used, including in the production of paints, paper, and cosmetics. In cosmetics they are used as tanning agents, whereas in the food industry they are utilized as food and color additives. Moreover, some phenolic compounds, the flavonoids, are used as antibiotics and antidiarrheal, antiulcer, and anti-inflammatory agents. They are also utilized for the treatment of diseases such as hypertension, vascular fragility, allergies, hypercholesterolemia, and others (Kuhnau, 1976; Saito et al., 1998; Singleton, 1981). Polyphenols may also play an important role in preventing obesity, coronary heart disease, colon cancer, and gastrointestinal disorders, and can also reduce the risk of diabetes (Altiok et al., 2008; Jitaru et al., 2005; Luthria & Pastor-Corrales, 2006).

Polyphenols are well known for such health promoting effects, and can be utilized as antioxidants—therapeutic agents that neutralize free radicals in biological systems (Heim et al., 2002; Yilmaz & Toledo, 2003). Polyphenols' antioxidant activity comes from their ability to scavenge free radicals, donate hydrogen atoms, and chelate metal cations. The antioxidant ability depends on the structure of the particular polyphenol, especially the position and number of hydroxyl groups and the nature of other substitutions on the aromatic structure (Balasundram et al., 2006). In phenolic acids, the antioxidant ability depends on the number and position of the hydroxyl groups in connection with the carboxyl functional groups (Rice-Evans et al., 1996; Robards et al., 1999). Due to polyphenols' antioxidant ability and its nutritional effects, the recovery of those valuable nutraceuticals has attracted researchers in the past years (Fontana et al., 2013).

Table 5.1: Polyphenolic content of different plant foods and beverages (Kuhnau, 1976).

Foods and Beverage^a	Total Polyphenols	Foods and Beverage^a	Total Polyphenols
Cereals (mg 100g⁻¹ dm)		Fruits (mg 100g⁻¹ fm)	
Barley	1200–1500	Blackcurrant	1400–1200
Corn	30.9	Blueberry	135–280
Millet	590–1060	Cherry	60–90
Oats	8.7	Cowberry	128
Rice	8.6	Cranberry	77–247
Sorghum	170–10,260	Gooseberry	22–75
Wheat	22–40	Grape	50–490
Legumes (mg 100g⁻¹ dm)		Grapefruit	50
Black gram	540–1200	Orange	50–100
Chickpeas	78–230	Peach	10–150
Cowpeas	175–590	Pear	2–25
Common beans	34–280	Plum	4–225
Green gram	440–800	Raspberry	37–429
Pigeon peas	380–1710	Red currant	17–20
Nuts (%dm)		Strawberry	38–218
Betel nuts	26–33	Tomato	85–130
Cashew nuts	33.7	Fruit Juices (mg L⁻¹)	
Peanuts	0.04	Apple Juice	2–16
Pecan nuts	8–14	Orange juice ^b	370–7100
Vegetables (mg 100g⁻¹ fm)			660–100
Brussels sprouts	6–15	Beverages	
Cabbage	25	Tea leaves (% dm)	
Leek	20–40	Green	20–35
Onion	100–2025	Black	22–33
Parsley	55–180	Tea, cup (mg 200mL ⁻¹)	150–210
Celery	94	Coffee beans	0.2–10
Fruits (mg 100g⁻¹ fm)		Coffee, cup(mg 150mL ⁻¹)	200–550
Apple	27–298	Cacao beans (%dm)	12–18
Apricot	30–43	Wine (mg L ⁻¹)	
		White (mg L ⁻¹)	200–300
		Red	1000–4000 (6500)
		Beer	60–100

^adm= dry matter; fm=fresh matter.

^bValues for different orange varieties.

Polyphenols are the third most abundant component in grapes and wines, after carbohydrates and fruit acids. Total extractable polyphenols present in grapes are about 10% or less in the pulp, 60–70% in the seeds, and 28–35% in the skin. Grape seeds contain lipid, protein, carbohydrates, and from 5% to 8% polyphenols by weight depending on the source (Shi et al., 2003). Polyphenolic compounds in grapes and wines can be classified into three main classes: phenolic acids (hydroxybenzoic and hydroxycinnamic acids), simple flavonoids (flavonols, catechins and anthocyanins), tannins and proanthocyanidins. The phenolics most commonly identified in grape

pomace are anthocyanins, hydroxybenzoic and hydroxycinnamic acids, flavan-3-ols, flavonols and stilbenes (Lu and Yeap Foo, 1999).

Grape is the world's largest fruit crop with annual production of more than 77 million tons. Almost fifty percent of the worldwide production of grape is used for winemaking (FAO, 2013). In 2014, Washington State's wine grape production totaled 227,000 tons. Moreover, Washington State ranks second in the United States (behind California) in the production of wine grapes and wine (Wine, 2014).

During wine and juice making from grape, millions of tons of residues including grape pulp, seeds and skins, called grape pomace, remain unused, requiring additional investment in waste management approaches (Bucić-Kojić et al., 2007). Industry uses a portion of these residues for tartaric acid extraction or ethanol production. The final solid fraction is used as a fertilizer, though high levels of phenol in this material might be a problem, inhibiting seed germination (Silva et al., 2000). Grape pomace has also been used as an additive in animal feed due to its high fiber content (Palma et al., 2001). However, even after wine and juice making, the grape pomace still contains high levels of polyphenols.

The current interest in polyphenols' health-promoting properties, combined with their high content in grape pomace, highlights an opportunity for developing a high-value food additive from a material that is (a) produced in large quantities in Washington State, and (b) currently considered a byproduct to be handled with organic waste management approaches. Development of such a food additive will require two steps: extraction of polyphenols from the grape pomace, and purification of the extract. If polyphenols can be extracted and purified easily, cheaply and safely from organic waste products, then their production can change the economic balance of an organics recycling facility. This, in turn, can lead to a shift in perception of such facilities from a multi-stream input operation focused on waste management, to a multi-stream output facility focused on production of value-added products.

5.2.1 Existing extraction methods

Extraction is a very important step in the separation, identification, and use of phenolic compounds. In the last few years, studies related to the extraction of the phenolic compounds present in natural products have attracted special interest. Though there is no single and standard extraction method, there are multiple alternatives that are adequate for polyphenol extraction from natural sources. Liquid-liquid extraction (Baydar et al., 2004) and extraction with a supercritical fluid (Bleve et al., 2008) are the most common separation techniques. Accelerated solvent extraction, ultrasound assisted extraction, microwave assisted extraction, subcritical water extraction, and enzymatic assisted extraction are other extraction techniques used (Fontana et al., 2013).

5.2.1.1 Solid-liquid extraction

A mass transport phenomenon in which solids contained in a solid matrix migrate into a solvent that is in contact with that solid matrix is defined as solid-liquid extraction. Many important food components such as sucrose from sugarcane, lipids and proteins from oilseeds, phytochemicals from plants, functional hydrocolloids from algae, and polyphenolic compounds from plants, fruits and vegetables can be recovered by applying solid-liquid extraction methods. The efficiency of the mass transport phenomena in solid-liquid extraction can be increased by

adjusting the concentration gradient—dependent on factors such as temperature, liquid:solid ratio, flow rate, and particle size—the diffusion coefficients, or the boundary layer between the solid and liquid phases (Corrales et al., 2009). Contact time and the ratio of liquid to solid are also important parameters in determining the efficiency of the total extraction process (Hayouni et al., 2007; Pinelo et al., 2004; Rubilar et al., 2003).

The solvents that are used in this as well as the related liquid-liquid extraction methods vary depending on the desired materials in the extracted stream. Acidified methanol and ethanol are the most common solvents used as extractants (Amr and Al-Tamimi, 2007; Awika et al., 2005; Caridi et al., 2007; Lapornik et al., 2005). Of the two, methanol is the most efficient extractant. It has been reported that methanol extraction recovers anthocyanin from grape pulp with 20% greater effectiveness than ethanol, and is 73% more effective than water extraction (Castañeda-Ovando et al., 2009). However, ethanol extraction is preferred by the food industry since methanol is a toxic compound. This trade-off between extraction efficiency and toxicity of the extractant makes solid-liquid extraction challenging for the efficient and cost-effective extraction of polyphenols from grape pomace to produce a food additive.

5.2.1.2 Supercritical fluid extraction

A promising alternative to organic solvent extraction of biological compounds is supercritical fluid extraction (SFE). Supercritical fluid extraction methods avoid the use of large amounts of potentially toxic solvents while being rapid, automatable, and selective. The basic principle of SFE is the rapid change in solvent properties in response to slight variations in pressure when the solvent is close to its “critical point” (Palenzuela et al., 2004). The use of SFE methods in industrial extraction has increased in recent years, due to the regulations and environmental concerns related to hydrocarbons, and the increase in ozone-depleting emissions, which have led processors to find alternatives to the use of organic solvent extraction methods. In addition, SFE occurs without exposure to light and air, thereby reducing the degradation effect of the extraction process (Bleve et al., 2008).

Supercritical carbon dioxide is the most commonly used extractant due to its environmentally friendly nature, low toxicity, non-flammability and compatibility with processed foodstuffs. Higher diffusivity, lower viscosity, and lower surface tension give supercritical CO₂ a solvation capacity similar to that of traditional extraction techniques using liquid organic solvents. An additional advantage is that it can easily be separated from solutes while having modest critical conditions.

The unique properties listed above—environmentally friendly, low toxicity, non-flammability—have made SFE the preferred method for extraction and isolation of natural products. In addition, the supercritical CO₂ separation method can be carried out at low temperatures, so it is an ideal approach for natural product extraction from plant materials, where low temperatures are required. Modern technologies allow for precise regulation of changes in temperature and pressure, and thus for manipulations of the solvation properties of the supercritical CO₂. These technologies therefore facilitate the extraction of natural products with a wide range of polarities (Nahar and Sarker, 2012). Adding modifiers such as methanol to supercritical CO₂ can change that polarity, so it can be used for selective separation. However, previous studies showed that the total polyphenol content and antioxidant activity of polyphenols extracted by using SFE, with and without modifiers, were lower than those extracted with solid-liquid extraction (de Campos

et al., 2008). Also, as previously studied, SFE of certain type of polyphenols—e.g. anthocyanins—requires high pressures and high percentage of modifiers (ethanol, methanol) (Bleve et al., 2008). So working under these conditions to extract these compounds incurs additional operating costs. Besides the unique properties of the SFE method, the requirement of a certain type of instrument to create supercritical conditions and operate at those conditions makes this extraction method highly costly.

5.2.1.3 Other extraction methods

Heating and boiling can also be used to extract natural phenolic compounds from industry byproducts. However, the long extraction time and the resultant loss of polyphenols due to ionization, hydrolysis, and oxidation limit the widespread use of these methods (Li et al., 2005).

In recent years, various other techniques have been developed for the extraction of nutraceuticals from plants, including ultrasound-assisted extraction, sonication-assisted extraction, microwave-assisted extraction, and high hydrostatic pressure extraction (HHP). Those assisted extraction methods are convenient modifications to the solid-liquid extraction method. A laboratory and pilot-plant scale method using enzyme-assisted extraction has also been developed for the extraction of polyphenols from grape pomace (Maier et al., 2008). Ultrasound- and sonication-assisted extractions seem the most promising, however, because they are inexpensive, simple and as efficient as conventional extraction techniques (Wang et al., 2008). These methods assist the extraction by increasing the penetration of the solvent into the solid matrix, and increasing the mass transfer between the solid matrix and the solvent. They also increase the efficiency of extraction by enhancing the solubility of the compound of interest and the diffusivity from the solid matrix to the solvent. Extraction of phenolic compounds from *Folium eucommiae* via ultrasound-assisted extraction were reported to also be more efficient than extractions by heating, microwave-assisted and enzyme-assisted extraction techniques (Huang et al., 2009). Such ultrasound-assisted methods are usually used for extraction of non-volatile and semi-volatile compounds from solids such as soil and sludge. They are also used to improve the extraction process of lipids, proteins, and phenolic compounds from plants.

The conventional solid-liquid extraction methods have the advantage of easy accessibility, applicability, and satisfactory results. By slightly modifying the solid-liquid extraction methods with assisting technologies, higher recoveries can be achieved without economical concerns. Supercritical fluid extraction can be an alternative to conventional extraction methods as its ability and suitability for extracting bioactive compounds has been demonstrated. However, when the extraction efficiency and the costs related to instrumentation and operation are compared, these additional costs make this extraction method less applicable.

5.2.2 Existing purification methods

The extraction process is nonselective, so crude extracts contain byproducts such as fruit acids, proteins, and carbohydrates, in addition to the targeted polyphenolic compounds. Those byproducts decrease the purity of polyphenols and may affect their stability (Liu et al., 2008). Moreover, given the complex nature and low content of plant extract samples, the dilution effect of these impurities restricts the detection limit and sensitivity of analytical and instrumental methods. A purification step—also known as a physical separation—is therefore essential for the recovery of polyphenols from grape pomace.

5.2.2.1 Synthetic polymers

Water-insoluble polyvinylpyrrolidone (PVPP) and water-soluble polyvinylpyrrolidone (PVP) are synthetic polymers that are also used to adsorb phenols from beverages. The former has high production costs, so regeneration of the polymers for reuse is necessary. The regeneration requires the use of strong acids and alkalis. After the regeneration, acids and alkalis may not be removed completely, and therefore the use of recovered compounds contradicts food regulations. Another drawback to the use of regenerated PVPP is that its activity and capacity to adsorb phenols is reduced after several uses (Ford, 1992).

5.2.2.2 Polymeric resins

Polymeric resins have been widely used to separate polyphenols from crude extraction solutions. The separation mechanism is based on hydrophobic interactions between the solutes (the polyphenols) and the adsorbent (the macroporous resin). The most commonly used polymeric macroporous adsorbents are polystyrene-divinylbenzene (PS-DVB) copolymers, which have hydrophobic surface properties. Generally, PS-DVB resins have affinity to polar compounds, as their surfaces comprise a large number of active aromatic sites that allow them to form interactions between compounds with aromatic structures. Two aromatic rings that are close enough to each other would attract each other due to the non-covalent interactions. These PS-DVB resins have relative selectivity towards solutes with only an aromatic structure due to the non-specific interactions they form.

In the group of polymeric resins, XAD-4 resins are commercially available, and they demonstrate the ability to separate phenolic compounds from the crude extraction solution. Nonetheless, this type of resin has some drawbacks, such as lack of selectivity, low recovery efficiencies due to weak interactions, and low loading capacity for highly polar compounds, such as polyphenols, which affects the amount of solutes that can be recovered from the crude extract (Leon-Gonzalez and Perez-Arribas, 2000). Since the macroporous resins are usually composed of polymeric aromatic structures, the polyphenols would be attracted to the aromatic sites of the resin. The recovery of the adsorbed polyphenols from the resins can then be accomplished by elution with organic solvents.

In addition to the polyvinyl-based synthetic polymers, styrene-based polymeric particles have also been used in the separation of polyphenols. Scordino et al. performed a separation process with commercially available styrene-divinylbenzene (S-DVB) and acrylic resins, selectively recovering hesperidin, anthocyanins, hydroxycinnamates, and cyanidin 3-glucoside from aqueous solutions. Their results showed that S-DVB resins were more effective than acrylic resins and the adsorbed polyphenols could be totally recovered by ethanol or methanol elution (Scordino et al., 2004; Scordino et al., 2003; Scordino et al., 2005). The ability of different adsorbent resins (XAD-4, XAD-16, XAD-7HP) to recover polyphenols—high value-added products—from olive oil mills' wastewater were compared. They concluded that both XAD-4 and XAD-16 were capable of adsorbing only hydroxytyrosol, whereas XAD-7HP failed to adsorb any phenolic compound (Agalias et al., 2007). The recovery of tobacco polyphenols from river water using XAD-4 resin was reported; Liu et al. (2008) showed that XAD-4 resins could only recover two types of polyphenols: chlorogenic acid and rutin, at concentrations of 32.8 and 19.2 $\mu\text{g L}^{-1}$ respectively.

Amide groups have been introduced onto the surface of macroporous cross-linked polystyrene and polyacrylamide adsorbents, in order to increase the selectivity and adsorption capacity of polymeric adsorbents for tea polyphenols (Huang et al., 2007). Hydrogen bonding affinity could be an alternative mechanism to separate polyphenolic compounds: polyphenols have several hydroxyl groups in their aromatic rings, and these groups could form hydrogen bonds with proton acceptors by donating their proton. Geng et al. (2009) used this approach to increase the selectivity of adsorbents towards natural flavonoids from plants. They aimed to produce functional, commercial adsorbents (XAD-4, D380, ADS-21, and AB-8) with ester, amino, and amide groups, and reported that adsorbents with functional amide groups showed the highest adsorption capacity (3 mg polyphenol g⁻¹ dry adsorbent) through hydrogen bonding (Geng et al., 2009). Since the separation is based on the interactions between the ligands and the polyphenols, the selection of the hydrogen bonding affinity ligand is the challenging step, as it affects the separation efficiency and the amount of recovered polyphenols. Geng et al. (2009) showed that hydrogen bonding affinity ligands can be used for the purification and separation of polyphenols, and that the effectiveness of the separation can be adjusted by changing those affinity ligands.

5.2.2.3 Magnetic particles

In recent years, magnetic particles have garnered great interest for their application in a wide range of disciplines including chemistry, biochemistry, biotechnology, biology, and medicine. They rapidly, easily, and cost-effectively remove compounds of interest from complex heterogeneous matrices without the need for filtration and centrifugation, both at experimental and pilot scales. Particles ranging from nonspecific to particles with affinity ligands offer a wide range of applications in the area of protein and enzyme immobilization, protein, DNA, and RNA purification, immunoassays, isolation of cells, and targeted drugs (Bilková et al., 2002; Lübbe et al., 1996; Šafařík & Šafaříková, 1999; Yu et al., 2000).

Magnetic particles are generally core-shell types of particles; that is, they consist of a magnetic core and an inert low or high molecular weight compound coating the core. The magnetic cores mostly exhibit superparamagnetism, meaning that they only express their magnetic property when they are in a magnetic field. The inert polymeric shell around the magnetic core prevents any direct contact or undesirable interactions between the solutes and the metal core. The polymeric shell also provides support for modifying the surface with functional groups. Natural and synthetic polymers can be used to coat magnetic particles.

Poly(methyl methacrylate) (PMMA) is the most commonly used polymer matrix for magnetic particles (Horák et al., 2007). Certain applications require that the magnetic particles have particular properties, such as no sedimentation, uniform and narrow size distribution, high and uniform magnetic content, biocompatibility, and high concentration of functional groups on the polymeric surface (Liu et al., 2004). Large particles offer relatively small amounts of surface area on which the functional groups can attach. For this reason, micrometer size and smaller magnetic particles are required, as they offer high specific surface areas across which to carry out any surface modification (Horák et al., 2007). However, if the particles are too small, they may not carry enough magnetite in their magnetic core, and may therefore fail to respond to magnetic operation. Moreover, depending on the particular application's requirements, proper surface functionality should be supplied—and the density of functional groups on the surface should be high enough—to be able to provide the required affinity (Khng et al., 1998).

5.2.3 Exploring magnetic particles' potential for purification of polyphenols

Several of the existing extraction methods have been successful at extracting polyphenolic compounds from organic residues such as grape pomace, and have the ability to do so cost-effectively, easily, and safely. However, existing purification methods have not proved to be sufficiently effective to allow a facility processing agricultural fruit residues to produce safe, high-purity polyphenols that can be used as a high-value food additive. The objective of this project, therefore, is to test the effectiveness of magnetic particles in the purification of polyphenolic extracts obtained from grape pomace.

5.3 Methods

5.3.1 Synthesis of magnetic particles

The synthesis of magnetic particles involved three steps: (1) the preparation of the magnetic core, (2) the synthesis of the polymer-coated magnetic particles, and (3) the modification of the particle surface with hydrogen bonding affinity ligands.

5.3.1.1 Preparation of the superparamagnetic core

Oleic acid-covered Fe_3O_4 magnetic fluid was used to make the core of the magnetic particles. There are several methods for modifying particle size, distribution, and magnetic properties of superparamagnetic particles, which vary in the reaction and process parameters used. The magnetic core was prepared by a conventional and convenient co-precipitation method (with some modifications), which provides the narrowest particle size distribution (Horák et al., 2007). Iron oxides were synthesized from aqueous salt solutions of $\text{Fe}^{2+}/\text{Fe}^{3+}$ with fast addition of a base (ammonia solution), under nitrogen gas protection, at 80°C . The precipitated iron particles were coated and stabilized with oleic acid. This coverage made the surface of the particles hydrophobic, which facilitated the remaining preparation steps.

5.3.1.2 Synthesis of polymer-coated magnetic particles

Magnetic polymer particles were prepared by emulsion polymerization of methyl methacrylate (MMA) with a cross-linker named divinylbenzene (DVB) and hydrophobic initiator benzoyl peroxide (BPO), in the presence of the magnetic core. In this step, the magnetic core—which was dissolved in an organic solvent—was dispersed in a monomer phase. The aqueous phase was prepared by dissolving polyvinyl alcohol (PVA1788)—as a stabilizer—with sodium chloride (NaCl) and methylene blue in deionized water. The mixing of the two phases is followed by the polymerization reaction, through which the iron oxide particles were encapsulated in the polymer coating. The polymer magnetic particles were then further processed to modify their surface with functional groups.

5.3.1.3 Surface modification with polyethylene glycol

Surface modification of magnetic particles is essential for stability, biocompatibility of the particles, to protect the particles from undesirable interactions, and to assist in the attachment of functional groups for certain types of applications (Horák et al., 2007). In this project, the surface modification was performed using polyethylene glycol 600 (PEG-600). Polyethylene glycol 600 is a non-toxic compound that is widely used in pharmacy, cosmetics and the feed industry. Polyethylene glycol 600 can form a complex with polyphenols through hydrogen bonding (Kim

et al., 2003). For this reason, PEG-600 was used as the surface functional group to enhance the separation process.

Polyethylene glycol 600 was grafted to the surface of the magnetic particles through a transesterification reaction to obtain hydrophilic hydroxyl-group-functionalized magnetic particles. The reaction (shown in Figure 5.1) was carried out at 100°C, in the presence of sodium methoxide-methanol as a catalyst.

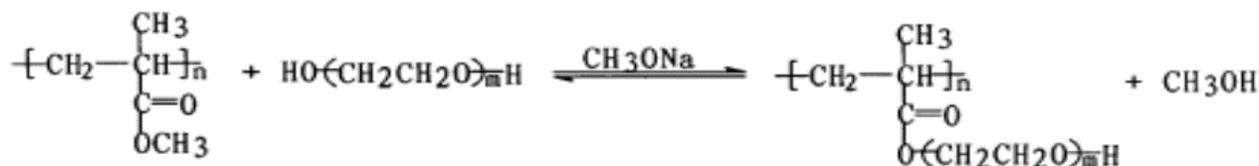


Figure 5.1: Transesterification reaction.

During this reaction, PEG-600 replaced the methoxide groups (-OCH₃) on the polymeric surface of the magnetic particles, completing the surface modification step. The synthesized particles were characterized in terms of their chemical properties. The surface modification of the polymer-coated magnetic particles was confirmed based on the Fourier Transform Infrared Spectroscopy (Shimadzu FT-IR) spectra of the particles before and after the transesterification reaction.

5.3.2 Preparation of the crude polyphenol extract

Grape seeds are the main components of grape pomace and they contain the highest amount of polyphenols compared to the other components present in the pomace. For this reason, this proof-of-concept study focused specifically on grape seeds as the winery waste from which polyphenols were extracted.

Polyphenolic compounds were extracted from grape seeds with sonication-assisted solvent extraction by using an aqueous ethanol solution. Grape seeds were lyophilized for 24 hours and then ground to powder (finer than 40 mesh). After grinding, the samples were vacuum-packed and stored at -20°C. The ground samples were mixed in an ethanol and water solution (30:70 volume:volume), such that the resultant solid to liquid (sample:solvent) ratio was 1:20 (weight:volume). Extraction was performed in a sonication bath for 2 hours, in the dark and at 25°C. The mixture was centrifuged at 10,000 rpm for 10 minutes, and then the supernatant was concentrated with vacuum evaporation at 35°C to remove the alcoholic (ethanol) fraction. The resulting crude polyphenol extract (CPE) was stored in a freezer at -20°C in preparation for the purification experiments.

5.3.3 Purification of polyphenols with magnetic particles grafted with polyethylene glycol

Before applying the proposed separation technology to a real system—the crude polyphenol extract obtained from grape seeds—the performance of magnetic particles was tested with model

polyphenolic compounds. Gallic acid was used as a model polyphenol, and the adsorption capacity of the magnetic particles was measured and compared to the adsorption capacity of commercially available Amberlite XAD-4 resins by performing a kinetic study. This study included measuring the optimum adsorption time (contact time) and the maximum adsorption capacities of both magnetic particles and XAD-4 resin.

Batch adsorption experiments were performed for both magnetic particles grafted with PEG-600 and XAD-4 resin in 250 ml glass-stoppered flasks, at 25°C. Due to stability and sensitivity issues, the flasks were equipped with a stopper and covered with aluminum foil to protect the gallic acid from light. The pH of 25 ml of the CPE solution was adjusted to 3.0. Then, predetermined amounts of dry adsorbents were introduced into the flask. Each adsorption system was shaken in an incubator at 200 rpm for 12 hours in the dark. At certain time intervals (for magnetic particles at 0, 5, 20, 40, 60, 90, 120, 150, 720 minutes; for XAD-4 resins at 0, 5, 15, 30, 60, 90, 120, 150, 360, 420, 540, 720 minutes) aliquots were taken from the adsorption system. After the adsorption process was complete, the magnetic particles were removed using a magnet, and the resin particles were separated by filtration. Subsequently, 20 ml of ethanol were added to the adsorbents to release the adsorbed polyphenols by shaking them at 200 rpm at 25°C for 1 hour. A calibration curve of aqueous gallic acid solution was prepared using different known concentrations of gallic acid in a Shimadzu UV-2550PC UV/Vis Spectrophotometer at 280 nm.

There are several spectrophotometric methods for quantifying phenolic compounds obtained from plants. These methods differ in the principles they are based on, and are used to determine the presence of different structural groups in the phenolic compounds being analyzed. Determination of total polyphenol content is a useful approach to characterize the sample of interest. Total polyphenol content also provides valuable information about the relative composition of a given sample. The simplest method to obtain a rough estimate of total phenolics in a sample is to measure the absorption at 280 nm wavelength of a properly diluted sample. The most commonly used method for determining total polyphenol content, however, is the Folin–Ciocalteu assay (Tsao and Yang, 2003). The Folin–Ciocalteu reagent is a mixture of phosphomolybdate ($\text{H}_3\text{PMO}_{12}\text{O}_{40}$) and phosphotungstate ($\text{H}_3\text{PW}_{12}\text{O}_{40}$) acids. These acids react with and oxidize the phenolic compounds when in an alkaline medium. The oxidation reaction results in the formation of a mix of blue oxides. Since polyphenols include a wide spectrum of compounds, one of them—usually gallic acid—is used as a standard unit for determining the total polyphenol content. When using spectrophotometric methods, therefore, total phenolics are expressed as gallic acid equivalents (GAE) (Lapornik et al., 2005).

Various polyphenolic compounds are contained in the mixture after the extraction and purification steps. It is not practical nor easy to detect each phenolic compound individually. Consequently, the polyphenols were measured in terms of total polyphenolic compounds. The concentration of total phenolics before (C_0) and after (C_e) the purification step were determined by the Folin–Ciocalteu colorimetric method, as previously described by Singleton and Rossi (1965). These concentration measurements and calculations were performed in duplicate by using the gallic acid calibration curve in UV-Spectroscopy. Total phenolics were expressed as gallic acid equivalents (GAE) in mg mL^{-1} of bulk solution or mg g^{-1} dry adsorbent. The maximum adsorption capacity of each adsorbent was determined using:

$$q_e = \frac{(C_0 - C_e) \times V}{W} \quad (5.1)$$

where q_e is the equilibrium adsorption capacity (mg g^{-1}), C_e is equilibrium concentration of solute in the bulk solution (mg L^{-1}), C_0 is the initial concentration of solute in the bulk solution (mg L^{-1}), V is the volume of the bulk solution, and W is the amount of dry adsorbent (g).

5.3.4 Determination of antioxidant activity

Polyphenols' antioxidant activity is due to their ability to scavenge free radicals, donate hydrogen atoms, and chelate metal cations. The antioxidant activity of polyphenols depends on their structure, especially the position and number of hydroxyl groups and the nature of other substitutions on the aromatic structure (Balasundram et al., 2006). Separation mechanisms may affect the antioxidant activity of polyphenols. In order to evaluate whether the magnetic particle separation method had such an effect, the antioxidant activity of (a) the crude polyphenol extract obtained from grape seeds, (b) the polyphenols separated using XAD-4 resin, and (c) the polyphenols purified by magnetic particles grafted with PEG-600 were tested using a 2,2-diphenyl-1-picrylhydrazyl (DPPH) free radical assay. The antioxidant activity tests were performed according to the procedure described previously by Brand-Williams et al. (1995). The results were expressed as Trolox equivalent antioxidant capacity, where the antioxidant capacity of polyphenols is compared to that of the standard antioxidant Trolox, a hydrosoluble form of Vitamin E.

5.4 Results and discussion

5.4.1 Characterization of the magnetic particles

The surface modification of the magnetic particles was verified by the FT-IR spectra of the magnetic particles before and after the transesterification reaction.

A characteristic strong peak appeared in the $1715 \pm 100 \text{ cm}^{-1}$ range, which indicated the presence of C=O (carbonyl group) stretching for both PEG-modified and unmodified magnetic particles (Figure 5.2). The characteristic bands of methyl ($-\text{CH}_3$) and methylene ($-\text{CH}_2$) appeared in the $2800\text{-}3000 \text{ cm}^{-1}$ range. Before the surface modification, there was no significant band characteristic to hydroxyl groups. However, after the surface modification with PEG-600, a characteristic broad peak in the $3200\text{-}3600 \text{ cm}^{-1}$ range appeared due to the hydroxyl groups on the surface of the magnetic particles (Figure 5.3). After the surface modification, the relative intensity ratio of peaks at around $2800\text{-}3000 \text{ cm}^{-1}$ to peaks at around $1715 \pm 100 \text{ cm}^{-1}$ ($I_{2800\text{-}3000}/I_{1715 \pm 100}$) was used to quantify the surface modification, and this ratio increased due to the amount of PEG-600 grafted on the surface of the magnetic particles. These findings confirmed the surface modification of magnetic particles during the transesterification reaction.

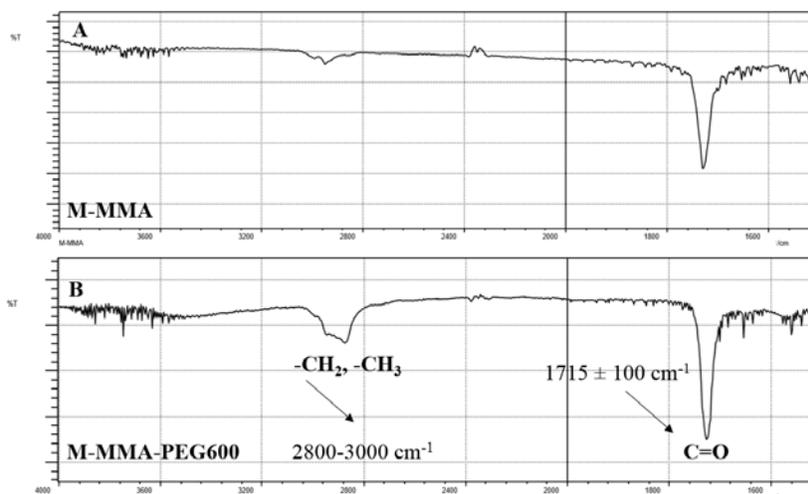


Figure 5.2: Comparison of FT-IR spectra in the 4000-1500 cm^{-1} region of magnetic particles grafted with PEG-600 before (A) and after (B) the transesterification reaction.

5.4.2 Adsorption and desorption performance

In this study PEG-600, which is well known as a phenolic compound binder, was used as the proton acceptor to combine the polyphenols through hydrogen bonding (Kim et al., 2003).

The adsorption selectivity of the magnetic particles synthesized in this study was remarkable. The polyphenol adsorption capacity of the magnetic particles was found to be 5-fold higher than that of the polymeric XAD-4 resins (Figure 5.3). Almost 40 mg of polyphenols were obtained per gram of dry grape seeds when using the magnetic particles. These findings can be attributed to the hydrogen bonding interactions involved in the separation process. Since the hydrogen bonding is short-range, and is not only fairly strong but is also a moderately directional and specific type of interaction, the magnetic particles—with their grafted, hydrogen-bonding affinity ligands—could separate polyphenols in high concentrations and purity. Furthermore, the results indicated that it took less time for the magnetic particles to reach adsorption equilibrium than it took the XAD-4 resin with high adsorption capacity (Figure 5.3). The purity of polyphenols—determined by gallic acid equivalent from UV-Visible absorption measurements—was also much higher when separated with magnetic particles than when commercially available resins were used.

Once the adsorbent captures the polyphenols in the extract, these must be released so that the value-added food additive can be developed. The magnetic particles' and the XAD-4 resins' ability to release the adsorbed polyphenols was evaluated by performing desorption kinetics. The magnetic particles' desorption was much faster than the XAD-4 resins'. For magnetic particles, an asymptotic curve was reached after 20 minutes of contact time, whereas it took 90 minutes for the XAD-4 resins to reach their asymptote (Figure 5.4). This means that within 20 minutes the magnetic particles were releasing the adsorbed polyphenols at their highest rate, a timeframe that was 4.5 times quicker than the XAD-4 resins'. Moreover, it is also important to mention that magnetic particles reached a 95% desorption rate in 10 minutes, whereas it took the

polymeric XAD-4 resins 120 minutes—12 times as long—to reach to the same desorption rate (Figure 5.4).

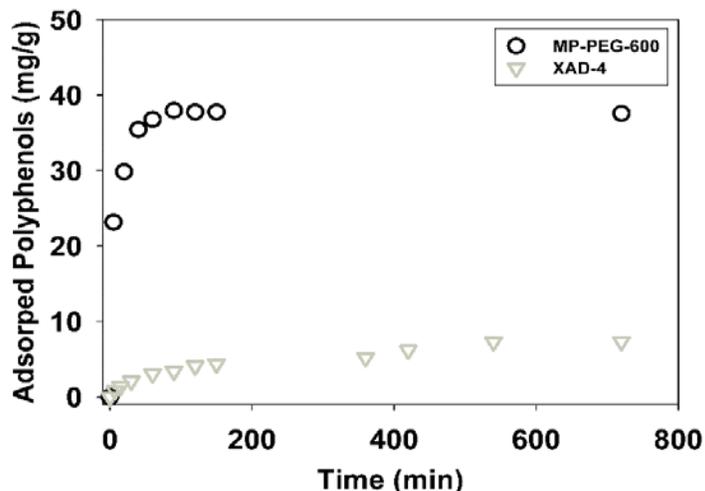


Figure 5.3: Adsorption capacities of magnetic particles grafted with PEG-600 and XAD-4 resin at 25°C.

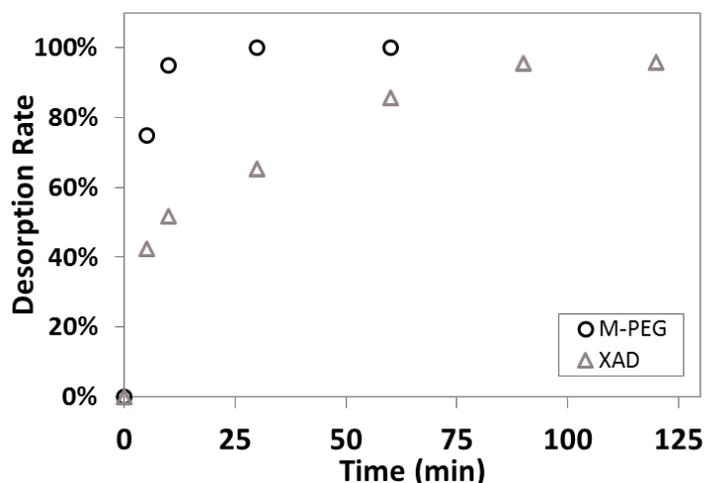


Figure 5.4: Desorption of magnetic particles grafted with PEG-600 and XAD-4 resin with ethanol at 25°C.

5.4.3 Antioxidant activity

Although high recovery amounts and rates of polyphenols are important factors for selecting the separation process, the resultant product must exhibit high antioxidant activity for the separation process to be effective at producing a value-added food additive. Therefore, the antioxidant activity of the resulting product is as important as the other evaluated factors.

Polyphenols separated with magnetic particles had 1.3- and 1.7-fold higher antioxidant activity compared to the polyphenols separated with polymeric XAD-4 resins and the CPE, respectively (Figure 5.5). The difference between the antioxidant activities of polyphenols obtained through different processes can be related to those different separation mechanisms, the resulting purity

of the bioactive compounds, as well as the type of antioxidant assay used to determine the antioxidant activity. Since the antioxidant potential of polyphenols depends on the number and position of hydroxyl groups they have, the higher antioxidant activity of polyphenols separated with magnetic particles could be attributed to a greater number of hydrogen bonding interactions. It is also possible that separation by magnetic particles through hydrogen bonding attracted polyphenols with more hydroxyl groups, which would result in higher antioxidant activity of polyphenols separated with this method.

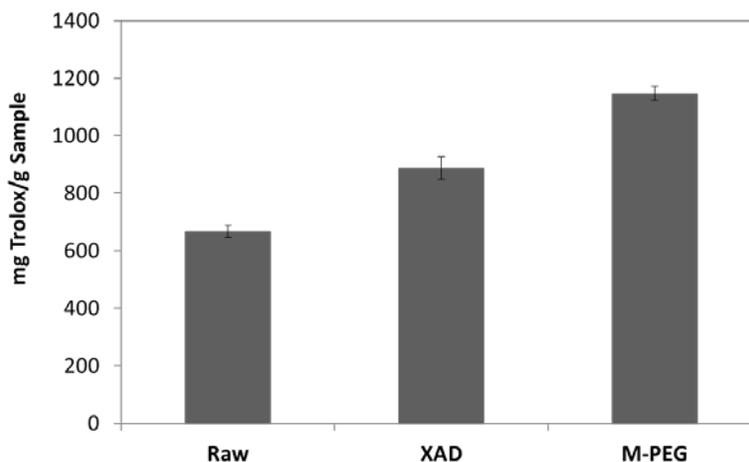


Figure 5.5: Antioxidant activity of crude polyphenol extract (Raw), polyphenols purified with XAD-4 resin (XAD) and polyphenols separated with magnetic particles grafted with PEG-600 (M-PEG).

5.5 Conclusions

This project studied the cost-effectiveness of an environmentally benign, innovative approach for the recovery of polyphenols from the byproducts of wine and grape juice industries. The method studied relies on the use of magnetic particles grafted with affinity ligands. This project found that, of the adsorbents that were evaluated—magnetic particles grafted with PEG-600 and commercially available XAD-4 polymeric resins—separation of polyphenols *via* magnetic particles provided not only a 5-fold higher adsorption capacity when compared to XAD-4 resins, but they also achieved faster desorption rates: desorption kinetics showed that it takes 12-fold less time for magnetic particles grafted with PEG-600 to release 95% of adsorbed polyphenols. An evaluation of the resultant polyphenols showed that the antioxidant activity of polyphenols separated *via* magnetic particles was 1.3-fold higher than those separated *via* XAD-4 resins, and also 1.7-fold higher than the CPE. This difference is likely due to the hydrogen bonding interactions possible thanks to the PEG-600 surface treatment.

These experimental results appear encouraging, and could be used as a starting point to scale up this separation process to a level where it is used to develop high-value-added food additives from byproducts of the wine and grape juice industries in Washington State and beyond.

Further studies are needed to evaluate the reusability of adsorbents, to use adsorption isotherms to better understand the interaction between the adsorbents and polyphenols, and also to characterize the magnetic particles in terms of their interaction with individual phenolics (e.g., by

using different types of modeling tools). The data obtained from such studies could then be used to help optimize these purification and separation processes, ultimately helping to scale them up operationally.

This proof-of-concept project's results strongly suggest that nutraceuticals with valuable health-related benefits can be produced from agricultural residues such as grape pomace. These results and further research will greatly enhance the sustainable utilization of grape pomace, thereby helping wineries reduce both their environmental footprint and the production cost of their main products, by complementing them with the production of high-value food additives. Processing waste products into high value nutraceuticals will also enable farmers to benefit economically. Furthermore, this study will help to support the technological application of bioactive compounds in diverse industries, increasing the overall value of Washington State's agriculture and related industries.

5.6 References

- Agalias, A., Magiatis, P., Skaltsounis, A.-L., Mikros, E., Tsaibopoulos, A., Gikas, E., Spanos, I., Manios, T. 2007. A New Process for the Management of Olive Oil Mill Waste Water and Recovery of Natural Antioxidants. *Journal of Agricultural and Food Chemistry* 55(7), 2671-2676.
- Altioek, E., Baycin, D., Bayraktar, O., Ulku, S. 2008. Isolation of polyphenols from the extracts of olive leaves (*Olea europaea* L.) by adsorption on silk fibroin. *Separation and Purification Technology* 62(2), 342-348.
- Amr, A., Al-Tamimi, E. 2007. Stability of the crude extracts of *Ranunculus asiaticus* anthocyanins and their use as food colourants. *International Journal of Food Science and Technology* 42(8), 985-991.
- Awika, J.M., Rooney, L.W., Waniska, R.D. 2005. Anthocyanins from black sorghum and their antioxidant properties. *Food Chemistry* 90(1-2), 293-301.
- Balasundram, N., Sundram, K., Samman, S. 2006. Phenolic compounds in plants and agricultural by-products: Antioxidant activity, occurrence, and potential uses. *Food Chemistry* 99(1), 191-203.
- Baydar, N.G., Ozkan, G., Sagdic, O. 2004. Total phenolic contents and antibacterial activities of grape (*Vitis vinifera* L.) extracts. *Food Control* 15(5), 335-339.
- Bílková, Z., Slovákova, M., Horák, D., Lenfeld, J., Churáček, J. 2002. Enzymes immobilized on magnetic carriers: efficient and selective system for protein modification. *Journal of Chromatography B* 770(1-2), 177-181.
- Bleve, M., Ciurlia, L., Erroi, E., Lionetto, G., Longo, L., Rescio, L., Schettino, T., Vasapollo, G. 2008. An innovative method for the purification of anthocyanins from grape skin extracts by using liquid and sub-critical carbon dioxide. *Separation and Purification Technology* 64(2), 192-197.
- Brand-Williams, W., Cuvelier, M., Berset, C. 1995. Use of a free radical method to evaluate antioxidant activity. *LWT-Food Science and Technology* 28(1), 25-30.
- Bucić-Kojić, A., Planinić, M., Tomas, S., Bilić, M., Velić, D. 2007. Study of solid-liquid extraction kinetics of total polyphenols from grape seeds. *Journal of Food Engineering* 81(1), 236-242.

- Caridi, D., Trenerry, V.C., Rochfort, S., Duong, S., Laughler, D., Jones, R. 2007. Profiling and quantifying quercetin glucosides in onion (*Allium cepa* L.) varieties using capillary zone electrophoresis and high performance liquid chromatography. *Food Chemistry* 105(2), 691-699.
- Castañeda-Ovando, A., Pacheco-Hernández, M.d.L., Páez-Hernández, M.E., Rodríguez, J.A., Galán-Vidal, C.A. 2009. Chemical studies of anthocyanins: A review. *Food Chemistry* 113(4), 859-871.
- Corrales, M., García, A.F., Butz, P., Tauscher, B. 2009. Extraction of anthocyanins from grape skins assisted by high hydrostatic pressure. *Journal of Food Engineering* 90(4), 415-421.
- D'Archivio, M., Filesi, C., Di Benedetto, R., Gargiulo, R., Giovannini, C., Masella, R. 2007. Polyphenols, dietary sources and bioavailability. *Annali-Istituto Superiore di Sanita* 43(4), 348-61.
- de Campos, L.M., Leimann, F.V., Pedrosa, R.C., Ferreira, S.R. 2008. Free radical scavenging of grape pomace extracts from Cabernet sauvignon (*Vitis vinifera*). *Bioresource Technology* 99(17), 8413-8420.
- Fontana, A.R., Antonioli, A., Bottini, R. 2013. Grape Pomace as a Sustainable Source of Bioactive Compounds: Extraction, Characterization, and Biotechnological Applications of Phenolics. *Journal of Agricultural and Food Chemistry* 61(38), 8987-9003.
- Ford, D.L. 1992. Removing and recovering plant polyphenols, US Patents 5141611.
- Geng, X., Ren, P., Pi, G., Shi, R., Yuan, Z., Wang, C. 2009. High selective purification of flavonoids from natural plants based on polymeric adsorbent with hydrogen-bonding interaction. *Journal of Chromatography A* 1216(47), 8331-8338.
- Hayouni, E.A., Abedrabba, M., Bouix, M., Hamdi, M. 2007. The effects of solvents and extraction method on the phenolic contents and biological activities in vitro of Tunisian *Quercus coccifera* L. and *Juniperus phoenicea* L. fruit extracts. *Food Chemistry* 105(3), 1126-1134.
- Heim, K.E., Tagliaferro, A.R., Bobilya, D.J. 2002. Flavonoid antioxidants: Chemistry, metabolism and structure-activity relationships. *Journal of Nutritional Biochemistry* 13(10), 572-584.
- Horák, D., Babič, M., Macková, H., Beneš, M.J. 2007. Preparation and properties of magnetic nano- and microsized particles for biological and environmental separations. *Journal of Separation Science* 30(11), 1751-1772.
- FAO. 2013. FAOSTAT-FAO Statistical Database. Food and Agriculture Organization of the United Nations. Available online at <http://faostat.fao.org/>.
- Huang, J., Huang, K., Liu, S., Luo, Q., Xu, M. 2007. Adsorption properties of tea polyphenols onto three polymeric adsorbents with amide group. *Journal of Colloid and Interface Science* 315(2), 407-414.
- Huang, W., Xue, A., Niu, H., Jia, Z., Wang, J. 2009. Optimised ultrasonic-assisted extraction of flavonoids from *Folium eucommiae* and evaluation of antioxidant activity in multi-test systems in vitro. *Food Chemistry* 114(3), 1147-1154.
- Jitaru, D., Ungureanu, D., Ciocoiu, M., Badescu, M., Popa, V., Anghel, N. 2005. Natural polyphenols as endocrino-metabolics modulators in the experimental diabet. *Revista Medico-Chirurgicala a "Societatii de Medici si Naturalisti" Iasi* 109, 33-37.
- Khng, H.P., Cunliffe, D., Davies, S., Turner, N.A., Vulfson, E.N. 1998. The synthesis of sub-micron magnetic particles and their use for preparative purification of proteins. *Biotechnology and Bioengineering* 60(4), 419-424.

- Kim, Y.-J., Uyama, H., Kobayashi, S. 2003. Regioselective Synthesis of Poly(phenylene) as a Complex with Poly(ethylene glycol) by Template Polymerization of Phenol in Water. *Macromolecules* 36(14), 5058-5060.
- Kuhnau, J. 1976. The flavonoids. A class of semi-essential food components: their role in human nutrition. *World Review of Nutrition and Dietetics* 24, 117-91.
- Lapornik, B., Prošek, M., Golc Wondra, A. 2005. Comparison of extracts prepared from plant by-products using different solvents and extraction time. *Journal of Food Engineering* 71(2), 214-222.
- Leon-Gonzalez, M., Perez-Arribas, L. 2000. Chemically modified polymeric sorbents for sample preconcentration. *Journal of Chromatography A* 902(1), 3-16.
- Li, H., Chen, B., Yao, S. 2005. Application of ultrasonic technique for extracting chlorogenic acid from *Eucommia ulmoides* Oliv. (*E. ulmoides*). *Ultrason Sonochemistry* 12(4), 295-300.
- Liu, Q., Cai, W.S., Shao, X.G. 2008. Determination of seven polyphenols in water by high performance liquid chromatography combined with preconcentration. *Talanta* 77(2), 679-683.
- Liu, X., Guan, Y., Ma, Z., Liu, H. 2004. Surface Modification and Characterization of Magnetic Polymer Nanospheres Prepared by Miniemulsion Polymerization. *Langmuir* 20(23), 10278-10282.
- Lu, Y., Yeap Foo, L. 1999. The polyphenol constituents of grape pomace. *Food Chemistry* 65(1), 1-8.
- Lübbe, A.S., Bergemann, C., Huhnt, W., Fricke, T., Riess, H., Brock, J.W., Huhn, D. 1996. Preclinical experiences with magnetic drug targeting: tolerance and efficacy. *Cancer Research* 56(20), 4694-4701.
- Luthria, D.L., Pastor-Corrales, M.A. 2006. Phenolic acids content of fifteen dry edible bean (*Phaseolus vulgaris* L.) varieties. *Journal of Food Composition and Analysis* 19(2-3), 205-211.
- Maier, T., Göppert, A., Kammerer, D.R., Schieber, A., Carle, R. 2008. Optimization of a process for enzyme-assisted pigment extraction from grape (*Vitis vinifera* L.) pomace. *European Food Research and Technology* 227(1), 267-275.
- Nahar, L., Sarker, S.D. 2012. Supercritical fluid extraction in natural products analyses. *Methods in Molecular Biology* 864, 43-74.
- Palenzuela, B., Arce, L., MacHo, A., Muñoz, E., Ríos, A., Valcárcel, M. 2004. Bioguided extraction of polyphenols from grape marc by using an alternative supercritical-fluid extraction method based on a liquid solvent trap. *Analytical and Bioanalytical Chemistry* 378(8), 2021-2027.
- Palma, M., Piñeiro, Z., Barroso, C.G. 2001. Stability of phenolic compounds during extraction with superheated solvents. *Journal of Chromatography A* 921(2), 169-174.
- Pinelo, M., Rubilar, M., Sineiro, J., Núñez, M.J. 2004. Extraction of antioxidant phenolics from almond hulls (*Prunus amygdalus*) and pine sawdust (*Pinus pinaster*). *Food Chemistry* 85(2), 267-273.
- Rice-Evans, C.A., Miller, N.J., Paganga, G. 1996. Structure-antioxidant activity relationships of flavonoids and phenolic acids. *Free Radical Biology and Medicine* 20(7), 933-956.
- Robards, K., Prenzler, P.D., Tucker, G., Swatsitang, P., Glover, W. 1999. Phenolic compounds and their role in oxidative processes in fruits. *Food Chemistry* 66(4), 401-436.

- Rubilar, M., Pinelo, M., Franco, D., Sineiro, J., Núñez, M.J. 2003. Agroindustrial residues as a source of antioxidants. *Afinidad: Revista de Química Teórica y Aplicada* 60(504), 153-160.
- Šafařík, I., Šafaříková, M. 1999. Use of magnetic techniques for the isolation of cells. *Journal of Chromatography B: Biomedical Sciences and Applications* 722(1–2), 33-53.
- Saito, M., Hosoyama, H., Ariga, T., Kataoka, S., Yamaji, N. 1998. Antiulcer Activity of Grape Seed Extract and Procyanidins. *Journal of Agricultural and Food Chemistry* 46(4), 1460-1464.
- Scordino, M., Di Mauro, A., Passerini, A., Maccarone, E. 2004. Adsorption of flavonoids on resins: cyanidin 3-glucoside. *Journal of Agricultural and Food Chemistry* 52(7), 1965-1972.
- Scordino, M., Di Mauro, A., Passerini, A., Maccarone, E. 2003. Adsorption of flavonoids on resins: hesperidin. *Journal of Agricultural and Food Chemistry* 51(24), 6998-7004.
- Scordino, M., Di Mauro, A., Passerini, A., Maccarone, E. 2005. Selective recovery of anthocyanins and hydroxycinnamates from a byproduct of citrus processing. *Journal of Agricultural and Food Chemistry* 53(3), 651-658.
- Shi, J., Yu, J., Pohorly, J.E., Kakuda, Y. 2003. Polyphenolics in grape seeds-biochemistry and functionality. *Journal of Medicinal Food* 6(4), 291-299.
- Silva, M.L., Macedo, A.C., Malcata, F.X. 2000. Review: Steam distilled spirits from fermented grape pomace *Food Science and Technology International* 6(4), 285-300.
- Singleton, V.L. 1981. Naturally occurring food toxicants: phenolic substances of plant origin common in foods. *Advances in Food Research* 27, 149-242.
- Singleton, V.L., Rossi, J.A. 1965. Colorimetry of total phenolics with phosphomolybdic-phosphotungstic acid reagents. *American Journal of Enology and Viticulture* 16(3), 144-158.
- Tomás-Barberan, F.A., Ferreres, F., Gil, M.I. 2000. Antioxidant phenolic metabolites from fruit and vegetables and changes during postharvest storage and processing. In: Attaur, R. (Ed.), *Studies in Natural Products Chemistry*. Elsevier, Volume 23, pp. 739-795.
- Tsao, R., Yang, R. 2003. Optimization of a new mobile phase to know the complex and real polyphenolic composition: towards a total phenolic index using high-performance liquid chromatography. *Journal of Chromatography A* 1018(1), 29-40.
- Wang, J., Sun, B., Cao, Y., Tian, Y., Li, X. 2008. Optimisation of ultrasound-assisted extraction of phenolic compounds from wheat bran. *Food Chemistry* 106(2), 804-810.
- Wine, 2014. Washington State Wine Facts. <http://www.washingtonwine.org/wine-101/state-facts/>.
- Yilmaz, Y., Toledo, R.T. 2003. Major Flavonoids in Grape Seeds and Skins: Antioxidant Capacity of Catechin, Epicatechin, and Gallic Acid. *Journal of Agricultural and Food Chemistry* 52(2), 255-260.
- Yu, H., Raymonda, J.W., McMahon, T.M., Campagnari, A.A. 2000. Detection of biological threat agents by immunomagnetic microsphere-based solid phase fluorogenic- and electro-chemiluminescence. *Biosensors and Bioelectronics* 14(10–11), 829-840.

6. Using Biochar to Remove Hydrogen Sulfide from Biogas

Raul Pelaez-Samaniego, Quanbao Zhao, Matt Smith, and Craig Frear

6.1 Abstract

While various physico-chemical media are currently used to remove hydrogen sulfide (H_2S) contaminants from raw biogas, the cost of purchasing the required media, such as activated carbon, continues to be a concern for dairy farmers. Anaerobically digested fibrous solids (AD fiber) produced on-site are seen as a possible raw media source, which—given thermal pretreatment—could be used as a scrubbing medium. This proof-of-concept project's objectives were to test the capacity of AD fiber for scrubbing H_2S , and to evaluate the alternative thermal treatments' effects on the fiber's H_2S scrubbing capacity.

Anaerobic digestion fiber was subjected to different thermal conditions (pyrolysis at temperatures ranging from 300 to 600°C for 30 and 60 minutes) to produce a char-like material. These chars were used for long (up to 2 months for some materials) H_2S scrubbing tests using synthetic biogas. Preliminary results suggest that biochar produced from AD fiber can be effective for H_2S removal from biogas, depending on the conditions of the pyrolysis process. Results showed that the more severe the pyrolysis process, the higher the H_2S removal, suggesting that higher temperatures, which leads to greater porosity, could enhance H_2S cleaning. Hydrogen sulfide scrubbing tests using AD fiber subjected to hot water extraction (HWE) at 180 and 200°C for 60 minutes, an alternative thermal pretreatment process, showed no removal of H_2S from biogas, indicating that the effect of water during the thermal treatment is undesirable, possibly due to removal of ashes. These results therefore suggest that the environment used for the thermal treatment plays an important role in the resultant char's performance in H_2S removal. Thermal processes that tend to increase porosity and that do not alter or remove ashes or compounds that could act as catalysts appear promising.

An additional test included a sodium carbonate impregnation of the char produced *via* pyrolysis, showing an important increase in biochar's capacity for H_2S sorption. Combined with the thermal treatment evaluation, these results suggest that both physical and chemical sorption happen during H_2S scrubbing using thermally treated AD fiber. Incorporation of a sodium carbonate impregnation step can be a valid strategy to enhance the performance of biochar produced from AD fiber to a level commensurate with commercial activated carbon. This proof-of-concept project's results are leveraging further work focused on understanding the physico-chemical phenomena occurring upon both thermal and impregnation treatments, as well as on determining the fate of the scrubbed sulfur and its resultant form. Once these additional studies are complete, results will be submitted for publication in a peer-reviewed journal, and will be presented to industry partners for engineering and economic review, informing potential commercialization and scale up.

6.2 Background

Hydrogen sulfide within raw biogas is corrosive to internal combustion engines (Fulton, 1991), and can be an environmental and human health hazard due to its odor and toxicity (Speece, 1996). In addition, in the exhaust of combined heat and power (CHP) systems, H₂S is almost completely converted to sulfur oxides (SO_x), a precursor to fine particulate matter, which regulatory agencies monitor to ensure air quality standards are respected (Ecology, 2012). Importantly, when raw biogas is converted to CNG for vehicle use, complete removal of H₂S is needed. Accordingly, manure digester projects often actively scrub H₂S out of the raw biogas stream as a strategy to protect downstream human health and engines.

The four most common methods currently used for removing H₂S are (a) addition of various types of iron salts prior to entry into the digester, (b) oxygen injection into the digester, (c) physico-chemical adsorption after digestion, and (d) biological treatment post-digestion.

Adding iron salts to the influent of the digester is relatively inexpensive and effective. The reaction between iron salts and sulfur forms iron sulfide salt particles, reducing the production of H₂S (Wellinger and Lindberg, 2005). Anaerobic digestion project developers have also found that co-digesting dairy manure with blood or dissolved air flotation (DAF) waste can also supply iron and drastically reduce H₂S production during AD (Kennedy et al., 2015). This approach can significantly reduce H₂S concentrations, but it is often incapable of reducing the concentrations enough for some value-added uses of the biogas.

The second technique, consisting of injecting oxygen into the digester, promotes the formation of sulfur-consuming bacteria (mainly *Thiobacillus*) that convert H₂S to elemental sulfur in the process of cellular respiration (Díaz et al., 2011; Ryckebosch et al., 2011). Addition of 2–6% oxygen to the headspace of the digester is typical (Ryckebosch et al., 2011). Support media for the bacteria is often also provided at or near the surface, supplying additional surface area, as well as a wetting action, for bacteria to propagate and thrive. Again, while inexpensive and a common practice, this approach does not lower the concentration enough for some value-added uses or even for some engine specifications, often requiring additional post-digestion treatment.

A third group of techniques that are quite common are physico-chemical adsorption techniques, implemented after digestion. These techniques include treatment with iron oxide or materials dosed with iron oxides, also known as iron-sponge. An example of one commercial approach uses a composite of hydrated iron oxide on a carrier of wood shavings or chips (Anerousis and Whitman, 1984). When gas is passed over the media, H₂S reacts with the iron oxide to produce iron sulfides and a small amount of water as a byproduct. Concerns regarding removal of spent media with concrete-like properties have been reported for some systems, increasing operation and maintenance costs. Other chemical processes are also used, including activated carbon and water scrubbing (Ryckebosch et al., 2011). Although these systems can be more costly, they can potentially be more effective for achieving extremely low H₂S levels in biogas.

A biological filter is a fourth strategy for removing H₂S (Syed et al., 2006). The underlying process is similar to oxygen dosing, though it occurs after AD is complete. Air is added to the biogas, which is then passed through a filter bed at a temperature of approximately 35°C. Sulfur-

consuming bacteria on this filter bed convert H_2S into elemental sulfur (Persson et al., 2006). Advantages of biological filters include low power consumption, and low quantity of byproducts such as elemental sulfur (Jensen, 2011). On the other hand, performance is highly dependent on the activity of the bacteria, and more rigorous monitoring, operation, and maintenance is often required to supply the desired temperature and nutrient requirements for optimal growth of the biological organisms (Ryckebosch et al., 2011).

Despite the existence of commercial processes and systems for H_2S removal from biogas, further work involving the use of on-site materials could be beneficial for dairy farms that are looking to both (a) reduce or avoid the purchase costs of necessary media and inputs, and (b) find value-added uses of the fibers produced on-site from manure AD. However, lignocellulosic materials (e.g., AD fiber or wood) are very poor at removing H_2S from gases, unless specific treatments are conducted, such as adding hydrated iron oxide to wood chips in the iron-sponge process. Thus, physical, thermal, or chemical processes that modify specific properties of lignocellulosics are required to provide these materials with the capability to scrub H_2S from biogas. The researchers hypothesize that relatively simple thermochemical processes such as pyrolysis (also referred to as carbonization) could be an effective method for AD fiber modification to enhance H_2S retention. Based on this premise, this project aimed to investigate how the thermal modification to fibrous solids from an AD, achieved *via* pyrolysis, would affect the resultant char's H_2S scrubbing performance. The researchers explored the effects that the conditions of the thermal treatment (environment, temperature, and treatment time) had on the H_2S sorption capacity of biochar produced from AD fiber.

6.3 Methods

6.3.1 Char production and preparation

Dairy fiber from AD was obtained from DeRuyter Dairy in Outlook, WA. After reception, the AD fiber was dried at $90^\circ C$ for 48 hours in an oven. The dry fiber was subjected to thermochemical processing to evaluate the influence of thermal treatments on the capacity of AD fiber for H_2S scrubbing. The evaluated thermochemical pretreatments consisted of pyrolysis conducted at $300^\circ C$, $400^\circ C$, $500^\circ C$, and $600^\circ C$, conducted for either 30 or 60 minutes. The pyrolysis process was carried out in duplicate using a spoon reactor (Thermoscientific tube furnace reactor, with a capacity of approximately 3 g of biomass per batch). After pyrolysis, the materials were ground to guarantee approximately similar particle size, using a laboratory knife mill grinder, equipped with a 40-mesh sieve. All char studies were completed as to ascertain performance as compared to activated charcoal control. Control studies were completed using activated carbon (activated charcoal, Sigma-Aldrich, untreated, granular, 8-20 mesh) that was ground using the laboratory knife mill to obtain approximately similar particle size than the tested biochars produced from AD fiber.

After preliminary tests that showed that materials processed at high temperatures for longer periods—i.e., above $400^\circ C$ for 60 minutes—presented better H_2S scrubbing ability, part of the materials pyrolyzed at 500 and $600^\circ C$ (1 g in each case) were subjected to an impregnation process, using a 3% Na_2CO_3 solution (prepared using E-pure water). This salt is one of the options for impregnating activated carbon for environmental remediation (Xiao et al., 2008;

Sitthikhankaew et al., 2011). The solution was mixed with the char and subjected to an evaporation and drying process for a complete removal of moisture. The selection of this Na_2CO_3 concentration was based on values that are common for producing commercially impregnated activated carbons.

An alternative thermal treatment consisted of hot water extraction of AD fiber. The process was conducted at 180°C and 200°C for 60 minutes, using a 1 L Parr 4521 Bench top reactor controlled by a 4842 Parr controller and coupled with a water circulating cooling system. Approximately 40 g of AD fiber were used for the treatments. E-pure water (Type I, ASTM D1193-06) was added to the container (a 1 L glass liner, Parr) to keep a water:wood relationship of 5:1 (mass:mass). The HWE materials were ground and tested for H_2S scrubbing following the same approach used in the case of the biochars produced *via* pyrolysis using the spoon pyrolysis reactor.

6.3.2 Hydrogen sulfide breakthrough experiment

A breakthrough experiment was conceived whereby tested biochars were placed in a column, serving as scrubbing media, while H_2S flowed through the media as the gas to be scrubbed. Measurements were taken at regular intervals for the duration of the experiment (in this case, up to two months). The concentration measured after scrubbing was compared to that in the original gas (which was measured before it reached the column). In these experiments, the breakthrough point was defined as the time at which the concentration of H_2S after treatment in the testing column was 10% of the original concentration of the tested gas (i.e., the measurement after the column was approximately 200 ppm).

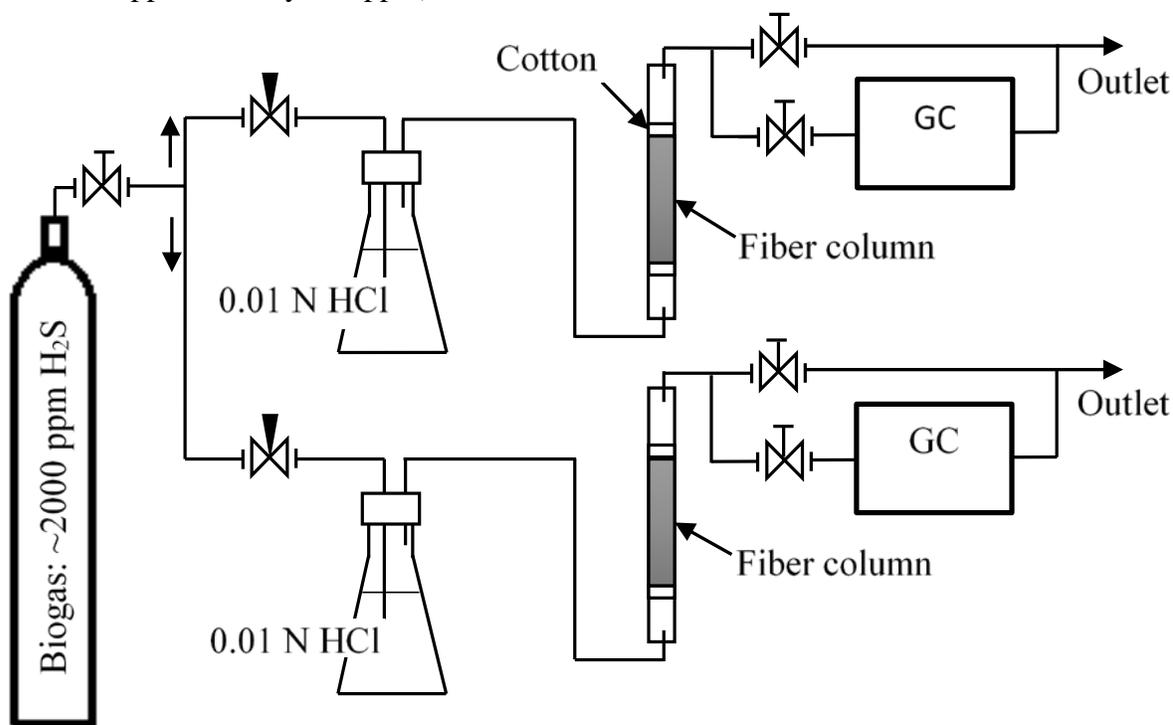


Figure 6.1: Schematic of the experimental setup designed to carry out the hydrogen sulfide breakthrough experiments.

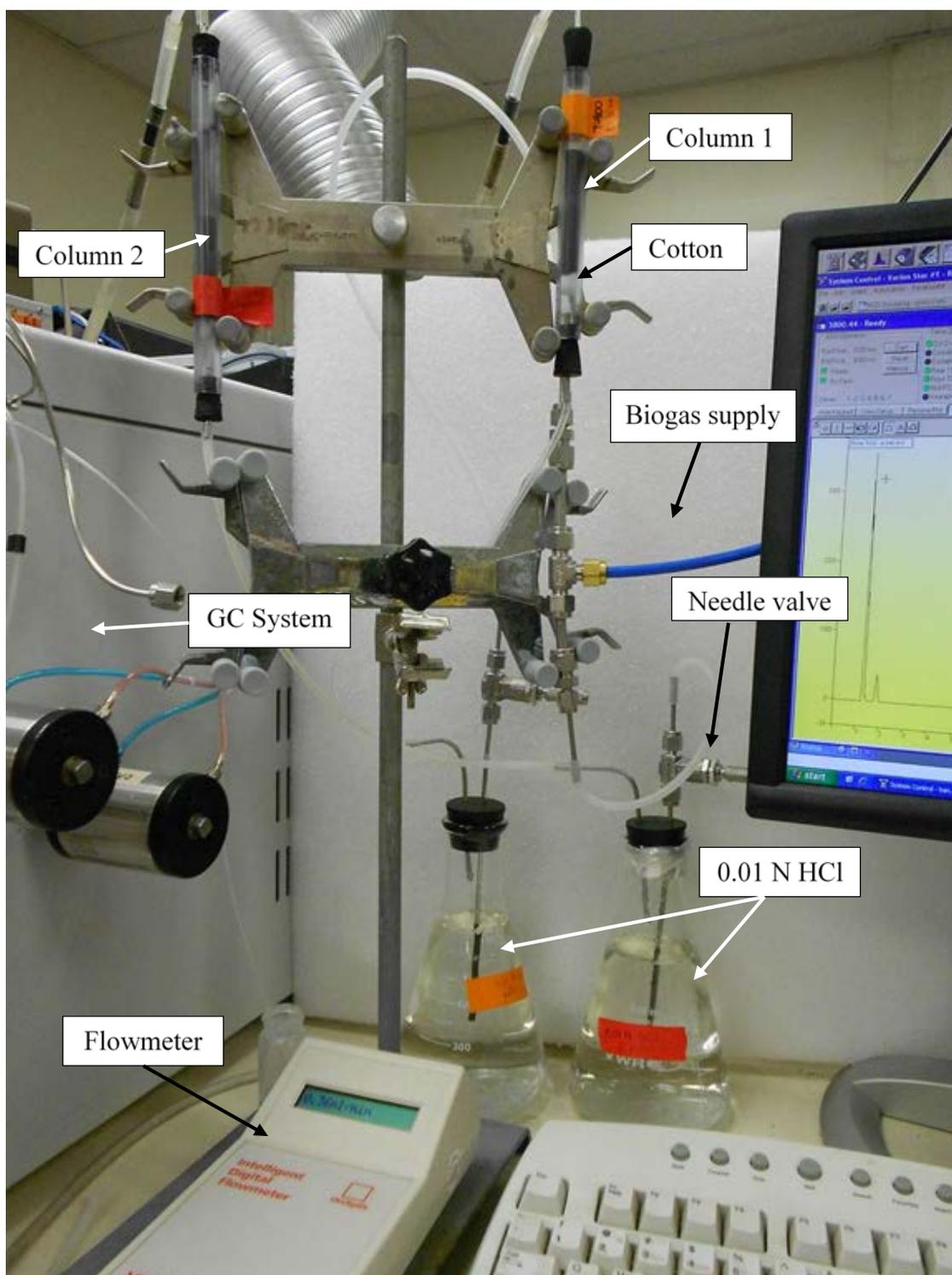


Figure 6.2: Actual experimental apparatus set up in the laboratory to carry out the hydrogen sulfide breakthrough experiment.

Figure 6.1 is a schematic representation of the study, and Figure 6.2 shows the laboratory apparatus used. The biogas used for the test was synthetic biogas (65.2% CH₄, 2045 ppm H₂S), supplied by Air Liquid Compressed Gases. The H₂S scrubbing column was manufactured from a polycarbonate tube (6.35 mm internal diameter, 250 mm long). One gram of each material was placed inside the tube in every run. The scrubbing materials were held inside the tube using small amounts of cotton close to the ends of the tubes. The biogas flow was adjusted to 5 mL min⁻¹ by means of needle valves, and verified using a VARIAN digital flowmeter. Further verification of the gas flow was conducted every two days. The system was checked for leaks at least twice a week, using a Restek leak detector. A 0.01 N HCl solution (500 mL, using tap water) was employed to moisturize the biogas before reaching the column. The pH of the solution was verified before and after each test, using a pH meter (Mettler Toledo SevenEasy). The H₂S content in the biogas after passing through the columns was monitored online using a gas chromatograph (GC; Varian GC3800, equipped with a CP-Silica PLOT 50 m x 0.53 mm x 4 μm column). Hydrogen sulfide scrubbing curves were prepared for each material.

6.4 Results and discussion

Preliminary results of the breakthrough experiment using AD fiber pyrolyzed under different conditions show that the conditions of the thermal pretreatments have a strong influence on the biochar's ability for H₂S scrubbing. Char produced by pyrolysis at higher temperatures (500°C and above) and for longer time (60 minutes) had breakthrough points that were notably longer than those of char produced at lower temperatures for shorter periods (30 minutes) (Figure 6.3). Results (not presented in Figure 6.3) showed that the H₂S scrubbing capacity of AD fiber charcoal produced at 300°C for 60 minutes is very poor, and therefore is not an attractive alternative for replacing activated charcoal. The scrubbing capacity of material pyrolyzed at 400°C for 60 minutes (T400-60) looked better, being able to retain approximately 50% of the H₂S for up to one month (720 hours), in the conditions of the experiment. However, its breakthrough point was below 24 hours, so it would still not be an attractive alternative for practical applications. In addition, the impact of Na₂CO₃ impregnation in this material (i.e., of the AD fiber pyrolyzed at 400°C) was negligible. The corresponding impregnated material showed only a slight improvement in its breakthrough point, suggesting that even with impregnation, this biochar is not suitable for at-scale H₂S scrubbing operations.

Charcoal produced from AD fiber at 500°C for 60 minutes had breakthrough points after 124 hours of operation. Charcoal produced at this and higher temperatures, therefore, are of interest for practical H₂S scrubbing applications. In addition, AD fiber pyrolyzed at 500°C for 60 minutes followed by impregnation showed a breakthrough point at approximately 200 hours of operation.

There is a notable positive impact of Na₂CO₃ impregnation on the performance of AD fiber pyrolyzed at 600°C for 60 minutes. It is impressive that the breakthrough point of this impregnated charcoal occurred at approximately 900 hours, which is the same as that of the control: activated carbon. This result shows that pyrolysis of AD fiber followed by Na₂CO₃ impregnation can be a valid strategy for H₂S scrubbing, and could offer a substitute for commercial activated carbon. Both the pyrolysis and the impregnation processes are simple and very quick, which would certainly be of interest for large-scale applications.

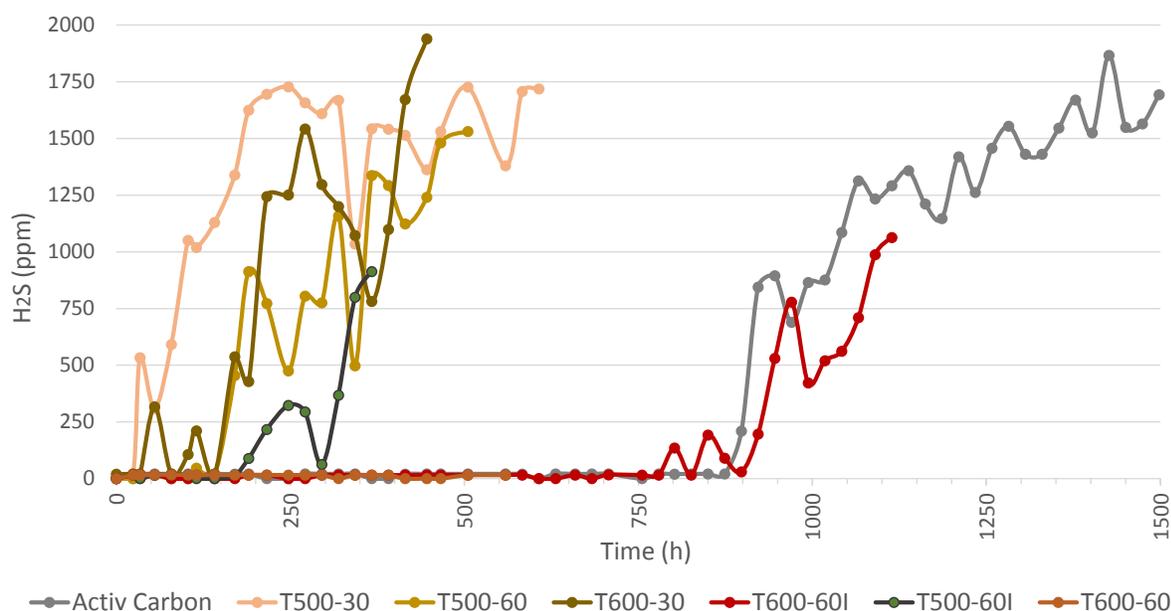


Figure 6.3: Hydrogen sulfide concentration in biogas after it has flowed through columns of materials being tested as H₂S scrubbing agents. The different curves reflect tested materials developed from AD fiber with different thermal treatments. The first number in the treatment name refers to the pyrolysis temperature (e.g., T500 was pyrolyzed at 500°C), and the second number refers to the length of treatment (e.g., 60 was pyrolyzed for 60 minutes). Treatment names with an “I” at the end were additionally impregnated with sodium carbonate before being tested.

In the case of the HWE treatment, although the treatment temperatures were relatively low—180°C and 200°C, for 60 minutes—it has been demonstrated that water in HWE acts as a catalyst, promoting the degradation of wood constituents and the modification of wood properties in a way that is comparable with the effect of thermal treatment in dry environments at higher temperatures (Pelaez-Samaniego, 2014). This led to the hypothesis that HWE AD fiber would perform similar to pyrolyzed char. However, the H₂S scrubbing test showed that the scrubbing capacity of the HWE AD fiber was negligible. Hot water extraction-treated materials behaved very poorly: in less than 24 hours, the H₂S concentration in the gas after the scrubbing column was similar to that of the biogas used.

These results led to the hypothesis that the H₂S removal capacity of impregnated biochar produced from AD fiber by pyrolysis at high temperatures (greater than 500°C) results from two complementary factors: (a) the porosity of biochar, which contributes *via* physical sorption of H₂S, and (b) the presence of chemical groups in the pores or on the surface of treated fibers, which promote chemical sorption of the gas. The hypothesis about the effect of porosity is based on the fact that the higher the pyrolysis temperatures, the greater the H₂S removal, and that porosity is known to increase with higher pyrolysis temperatures (Pelaez-Samaniego, 2014). The chemical sorption hypothesis also arises from the work of Pelaez-Samaniego (2014), who showed that the liquid fraction remaining after HWE of AD fiber contains part of the degraded materials released from the fiber, and who demonstrated that HWE partially removes ash from wood. This led to the hypothesis that the low H₂S scrubbing capacity of AD fiber treated with

hot water was not necessarily due to the low temperatures of the pretreatment, but might be explained by the lack of certain minerals washed away with the ash during the HWE treatment.

6.5 Conclusions

Preliminary results from this proof-of-concept project suggest that thermally modified AD fiber can be effective for H₂S removal from biogas if the thermal treatment occurs at high temperatures (greater than 500°C), and if the treatment is not done with hot water. Results indicated that the more severe the pyrolysis treatment, the higher the H₂S removal, suggesting that increase in porosity—known to increase at higher temperatures—could enhance the scrubbing process. The lack of H₂S removal from the biogas when AD fiber was treated using HWE indicated that the effect of water during the thermal treatment was undesirable, due possibly to the removal of ashes—known to act as catalysts—from the AD fiber. This combination of factors suggests that both physical and chemical sorption happen during H₂S scrubbing using thermally treated AD fiber. In addition, impregnating the char with sodium carbonate appeared to be a valid strategy for enhancing the performance of char produced from digested fiber, as it achieved a performance level commensurate with that of activated carbon.

This proof-of-concept project's results are currently leveraging further work focused on (a) understanding the physico-chemical phenomena occurring during both thermal and impregnation treatments, and (b) determining the fate of the scrubbed sulfur and its resultant form. Once these additional studies are complete, results will be submitted for publication in a peer-reviewed journal, and will be presented to industry partners for engineering and economic review, informing potential commercialization and scale up. It is clear, however, that pyrolyzed AD fiber may become a practical alternative to activated carbon for scrubbing H₂S from biogas.

6.6 References

- Anerousis, J.P., Whitman, S.K. 1984. An updated examination of gas sweetening by the iron sponge process. SPE 13280. Society of Petroleum Engineers of AIME, Dallas, TX.
- Díaz, I., Pérez, S.I., Ferrero, E.M., Fdz-Polanco, M. 2011. Effect of oxygen dosing point and mixing on the microaerobic removal of hydrogen sulphide in sludge digesters. *Bioresource Technology* 102(4), 3768-3775.
- Ecology. 2012. Technical support document for dairy manure anaerobic digester systems with digester gas fueled engine generators. Olympia, WA.
- Fulton, A.C. 1991. The Effect of Hydrogen Sulphide on CHP Engines at Countess Wear Sewage-Treatment Works, Exeter. *Water and Environment Journal* 5(2), 172-177.
- Jensen, J. 2011. Biomethane for transportation – Opportunities for Washington State. Washington State University Extension Program. Olympia, WA.
- Kennedy, N., Yorgey, G., Frear, C., Kruger, C. 2015. Project Considerations for On-Farm Co-digestion of Dairy Manure. Washington State University Extension. Pullman, WA.
- Pelaez-Samaniego, M.R. 2014. Thermochemical pretreatment of underutilized woody biomass for manufacturing wood composites. Ph.D. dissertation, Department of Biological Systems Engineering, Washington State University. Pullman, WA.

- Persson, M., Jonsson, O., Wellinger, A. 2006. Biogas Upgrading to Vehicle Fuel Standards and Grid Injection. Swedish Gas Center. Malmo, Sweden.
- Ryckebosch, E., Drouillon, M., Vervaeren, H. 2011. Techniques for transformation of biogas to biomethane. *Biomass and Bioenergy* 35(5), 1633-1645.
- Sitthikhankaew, R., Predapitakkun, S., Kiattikomol, S., Pumhiran, S., Assabumrungrat, S., Laosiripojana, N. 2011. Comparative Study of Hydrogen Sulfide Adsorption by using Alkaline Impregnated Activated Carbons for Hot Fuel Gas Purification. 9th Eco-Energy and Materials Science and Engineering Symposium, *Energy Procedia* 9, 15–24.
- Speece, R.E. 1996. *Anaerobic biotechnology for industrial wastewaters*. Archae Press, Nashville, Tennessee.
- Syed, M., Soreanu, G., Falletta, P., Béland, M. 2006. Removal of hydrogen sulfide from gas streams using biological processes – a review. *Canadian Biosystems Engineering* 48, 2.
- Wellinger, A., Lindberg, A. 2005. Biogas upgrading and utilization. IEA Bioenergy Task 24: Energy from biological conversion of organic waste.
- Xiao, Y., Wang, S., Wu, D., Yuan, Q. 2008. Experimental and simulation study of hydrogen sulfide adsorption on impregnated activated carbon under anaerobic conditions. *Journal of Hazardous Materials* 153, 1193–1200.

7. A Pre-market Analysis of Finished Compost Marketing

Jim Jensen

7.1 Abstract

Compost production has been used as a strategy to manage organic waste materials from dairy farms, food processing, and municipal solid waste. Extensive research exists on the benefits of adding different organic materials to soils under production. The purpose of this proof-of-concept project was to evaluate the opportunities and challenges of marketing finished compost in Washington State, with the ultimate goal of furthering the development of compost markets and the diversion of organic materials toward applications for agriculture.

Relevant information on the supply and potential demand of finished compost in Washington State was gathered. Compost production in Washington State is relatively concentrated, with the top ten facilities producing 80% of finished compost, mostly from organic materials from municipal solid waste streams. These facilities are not evenly distributed across the state, with facilities in western Washington dominating both production and marketing. Potatoes were used as a representative crop to evaluate the agricultural demand for finished compost. If 10% of potato production acres in Washington State used compost at a rate of 15 tons per acre over a three-year cycle (5 tons per year)—as is current practice where it has been applied—they would require 80,000 tons of composted product each year, with an annual economic value approaching \$2.4 million. This amounts to 7% of current compost production in the state, but is 25% greater than all of the compost currently produced from agricultural organic waste products in eastern Washington. Focusing on these geographically co-located sources of compost—at least initially—is a strategy that may be worth considering. Producers looking for more sustainable production alternatives will evaluate the value of compost against other soil amendments. The relative cost and ease of implementation of some of these alternatives may continue to be a challenge for marketing finished compost for agricultural use.

7.2 Background

Compost production has been used as a strategy to manage organic waste materials from dairy farms, food processing, and MSW. Extensive research exists on the benefits of adding different organic materials to soils under production, and such practices have been used in agricultural systems for millennia. These benefits, summarized below, may be necessary for recycled organics compost to shift from being seen as a byproduct to being a value-added, marketable product.

7.2.1 Benefits of compost

The benefits derived from using compost in soils under production include improvements in soil organic matter, moisture, increased nutrient availability, as well as reduced pest abundance.

More recently, research has also focused on quantifying the contributions of such improvements on the climate change mitigation capabilities of agricultural soils.

7.2.1.1 Soil organic matter

Soil organic matter is widely considered an indicator of general soil health (Organic Agriculture Centre of Canada, 2005). Using compost and other stable forms of recycled organic materials as a soil amendment is thought to be an effective means of increasing the soil organic matter content of soils, and this benefit is often mentioned first among the many values of compost. Such increases in soil organic matter lead to improvements in soil health and, as a result, improvements in crop yields (Termorshuizen, 2004).

7.2.1.2 Moisture holding capacity

Compost use can impact soil moisture holding capacity in several ways. The high organic matter content is one way compost increases a soil's moisture holding capacity. Andrew McGuire (WSU Extension, Irrigated Agronomy) shared results from Hudson (1994), who found that increasing soil carbon (the main component of soil organic matter) by a factor of four led to plant available water increasing by a factor of 2.2 to 2.5 (McGuire, 2014). McGuire discusses the fact that, though such improvements in soil organic matter content are possible, they would require significant investments to achieve. More realistic increases, he argued, can still significantly improve water holding capacity, and provide reason for maintaining and adding organic matter to soils (McGuire, 2014).

Microbial activity that increases pore spaces benefits the air and water balance of the soil. The binding properties of humus in compost also support water retention (Bell and Platt, 2013). These various increases in moisture holding capacity gain interest as drought conditions arise, and they can be especially valuable on irrigated soils (Brown et al., 2011).

7.2.1.3 Nutrient availability

While composts generally do not contain high quantities of major plant nutrients, such as nitrogen, phosphorus, or potassium (N, P, K), those nutrients they do provide are often in slow-release and plant-available forms. These compost-provided nutrients would otherwise have to be provided by synthetic fertilizers. In addition to these macronutrients, compost products are good sources of many micronutrients essential to different crops. Compost nutrients are reported to be less likely to leach than nutrients from other fertilizers, due to the stable organic matter in compost, which better allows plants to take up what they need (Bell and Platt, 2013).

7.2.1.4 Pest management

A survey of the literature by the EPA summarizes the potential for compost products to suppress soil-borne pathogens, plant diseases, and crop pests (EPA, 1997). The pest reduction benefits of compost products can result from biological and chemical means. A similar survey of all the sustainable or organic methods of managing soil-borne diseases by the National Center for Appropriate Technology also summarized the mechanisms of disease suppression by compost (Sullivan, 2004). These reports identify several mechanisms for such disease control, linked to the greater abundance and diversity in microbial communities, where beneficial microorganisms:

- compete successfully for nutrients;
- produce antibiotic compounds; and
- prey and parasitize pathogens.

In addition, compost appears to activate disease-resistant genes in plants (EPA, 1997).

7.2.1.5 Resilience

Resilience—defined as the capacity of a soil to recover its structural and functional integrity after a disturbance (Seybold et al., 1999)—is another general benefit of compost. For example, a potential source of resilience under drought conditions would be related to the greater moisture-holding capacity in compost-amended soils, as described earlier. Resilience of soils and landscapes under flood conditions can follow from the capacity of compost-amended soils to enhance drainage. The improved microbial environments of compost-amended soils that support disease suppression may also offer resilience to new kinds of pest or disease outbreaks fostered by changing climates.

7.2.1.6 Carbon sequestration

Among agricultural scientists there exists a consensus view that agriculture can provide a modest but important contribution to sequestering atmospheric carbon (Kruger, 2012). Kruger states that a few key agri-climatic factors drive productivity, influencing the degree to which carbon can be stored in soils. Those factors include precipitation and fertilization (both of which are positively related to total biomass production), crop rotation (due to the differences in biomass produced by different crops, including cover crops), use of perennial crops, tillage (which reduces carbon inputs by oxidizing crop residues), and the application of organic soil amendments (such as manure or compost) (Kruger, 2012). It is important to note that the use of organic soil amendments is simply one part of a complex system, and may be more or less important than the use of cover crops, no-till practices, and other management strategies.

7.2.1.7 Other climate mitigation benefits

As described earlier, the incorporation of organic soil amendments will affect the availability of nitrogen and the demand for synthetic nitrogen. This can lead to related climate mitigation effects in two ways. First, the use of synthetic nitrogen is associated with greenhouse gas emissions from fossil fuels used in its manufacture and distribution. Second, the use of nitrogen in cropping systems—especially the over-application of synthetic forms—can result in N₂O emissions, which have a very high global warming potential (EPA, 2010).

7.2.2 The Washington Biomass Inventory needs a market component

In 2013, the WSU Energy Program led by Mr. Jim Jensen (Senior Bioenergy and Alternative Fuel Specialist, Energy Program) completed an update of the Washington Biomass Inventory (<http://www.pacificbiomass.org/WABiomassInventory.aspx>). The inventory was first completed in 2005 by Dr. Craig Frear (Assistant Professor, Department of Biological Systems Engineering) and his team, on behalf of the Washington Department of Ecology. The biomass inventory includes data about potential feedstock sources for bioenergy, as well as materials for soil amendments, such as animal manures and food processing residues.

The Pacific Northwest compost industry, however, is concerned about the quality, value, and size of the market for finished compost. A particular challenge is the geographic distance existing between compost production facilities and the users of finished compost. A search of the literature did not find any report or publication that detailed the current marketplace for nutrients in Washington State. Individual elements—such as the Department of Agriculture’s annual fertilizer reports—are available, but nothing that places the demand for plant nutrients in a geographical or seasonal context.

A market-based evaluation that examines opportunities for how such materials might fit into the conventional marketplace is therefore a natural extension of the Washington Biomass Inventory that would directly address the industry's concerns. The purpose of this proof-of-concept project is therefore to evaluate the opportunities and challenges of marketing finished compost, with the ultimate goal of furthering the development of compost markets and the diversion of organic materials toward applications for agriculture around Washington State.

7.3 Methods

The intent of this proof-of-concept project is to draw some connections between the organic materials available in Washington State, especially those that are landfilled—and therefore at the very low end of the “highest and best use” continuum—and the demand for nutrient fertilizers and soil amendments in the state. This is an initial effort to outline some potential areas for deeper investigation.

This research was focused on two main objectives:

1. To describe the supply of finished compost in Washington State, including the sources of organic materials composted, the companies producing finished compost, and the distribution—market share and geographical distribution—of those companies.
2. To identify and describe the challenges and opportunities for marketing finished compost for agricultural use in Washington.

This initial research project was accomplished by gathering relevant information on the supply and potential demand of finished compost in Washington State. Sources of data and information targeted were:

- (a) Washington state agency websites, and other websites with Washington data,
- (b) Literature searches about recycled organic products, and
- (c) Personal communications with knowledgeable experts in these fields.

Additional resources consulted during this project but not specifically cited in this chapter are listed in Appendix M.

7.3.1 Understanding the demand for crop nutrients in Washington State

One of the first efforts of this project was to gather available data about sales of various fertilizers. Data were obtained from the WSDA and the U.S. Department of Agriculture (USDA). The most significant source of data was Washington's “*Annual Tonnage Report: Commercial Fertilizers Including Liming Materials*” (WSDA, 2014). Data were also compiled on compost production facilities registered in the state, particularly their production levels and geographical locations. These data were complemented with additional information obtained *via* interviews with compost marketers and crop experts about the sources of organic materials being used. Additional data were gathered on the availability or use of beauty bark, mulches, and biosolids products. These data were qualitatively analyzed to identify and describe patterns in the supply of finished compost in Washington State.

7.3.2 Identifying challenges and opportunities for marketing finished compost for agricultural use

The approach taken to address the second objective in this proof-of-concept project was to select one crop to serve as a model for evaluating the challenges and opportunities for marketing finished compost for agricultural use. The criteria used for selecting the target crop were (a) its importance—in terms of acreage planted and its market value—in Washington State, and (b) the likelihood of the crop benefiting from using compost as a soil-amendment practice. In addition to these two more objective criteria, the industry’s interest in marketing compost for use in the selected crop was also considered.

The technique used to investigate the demand side of the market was to create a nutrient demand profile for the selected representative crop. A nutrient demand profile describing the nutrient and soil quality requirements was developed to help characterize the nutrient needs—and therefore demand—of Washington’s agriculture markets, and to illuminate potential pathways for recycled organic products—such as compost—to meet those needs. The creation of the nutrient profile for the selected representative crop relied on published information and interviews with key WSU extension specialists about the recommended use of macro- and micronutrients and organic matter for the target crop, as well as the practical and typical uses currently applied by growers across the state. Additional, informal interviews were carried out with compost producers and marketers active in eastern Washington agriculture to obtain their perspectives on the finished compost market. These included Ron Reyer, the chief of operations for Cascade Agronomics; Greg Ovenell, owner of Ovenell Farms; and Thad Schutt, of Royal Organics Products.

7.4 Results and discussion

7.4.1 The demand for crop nutrients in Washington State

7.4.1.1 Fertilizer nutrients in Washington

Each year, the WSDA compiles data and publishes its “*Annual Tonnage Report: Commercial Fertilizers including Liming Materials*”. The 2013-14 report (WSDA, 2014) covers seven broad categories of soil and plant fertilizer nutrients, and the total tonnage of each category that has been distributed (Table 7.1).

Table 7.1: Summary of soil and plant fertilizer nutrients in Washington State, 2013-2014 (WSDA 2014).

Type of soil and plant fertilizer	Tonnage distributed
Nitrogen materials	558,754.00 tons
Phosphate materials	89,353.19 tons
Potash materials	94,425.76 tons
Secondary/micro materials	141,238.76 tons
Natural organic materials	47,920.95 tons
Liming materials	144,002.55 tons
Miscellaneous materials	412,358.95 tons

The more common nitrogen materials include nitrogen solutions, urea, ammonia anhydrous, and ammonia aqua. The more common phosphate materials include monoammonium phosphate and liquid ammonium phosphate. The natural organic materials category includes dried blood, compost, fish scrap, and manipulated manure, which are registered as fertilizers and thus reported as part of this process. These data can be valuable for placing the market for composts in context with the larger market for plant nutrients, whether synthetic or naturally-derived.

7.4.1.2 Compost production and markets

The top ten existing Washington compost facilities, based on their size, process 928,954 tons of materials per year, resulting in almost 80% of the statewide total (first 10 rows in Table 7.2). These facilities are primarily processing organic materials from the MSW stream. About half are processing some volume of food scraps. Two of the facilities have agricultural composting as their primary activity. The organic materials from MSW streams are primarily yard, garden, and landscape materials, as well as increasing amounts of food scraps. Compost made from these materials will have unique qualities compared with compost made from more homogeneous agricultural materials, such as dairy manure.

Two companies market more than half of the state's composted material. Cedar Grove markets the compost and potting soil products produced at its two facilities (in Maple Valley and Everett). This represents 33% of all the composted material in the state. Compost produced from the LRI Compost Factory, Silver Springs, and Pierce County (Purdy), representing another 22%, is marketed as Cascade Compost under an agreement with Corliss Resources.

An additional 11 facilities each compost more than 10,000 tons of organics per year (rows 11 to 21 in Table 7.2). Together, these top 21 facilities in the state process just over 95% of all composted materials. Of these 21 facilities, ten primarily process organics from food processing, fiber and paper, or agricultural byproducts or manures, accounting for about 20% of the state's total compost feedstock. As mentioned earlier, the majority of composted materials—80%—is primarily from the MSW stream. This raises the imperative for learning more about the qualities of these composts, and for expanding the markets for products derived from municipal material.

It is also interesting to look at the geographical distribution of facilities across of the state, given the industry's concern about the challenge that distance poses to efforts to market finished compost for agricultural use. Of the 59 facilities permitted in the state, 21 are located in Eastern Washington. They process 277,500 tons or 23.8% of the organic materials processed in the state. The 38 facilities in Western Washington process 888,696 tons or just over three-quarters of the materials composted in the state.

Most of the top 21 major compost facilities abide by testing regimes that meet or exceed the standards set forth by the U.S. Composting Council's Seal of Testing Assurance (STA) Program. At least ten of these larger facilities, processing two-thirds of the materials composted in Washington, have their products certified for use in organic production by WSDA's Organic Program.

Table 7.2: Compost production by registered facilities in Washington State. Facilities processing dairy manure and agricultural, food processing, and municipal solid waste organics (such as yard and garden materials and food scraps) are included (Ecology, 2013).

County	Facility Name	City	Facility Feedstocks (tons)
King	Cedar Grove Composting Co. Maple Valley	Maple Valley	248,417
Pierce	LRI Compost Factory	Puyallup	139,362
Snohomish	Cedar Grove Composting, Inc.	Everett	132,450
Snohomish	Pacific Topsoils - Maltby	Woodinville	91,115
Lincoln	Barr-Tech Composting Facility	Sprague	67,152
Thurston	Silver Springs Organics Composting LLC	Rainier	64,260
Pierce	Pierce County (Purdy) Composting Facility	Gig Harbor	54,853
Grant	Royal Organic Products	Royal City	48,906
Snohomish	Lenz Enterprises Inc	Stanwood	42,922
Yakima	Natural Selection Farm Composting Facility	Sunnyside	39,517
Yakima	Sunnyside Dairy	Sunnyside	24,050
Walla Walla	Boise White Paper LLC	Walla Walla	22,506
Pierce	Green Hills Farm	Gig Harbor	20,224
Mason	North Mason Fiber Co	Belfair	19,846
Chelan	Stemilt World Famous Compost Facility	Wenatchee	19,022
Snohomish	Bailand Farms Yardwaste (Bailey) Compost	Snohomish	19,000
Grant	Lawrence Farms LLC Compost Facility	Royal City	16,025
Skagit	Skagit Soils Inc	Mount Vernon	13,670
Whatcom	Green Earth Technology (Compost)	Lynden	12,293
Grant	Ovenell Farms Composting Facility	Quincy	10,950
Whitman	WSU Compost Facility	Pullman	10,799
Benton	City of Richland, Horn Rapids Composting	Richland	7,276
Skagit	LaConner WWTP*	LaConner	6,024
Walla Walla	Sudbury Landfill Compost Facility	Walla Walla	4,189
Clallam	City of Port Angeles Compost Facility	Port Angeles	3,797
Pierce	JBLM Composting Facility	Fort Lewis	3,340
Jefferson	Port Townsend Biosolids Compost Facility	Port Townsend	3,087
Skagit	Dykstra Farm	Burlington	2,457
Spokane	Cheney WWTP	Cheney	2,272
Snohomish	Riverside Topsoil Inc	Snohomish	2,250
Kittitas	Kittitas County Compost Facility	Ellensburg	2,012
King	GroCo Inc.	Kent	1,680
King	Steerco/Sawdust Supply	Kent	1,629
Grant	Quincy Compost	Quincy	1,234
Island	Mailliard's Landing Nursery	Oak Harbor	1,124

Table 7.2 (continued): Compost production by registered facilities in Washington State. Facilities processing dairy manure and agricultural, food processing, and municipal solid waste organics (such as yard and garden materials and food scraps) are included (Ecology, 2013).

County	Facility Name	City	Facility Feedstocks (tons)
Clark	H & H Wood Recyclers	Vancouver	875
Walla Walla	Walla Walla University	College Place	832
Whatcom	Lynden WWTP	Lynden	700
Jefferson	Shorts Family Farm	Chimacum	575
King	Woodland Park Zoo	Seattle	443
Chelan	Chelan County Compost Facility	Dryden	427
Snohomish	Arlington WRF	Arlington	398
Snohomish	Granite Falls WWTP	Granite Falls	283
Grays Harbor	Stafford Creek Corrections Center	Aberdeen	234
Grays Harbor	Westport WWTP	Westport	230
Island	Langley WWTP	Langley	216
Island	Wildwood Farm	Oak Harbor	214
Mason	WA Corrections Center Composting Facility	Shelton	214
Walla Walla	WSP Correctional Industries Compost Facility	Walla Walla	188
King	Miller Creek WWTP	Normandy Park	158
Jefferson	Olympic Corrections Center	Forks	148
Lewis	Centralia Composting	Centralia	77
King	Seattle University Onsite Composting	Seattle	69
Clallam	Columbia Compost	Dayton	62
Chelan	Entiat WWTP	Entiat	49
Garfield	Pomeroy WWTP	Pomeroy	39
Franklin	Kahlotus Compost	Kahlotus	37
Klickitat	WSDOT Goldendale Compost Facility	Goldendale	18
Lewis	Centralia WWTP	Centralia	0
Feedstock Total (tons):			1,167,053

* WWTP: Wastewater treatment plant.

In summary, compost production in Washington State is relatively concentrated, with the top ten facilities producing 80% of the finished compost, mostly from organic materials from MSW streams. These facilities are not evenly distributed across the state, with six out of ten facilities based in western Washington, producing over 75% of finished compost. The marketing of finished compost is also concentrated, with only two companies marketing about half the compost produced in the state, both located in western Washington.

7.4.2 Challenges and opportunities for marketing finished compost for agricultural use

7.4.2.1 Anaerobic digestion of dairy solids and associated nutrient recovery

In addition to compost produced from livestock manure, municipal yard and garden waste, and food scraps, anaerobic digesters located on Washington dairy farms present unique opportunities for recovering and producing nutrient fertilizer replacements. Dairy digesters produce digestate or effluent like other digesters. This digestate is often separated into liquid and solid fractions. The uses for the separated liquids and solids vary by project and local markets. The nitrogen-rich liquids may be stored in lagoons for later use on fields to grow silage crops. The fibrous dairy solids have been used as bedding for the cows or as a component to topsoils, composts, or peat moss replacements.

The opportunity to create direct fertilizer replacements through digester systems is driven by the need to export nutrients from a host farm. This may result from the lack of available land on which to apply the AD products, agronomic limits to nutrient application, or by increases in nutrient loading through the addition and co-digestion of high-nitrogen poultry manure or food processing byproducts.

Washington State University researchers, in cooperation with the private sector, have developed a commercially viable process for partitioning the nitrogen and phosphorus components in the liquid digestate from dairy digesters into products that closely resemble fertilizers already in use by crop farmers in conventional agricultural crop production. The researchers compared and contrasted several systems for recovering marketable nitrogen and phosphorus via emerging nutrient recovery technologies for farm-based anaerobic digesters and other renewable energy systems.

Because of the proximity of dairy digesters to major crop production areas in Washington, the nutrient or other soil-amendment products may be able to take advantage of agricultural demand for these sustainable products.

7.4.2.2 A nutrient and fertilizer profile for a representative crop

7.4.2.2.1 Selecting a representative crop

Washington's 37,249 farms power a diverse agricultural economy, led by the state's apple industry (with 70% of U.S. production), followed by wheat and milk (each at about half the value of apples), and then by potatoes, hay and cattle (at about one third to one quarter the value of the top commodity) (Table 7.3). The eight crops in Washington's top ten commodities (Table 7.3) were considered as potential target crops for this project.

Of these eight potential crops, potatoes have one of the highest values per acre, and may therefore be expected to afford soil amendments. In addition, potato production has a close relationship to the soils they are grown in. Cropland under potato production generally has low organic matter content, so supplementing the soil with organic matter may lead to noticeable benefits. Therefore, for the purpose of this proof-of-concept research, potatoes were selected as the representative crop used to consider nutrient demands and how they might benefit from greater use of compost, thereby coinciding with opportunities to market finished compost.

Compost producers already have efforts underway to market compost to potato growers. Their interest in this crop supported its selection as a representative crop for this proof-of-concept project, increasing the likelihood that the results would prove useful to furthering the development of compost markets in Washington State.

Table 7.3: Top ten commodities in Washington State in 2012 (Washington Department of Agriculture).

Top 10 Commodity	2012 Value of Production
Apples ¹	\$2.25 billion
Wheat	\$1.18 billion
Milk	\$1.16 billion
Potatoes	\$700 million
Hay	\$679 million
Cattle/Calves	\$624 million
Sweet Cherries ¹	\$499 million
Nursery/Greenhouses	\$305 million
Grapes	\$236 million
Pears ¹	\$206 million

¹ First in U.S. production.

7.4.2.2.2 *A nutrient and fertilizer profile for potatoes*

According to USDA statistics, potato production in Washington can yield approximately 60,000 pounds per acre, higher than surrounding states. A number of varieties are grown in Washington, dominated by russet varieties. Meeting the basic demand for Washington potatoes—grown for French fries, potato chips, and to be sold fresh through supermarkets or for preparation in restaurants—requires 160,000 acres of production (Washington Potato Commission, 2015). These would be irrigated acres and account for the necessary four-year rotation of potatoes, recommended to prevent the build-up of disease and pests in the soil. Of these 160,000 acres of potatoes, a little more than 1,000 acres are under organic production.

Potato production in Washington is greatest in Grant, Adams, Benton, Franklin, and Walla Walla counties in south-central Washington, and in Skagit and Whatcom counties in the northwest corner.

Interestingly, state maps showing the abundance of potato culls and dairy animal waste, taken from the Washington Biomass Inventory (2013), show significant areas of overlap between the potential availability of dairy-based, recycled organic products and major potato production areas (Figure 7.1).

Nutrient needs for potatoes are well documented. For example, a guide to organic potato production by the University of Idaho Extension notes that the nutrient needs for potato production are significant, with Russet Burbank potatoes requiring 220 pounds nitrogen (N) per acre, 70 pounds of phosphorus (P₂O₅) per acre, 360 pounds of potassium (K₂O), and 20 pounds of sulphur (S) per acre (Moore et al., 2013).

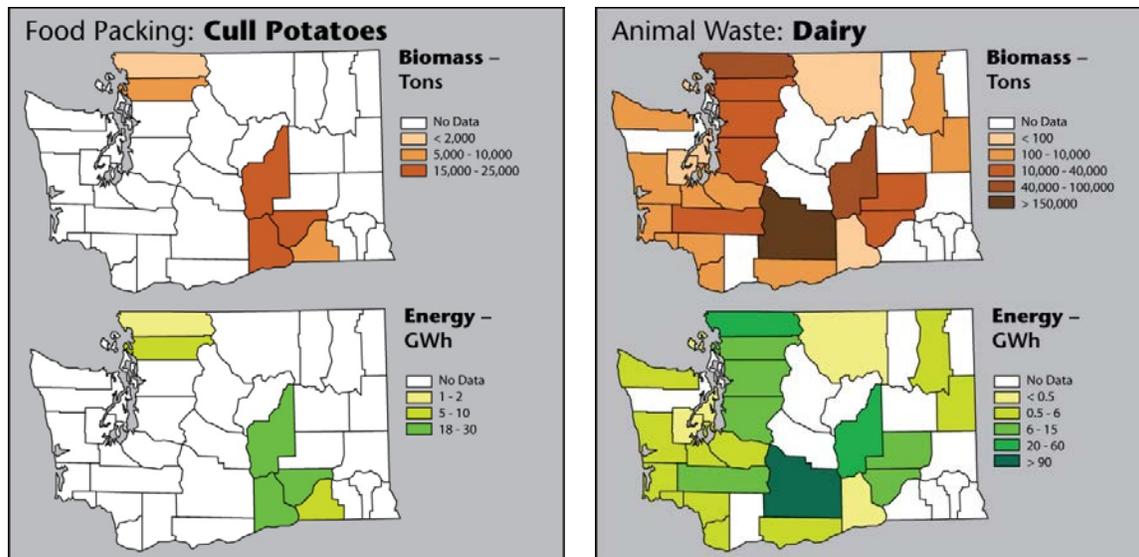


Figure 7.1: County-level distribution of cull potatoes from food packing plants (left panel) and manure from dairy farms (right panel) (Washington Biomass Inventory, 2013).

In addition, best management practices have been developed to guide appropriate nutrient management, with the goal of providing a crop with sufficient nutrients for growth, while avoiding applying nutrients in excess of plant needs, overall and at specific phenological phases (Lang et al., 1999). Lang also establishes the importance of following best management practices in farming, highlighting that the amount of fertilizer applied to a potato crop should depend on the supplying power of the soil, the potential for nutrient loss, and the growth potential of the cultivar (Dean, 1994).

Current best management practices for potato production provide the following insights into the crop's nutrient demands and the management practices that can help meet those demands (Mikkelsen, 2006):

- Potatoes managed for maximum productivity have a high demand for soil nutrients, some of which accumulate in the vines and tops, and others are removed from the field in the harvested tubers. Since potatoes are commonly grown on sandy-textured soils, additional challenges for nutrient management are present.
- Potatoes grown for processing are valued for yield, size, and also for dry matter content (measured by specific gravity). Either deficient or excessive plant nutrition can reduce tuber bulking and quality.
- Proper nitrogen management is one of the most important factors required to obtain high yields of excellent quality potatoes. An adequate supply of N early in the season is important to support vegetative growth, but excessive soil N later in the season will suppress tuber initiation, reduce yields, and decrease the specific gravity in some cultivars. Even later, excess soil N can also delay maturity of the tubers, and lead to poor skin set, which reduces tuber quality and storage properties.
- Roots absorb phosphate ions only when the ions are dissolved in the soil water. Phosphorus deficiencies can therefore occur even in soils with abundant available

phosphorus if drought, low temperatures, or disease interfere with P diffusion to the root through the soil solution, or otherwise stunt normal root development and function.

- Potatoes require large amounts of soil potassium, a nutrient that is crucial to metabolic functions such as the movement of sugars from the leaves to the tubers and the transformation of sugar into potato starch. Potassium deficiencies reduce the yield, size, and quality of the potato crop. A lack of adequate soil K is also associated with low specific gravity in potatoes.

The relationship between soil organic matter and soil health is not an obvious given with potato production. Andrew McGuire (WSU Extension) points out some paradoxical data regarding potato production in Washington: though yields in Washington surpass those of other potato-growing states (Nebraska, Wisconsin, Maine, Idaho) by 21% to as much as 128%, the productive soils in the Columbia Basin often have soil organic matter levels less than 1%, notably lower than the level considered adequate for proper functioning or to be considered high-quality soils (McGuire, 2014). McGuire (2014) points out that this paradox highlights a problem with the concept of soil quality: it does not take into account the management practices that farmers employ to overcome problems in soil quality.

The complexities of soil quality and soil health relative to production practices require additional investigation. These complexities also highlight potential differences between conventional and organic potato production, which the composting industry may need to consider as it continues to market its products for use in agriculture. Organic producers—who do not have the ability to add synthetic NPK fertilizers to their potato crops—are likely particularly conscious that soil degradation is difficult to avoid under intensive (short rotation) potato production systems, as they return little or no organic matter back into the soil (Organic Agriculture Centre of Canada, 2005). Recent research (referenced in Organic Agriculture Centre of Canada, 2005) suggests that biological indices of soil health fail to recover when the frequency of potato in rotation is high. Organic potato production systems, therefore, tend to be characterized by extended rotations (four or more years) involving leguminous crops as green manures, often combined with organic amendments (Organic Agriculture Centre of Canada, 2005).

7.4.2.2.3 Where is the place for compost in potato production?

Available research literature and other resources about conventional potato production provide little insight or instruction about the uses of compost on potato acreage.

Research about sustainable potato production, on the other hand, has looked at issues related to water availability, including the value of better irrigation methods, such as drip irrigation as an alternative to overhead, pivot irrigators. Few data are available on the value of compost and its ability to improve the soil's moisture holding capacity as part of the solution. Similarly, research focused on production adjustments in response to drought conditions, such as deficit irrigation, lists a range of choices for potatoes, including (a) using more drought-tolerant varieties, (b) modifying seed condition and spacing, (c) adjusting irrigation efficiency, and (d) adjusting nitrogen fertilization during times of water stress. Only one resource referenced soil conditions in the context of "field choice," noting that "soils with relatively high water-holding capacities, such as loams and silt loams, allow water stress to develop at a slower rate, reducing its impact

on yield and quality” (Stark, 2006). It did not, however, describe compost use as of means to achieving such beneficial soil conditions.

A coordinated research project intent on promoting sustainable potato cropping systems investigated the use of agricultural chemicals for nutrients and as herbicides and pesticides (Hopkins et al., 2005). This research highlighted concerns related to farm chemical use, namely (a) nitrate concentrations in groundwater supplies, (b) phosphorus loading in surface waters, (c) pesticide residues in water supplies and food stuffs, (d) soil quality reductions related to depletion of beneficial organisms, (e) pesticide resistant organisms, and (f) farm worker exposure to toxic materials.

The project also included an informal assessment of potato production practices, and found that the majority of growers tended to over-apply agricultural chemicals and fertilizers by 5 to 30% (Hopkins et al., 2005). The researchers concluded that this overuse stemmed from two problems: (a) a maximum yield with high input mentality, and (b) intense cropping systems that do not take advantage of natural pest control and fixation and recovery of existing nutrients.

There is no mention of compost in this compilation of research on sustainable potato production, even though it is known to increase soil organic matter content, which in turn is known to help solve such nutrient and pest management issues.

The authors who compiled existing sustainable potato production research identified the risk of failure of new approaches as a significant obstacle to overcome when attempting to get growers to adopt practices they are not familiar with and have no confidence in (Hopkins et al., 2005). They present as an example the lack of widespread adoption of green manures as an alternative to using fumigants:

“Several studies have shown that certain green manure crops have the potential to provide biological control of certain soil borne diseases, nematodes, and weeds (Araji and Hafez, 2000; Hafez and Sundararaj, 2000a; Hafez and Sundararaj, 2000b; Eberlein, 1999; Al-Rehiyani et al., 1999; Al-Rehiyani and Hafez, 1999; Boydston and Hang, 1995). Despite this work, less than one percent of the acreage represented in the aforementioned survey used green manures in rotation with potatoes” (Hopkins et al., 2005).

Past research does suggest there is potential for positively impacting the yield and resilience of potato production through soil modification, in this case through the use of a soil additive called Wet-Sol® (Neibling and Seyedbachergi, 2013). Wet-Sol® Concentrate is a biodegradable, non-ionic surfactant that aids irrigation and weed control. It can be used as a soil penetrant, which loosens compacted soil to support irrigation moisture deeper into the ground. Neibling and Seyedbachergi (2013) reference replicated studies by Dr. Robert Thornton—and others at WSU—on center pivot irrigated potato fields from 1985 through 1994, which initially showed that application of the soil enhancer Wet-Sol resulted in deeper soil moisture penetration during the growing season. Later trials indicated that petiole nitrate N levels of treated plants were higher and vine lengths were longer than the untreated control plants, indicating greater N uptake. Total tuber yield and marketable yields were higher, and certain soil types showed a lower incidence of internal tuber disorders. These studies also included soil compaction tests in

1993-94, and results showed that application of Wet-Sol to heavy (loam) and sandy soils increased the depth down to where compacted soil could be detected and resulted in deeper soil moisture penetration (Neibling and Seyedbachergi, 2013).

Neibling and Seyedbachergi (2013) also describe related evaluations of different compost sources—feedlot, dairy, and wood products—applied at rates of 5, 10, 15, and 20 tons per acre. These evaluations found that compost use increased vertical and horizontal water penetration and led to the soil retaining optimal moisture at the root zone. Compost treatments also helped compacted soil and alleviated clodding and crusting problems. They concluded that applying organic soil amendments will enhance a soil's physical, chemical and biological activities, which enhance fertilizer and water use efficiency (Neibling and Seyedbachergi, 2013).

However, the researchers also identified several agronomic and management issues that can be compounded by amending with compost, such as high carbon:nitrogen ratios, the timing of compost application relative to planting, and adjustments to irrigation plans after compost use (Neibling and Seyedbachergi, 2013). Research looking at the application of humic acid products on the production of potatoes has found similar results (WSU Extension).

Researchers in Maine carried out experimental trials to determine the value of compost as an alternative to irrigation in potato production (Halloran, 2013). They incorporated 19 Mg ha⁻¹ of composted dairy manure (dry weight basis) (roughly 8.5 ton dry weight compost per acre) during each year of a three-year rotation involving barley, timothy, and finally potatoes. The results of their trials and associated economic analysis found that these amendments led to yield increases, and that composted dairy manure could be cost competitive compared to irrigation with existing systems. Their economic analysis was based on compost costs of \$30 to \$40 Mg⁻¹ (roughly \$27 to \$36 per ton). Compost amendments were especially viable alternatives to supplemental irrigation, in areas where irrigation did not already exist, or where regular irrigation is challenging or costly. Interestingly, they concluded that the impact of compost is as a moisture regulator in the soil, buffering the crops through high moisture levels and conserving moisture in the soil through moisture deficient periods (Halloran et al., 2013).

In much of the organic production literature the initial emphasis is on crop rotation and green manures to control disease and improve soils. The focus of organic matter and soil improvement research has been on cover cropping (green manures), and on organic sources of nutrients. Green manures are likely the biggest competitor to compost applications for sustainable production of potatoes. Green manures are good sources of organic matter, some nutrients, and disease control in some cases. It may be more easily grown and incorporated by farmers than composts (Finnigan, 2001).

Obtaining organic versions of nutrients—nitrogen, phosphorus, potassium, sulphur—in sufficient quantities to meet the crop's nutrient needs, and at the right time, is challenging. A guide to organic potato production points to the importance of varietal selection for success in yield and quality under organic conditions, along with crop rotation and the use of nitrogen-fixing cover crops and other nutrient-rich organic fertilizer sources (Moore et al., 2013). It does observe the potential value of Idaho's abundant sources of dairy manure, fresh and composted, with the composted dairy manure being preferable, due to its reduced number of pests, weed seeds, and

lower disease risk. Composted products are also less restricted in terms of timing, being available for use at any time during the growing season. It is critical to understand the levels of different forms of nitrogen in the soil and in compost to assure optimum availability of plant-available nitrogen at the appropriate time (Moore et al., 2013).

On-farm research on organic potato systems is on-going at the University of Idaho, focusing on nitrogen mineralization from compost, as well as rapeseed meal, radish as a green manure crop, and commercially available humic substances. Composted dairy manures are good sources of phosphorus, potassium, and many critical micronutrients. As a source of nitrogen, growers must be careful to manage and account for nitrogen availability through mineralization of the organic nitrogen in composts. This can happen over multiple seasons. Supplemental nitrogen and other nutrients may still be required from other sources. Growing nitrogen-rich cover crops in combination with soil organic matter additions can be valuable (Moore, 2013).

Research at the University of Manitoba has focused on the potential value of composted animal manures (beef and swine) on reduction of *Verticillium* wilt, the major disease agent causing potato early dying (Molina and Tenuta, 2011). Results suggest that compost and seed-meal appear as promising alternatives for control of *Verticillium dahlia*. In their trials, compost reduced disease and increased potato yield, which researchers found was associated with improved nutrient availability (phosphorus and sulfate) in soil (Molina et al., 2014).

In northwest Washington State, Snohomish County Extension has undertaken multi-year research trials and demonstrations of the use of compost in a wide range of crop production systems. Their Compost Outreach Program has provided compost and technical support to dozens of producers growing many different crops. Through randomized, replicated crop trials they have documented favorable yield improvements for beet seed, cucumber, and green bean crops. Though none of the trials have been for potatoes, the project has documented favorable reactions by growers about compost improvements to crop production and soil quality. The project has also identified as main barriers “compost price, compost quality, and spreading equipment and time” (Corbin and Harness, 2014).

Additional research in northwest Washington examined the agricultural use of biosolids compost (Youngquist, 2014). The compost is produced from biosolids combined with shredded yard waste or wood shavings (1:2 by volume). The results is a Class A biosolids compost that is qualified for unrestricted use on agriculture crops. Youngquist completed trials of the use of this biosolids compost on winter and spring wheat crops and potato fields in rotation. Compost was applied at a high rate: 63 MT ha⁻¹ dry weight (roughly 28 tons per acre dry weight).

Youngquist (2014) found that compost significantly increased total potato yield and tuber size. Plots treated with compost—alone or in combination with additional N—produced the most tubers in the 5-8 oz. and 9-12 oz. size class and the fewest tubers in the <2 oz. size class, and led to improvements to soil organic matter and soil physical properties. The trials also showed some examples of significant compost effects on primary and secondary nutrients and on micronutrients (Youngquist, 2014).

Youngquist (2014) also discussed some of the barriers to the use of organic amendments in northwestern Washington potato production, including:

- Organic soil amendments are considered too expensive to purchase, haul, and apply.
- Farmers in the region are concerned that the use of organic amendments will increase incidences of potato scab caused by *Streptomyces scabies*, although this link has not been proven (Debra Inglis, Professor and Extension Plant Pathologist, WSU; personal communication).
- Complex crop rotations and seasonal land leases are not conducive to farmers' investments in building soil quality. It would likely take 3-4 years of repeated compost applications before growers start to see significant changes in soil bulk density, infiltration or other physical properties if compost is the only significant source of soil carbon (Youngquist, 2014).

These results led Youngquist (2014) to conclude that biosolids compost:

- (1) Was primarily valuable as a source of N, plant available P, and soil organic matter,
- (2) May be a valuable source of carbon to increase soil organic matter and improve soil physical properties in local agriculture,
- (3) May be a valuable source of sulfur, zinc, manganese, and iron where these nutrients are limiting, but
- (4) Is not likely a practical source of potassium, calcium, magnesium, or boron.

In summary, research in Washington State, Idaho, and other potato producing regions in North America have found that using compost as a soil amendment in potato production can address challenges such as management of water availability, pests, and nutrients by increasing soil organic matter and associated microbial activity. Though these benefits may be of particular value to organic potato production, they can also improve the sustainability of conventional potato production systems, avoiding the risk of overuse of synthetic fertilizers and pesticides.

7.4.2.3 Value of the benefits of compost

Are the known benefits to using compost to amend agricultural soils sufficient for this to be a practical solution to production challenges in Washington State? Is the cost:benefit ratio such that agricultural uses can become an important share of the finished compost market? Some organic matter benefits have direct monetary value (e.g., carbon sequestration), while the value derived from other benefits is indirect (e.g., increased soil moisture leading to greater crop yield). Even when an additional monetary value can be obtained from some benefits, such as carbon sequestration, the monetary value gained through carbon credits in established markets may be relatively minor when compared to other, more salient benefits of soil organic matter, as the following example illustrates.

For more than 15 years Dale Gies, a potato and wheat farmer from Moses Lake, has used cover crops and new management regimes to build soil organic matter (i.e., carbon), raising his soil carbon from 0.6% to 1.3%, while at the same time increasing his water holding capacity by approximately 30%. Over this time period, the current carbon market value of the sequestration may have amounted to \$50 to \$100, while the added water holding capacity through avoided crop loss could be as much as \$100 acre⁻¹ during a water short year (Kruger, 2013).

However, amending soils with commercial compost, while effective at increasing soil organic matter—with its associated benefits—must compete economically with many other ways of accomplishing similar results. As McGuire’s (2014) article illustrates, techniques for increasing soil water holding capacity include high residue farming (retaining crop residues on the field from season to season), incorporating cover crops (also known as green manures), and using no-till or conservation tillage practices, to name a few.

7.4.2.4 Observations from the field

Compost producers and researchers will point to experience and results showing many similar benefits for sustainable crop production through the use of compost: reduced compaction, improved soil texture and penetration, improved carbon sequestration, greater moisture holding capacity, and greater plant production resilience. Insights from producers and marketers of compost active in eastern Washington offer the most promising evidence of potential value in using compost in potato production yet.

Cascade Agronomics is reported to be working with dozens of potato growers, involving thousands of acres, who are incorporating composted chicken manure or composted steer manure at rates ranging from 10 to 15 tons per acre into their potato production. The compost application rate varies based on soil analysis results, and is considered when making the rest of their soil recommendations. Along with valuable contributions of phosphorus and potassium, the growers are getting the benefits of improved organic matter and abundant trace nutrients such as calcium, sulfur, zinc, and boron.

Ovenell Farms reports similar success, working with a half dozen growers, covering thousands of acres in Grant County and beyond. They are incorporating screened, composted dairy and steer manures. In one type of application they are applying up to 5 tons per acre per year for three years prior to planting potatoes. This is typically at a total cost, including transportation and application, of \$30 per ton applied. This is lower than most compost producers who process yard and garden waste, and food scraps can afford.

Ovenell reports strong interest by landowners, more than renters. Landowners see it as a long-term investment in maintaining and building soil health and tilth. The growers appreciate the composted products for their macro- and micronutrient contributions and the increased microbial activity, especially on ground that is frequently fumigated prior to potato plantings. Ovenell indicated they have tried to use NPK as a possible index for value early on. Now they place more emphasis on the biological activity and water holding capacity of composts. Significant continuing education is required to continue making progress.

Ovenell also emphasized the importance of adherence to Good Agricultural Practices as defined by the USDA and the FDA. He believes these guidelines have a basis in the marketing of potatoes from producers to buyers. USDA’s Specialty Crops Inspection (SCI) Division Audit Programs provides voluntary audits of Good Agricultural Practices (GAP) and Good Handling Practices (GHP). The GAP and GHP audits verify adherence to the recommendations made by the FDA and other industry-recognized food safety practices (FDA, 1998).

Thad Schutt, of Royal Organics Products, echoed many of the sentiments about the value of compost to potato producers, including the value of water-holding capacity, greater biological

activity, improved cation exchange capacity with improved nutrient uptake, and increased organic matter holding nitrogen closer to root zones.

Royal Organics is taking a different approach, citing the problems with the cost of transporting and applying the bulk and mass of composts as hindrances to widespread adoption of compost use in agriculture. They are creating a specialized pelletized version of their branded compost products that they are calling Compell. This product will be capable of being incorporated into the seed zone during planting, delivering the key micronutrient and biological benefits of composts at the key zone for growing plants. It will have a higher cost, but will be used in smaller quantities. In wheat production they have tested applications as little as 40 pounds per acre. Their internal research showed tremendous yield increases in the 2014 crop year: canola increased 31%, barley increased 28.8% and oats increased 15%. The ease of transporting this compost product in tote bags and applying just pounds of the product in the seed zone with conventional planting equipment will have a greater effect than spreading tons of loose compost on cropland. Royal Organics hopes to make this a game-changing product in agricultural production.

The interviews with compost producers and marketers working in Washington State provide some interesting examples of how the industry is highlighting the benefits of compost for agricultural use, addressing the challenges such use poses, and developing innovations that can foster the development of compost markets and the diversion of organic materials toward applications for agriculture around Washington State.

7.5 Conclusions

Compost products from manure, biosolids, and source-separated organics can play a role in improving the sustainability and resiliency of potato production, especially through improved water holding capacity, enhanced nutrient availability, and reduced pest abundance. However, these benefits have been difficult to isolate and quantify in monetary terms that lend themselves to cost-benefit analyses. A clear and timely need is for better understanding of the costs and benefits of compost in a variety of perennial and annual crop systems, as well as the impact of crop contracts in setting requirements and limits on the use of compost amendments.

The cost of compost relative to perceived benefits and the challenge for producers to apply compost remain important barriers. For producers looking for more sustainable or resilient production alternatives, the value of compost applications will be evaluated against other alternatives, such as use of raw manures, high-residue or green manure practices, and the use of organically-derived fertilizer nutrients. The relative cost and ease of implementation of some of these alternatives, as compared to composting, may continue to be a challenge for marketing finished compost for agricultural use. Overcoming this challenge may require further research and outreach efforts to demonstrate the benefits of compost relative to these different practices, and innovations to reduce or eliminate the difficulties in applying compost, such as those being introduced by Washington companies like Ovenell Farms and Royal Organics.

It is reasonable to look more closely at sustainable and organic potato production as potential markets for—in particular—composted dairy manure products and for organic nutrients derived

from anaerobic digestion projects. The geographical synchrony between dairy production and potato acreage across the state suggests that this approach might help overcome some of the transportation cost challenges highlighted in this project.

Current market practice, where producers have purchased compost for potato production, has been to apply up to 15 tons per acre over a two- to three-year cycle (i.e., approximately 5 tons per year), at a final delivered and applied price of not more than \$30 per ton. If 10% of potato production acres used compost at such a rate over a three-year cycle, the resulting demand would require 80,000 tons of composted product each year, with an annual economic value to compost producers approaching \$2.4 million. This amounts to approximately 7% of current compost production in the state, but is approximately 25% greater than all of the compost currently produced from agricultural organic waste products such as dairy manure in eastern Washington (Natural Selection and Sunnyside Dairy facilities). Given the geographical synchrony described above, focusing on these sources of compost—at least initially—is a strategy that may be worth considering.

Realizing any carbon sequestration benefit from the use of recycled organics products (e.g., compost, biochar) will depend on a price of this service, separate from the other benefits such products provide. Currently, monetary benefits that might be derived from carbon credits in an open market appear not to be sufficient to move the compost market significantly. If demand for carbon sequestration increases as part of regional or national plans for climate change mitigation, then the carbon sequestration benefits of compost use will take on greater value and importance.

7.6 References

- Al-Rehiayani, S. Hafez, S. 1999. Host Status and Green Manure Effect of Selected Crops on *Meloidogyne chitwoodi* Race and *Pratylenchus neglectus*. *Nematropica* 28, 213-230.
- Al-Rehiayani, S., Hafez, S., Thornton, M., Sundararaj, P. 1999. Effects of *Pratylenchus neglectus*, *Bacillus megaterium*, and Oil Radish or Rapeseed Green Manure on Reproductive Potential of *Meloidogyne chitwoodi* on Potato. *Nematropica* 29, 39-51.
- Araji, A. Harez, S. 2000. The Economic and Environmental Impact of Nematode Research and Extension Program on the Idaho Agricultural Industry. University of Idaho, College of Agriculture, Extension Bulletin 818.
- Bell, B., Platt, B. 2013. Building Healthy Soils with Compost to Protect Watersheds. Institute for Local Self Reliance, Minneapolis, MN.
- Boydston, R., Hang, A. 1995. Rapeseed (*Brassica napus*) Green Manure Crop Suppresses Weeds in Potato (*Solanum tuberosum*). *Weed Technology* 9, 669-675.
- Brown, S., Kurtz, K., Bary, A., Cogger, C. 2011. Quantifying Benefits Associated with Land Application of Organic Residuals in Washington State. *Environmental Science and Technology* 45(17), 7451-7458.
- Corbin, A., Harness, H. 2014. SCACROP! The Snohomish County Agricultural Compost Research and Outreach Project. Snohomish County Extension.
- Dean, B.B. 1994. Cultivation, fertilization, and irrigation. In: *Managing the potato production system*. Haworth Press, Inc. New York. pages 69–83.

- Eberlein, C. 1999. *Brassica* Green Manure Systems for Weed, Nematode, and Disease Control in Potatoes. Sustainable Agriculture Research and Education Program SW95-021 Final Report.
- EPA. 1997. Innovative Uses for Compost: Disease Control for Plants and Animals. US Environmental Protection Agency, Washington, DC.
- EPA. 2010. Methane and Nitrous Oxide Emissions from Natural Sources. US Environmental Protection Agency, Washington, DC.
- FDA. 1998. Guidance for Industry: Guide to Minimize Microbial Food Safety Hazards for Fresh Fruits and Vegetables. U.S. Department of Health and Human Services, Food and Drug Administration, Center for Food Safety and Applied Nutrition (CFSAN). 43 pp.
- Finnigan, B. 2001. The value of green manures in potato cropping systems. University of Idaho Potato Conference.
- Hafez, S., Sundararaj, P. 2000a. Concomitant interaction of *Meloidogyne chitwoodi* and *Pratylenchus neglectus* in Potato Cropping System. *Nematologia Mediterranea* 28, 89-92.
- Hafez, S., Sundararaj, P. 2000b. Evaluation of Chemical Strategies along with Cultural Practices for the Management of *Meloidogyne chitwoodi* and *Pratylenchus neglectus* in Potato. *International Journal of Nematology* 10(1), 89-93.
- Halloran, J.M., Larkin, R.P., DeFauw, S.L., Olanya, O.M., He, Z. 2013. Economic Potential of Compost Amendment as an Alternative to Irrigation in Maine Potato Production Systems. *American Journal of Plant Sciences* 4(2), 27756.
- Hopkins, B., Ellsworth, J., Geary, B., Harding, G., Horneck, D., Newberry, G., Olsen, N., Pavek, M., Thornton, R. 2005. Promoting Sustainable Potato Cropping Systems. Final Report, Sustainable Agriculture Research and Education (SARE) program.
- Hudson, B.D. 1994. Soil organic matter and available water capacity. *Journal of Soil and Water Conservation* 49(2), 189-194.
- Kruger, C. 2012. Can soil carbon storage really make a difference to our climate? Do we have the right data to answer? Perspectives on Sustainability, Blog of the Center of Sustaining Agriculture and Natural Resources, Washington State University. Available online at <http://csanr.wsu.edu/soilcarbon/>
- Kruger, C. 2013. When soil carbon sequestration REALLY pays. Perspectives on Sustainability, Blog of the Center of Sustaining Agriculture and Natural Resources, Washington State University. Available online at <http://csanr.wsu.edu/soil-carbon-really-pays/>
- Lang, N.S., Stevens, R.G., Thornton, R.E., Pan, W.L., Victory, S. 1999. Potato Nutrient Management for Central Washington. Washington State University Cooperative Extension. EB1871. Available online at <http://www.exactscientific.com/assets/files/WSU%20Potato%20Management.pdf>.
- McGuire, A. 2014. Soil Organic Matter Boosts Water Holding Capacity. Washington State University Irrigated Agriculture. Posted May 7, 2014. Available online at <http://irrigatedag.wsu.edu/soil-organic-matter-boosts-water-holding-capacity/>
- Mikkelsen, R. 2006. Best Management Practices for Profitable Fertilization of Potatoes. *Better Crops* 90(2), 12-13.
- Molina, O.I., Tenuta, M., El Hadrami, A., Buckley, K., Cavers, C., Daayf, F. 2014. Potato early dying and yield responses to compost, green manures, seed meal and chemical treatments. *American Journal of Potato Research* 91(4), 414-428.
- Molina, O., Tenuta, M. 2011. Composted manures and control of potato early dying in Manitoba. University of Manitoba. Available online at

- http://compost.org/English/PDF/WRW_2014/MB/M_Tenuta_U_Manitoba_Composted_Manures_Control_Potato_Early_Dying.pdf
- Moore, A., Olsen, N., Satterwhite, M., Frazier, M.J. 2013. Organic potato production in Idaho: Nutrient management and variety selection. University of Idaho Extension Bulletin 885. Available online at <http://www.cals.uidaho.edu/edComm/pdf/BUL/BUL885.pdf>
- Neibling, H. Seyedbahergi, M.-M. 2013. Influence of Soil Amendments on Soil Health and Crop Production. Sugar Producer. Available online at <http://www.sugarproducer.com/2013/05/influence-of-soil-amendments-on>
- Organic Agriculture Centre of Canada. 2005. Soil Health in Organic Potato Systems. Introductory Research Report E2006-22.
- Seybold, C. A., Herrick, J. E., Brejda, J. J. 1999. Soil resilience: A fundamental component of soil quality. Soil Science 164(4), 224-234.
- Stark, J., King, B., Love, S. 2006. Managing a Potato Crop with reduced water supplies. University of Idaho Potato Conference.
- Sullivan, P. 2004. Sustainable Management of Soil-Borne Plant Diseases. National Center for Appropriate Technology, Fayetteville, AR. Available online at <https://attra.ncat.org/attra-pub/summaries/summary.php?pub=283>
- Termorshuizen, A.J. 2004. The value of compost. Reviews in Environmental Science and Biotechnology 3(4), 343-347.
- WSDA. 2014. Annual Tonnage Report: Commercial Fertilizers Including Liming Materials 2013-2014. Washington Department of Agriculture AGR PUB 632-336. Available at <http://agr.wa.gov/pestfert/pesticides/docs/annualtonnagereport20132014.pdf>
- Youngquist, C.P. 2014. Local biosolids compost: agricultural use, fate of antibiotics, and community engagement. Doctoral Dissertation, Washington State University.

Author's note: For additional references related to the marketing of finished compost, please refer to Appendix M.

8. Appendices

Appendix A. Questions for pre-survey interviews

**Questions for Needs Assessment Survey Development Discussions
(Following a Semi-Structured Interview Format)
January 29, 2014**

Explain that we are planning to conduct a needs assessment survey of the Ecology Beyond Waste Organics Program as it impacts the collection, processing, and end use municipal, agricultural, and other organic wastes. Use the framework description and review the Ecology plan for organics materials, especially the recommendations and milestones.

1. Does the Ecology program plan (Recommendations and Milestones) effectively describe the key end results that the state and the industry want for organics materials? If not, why not?
2. Describe any additional end results that you feel we should include during the survey.
3. Given your perspective about the industry, are there specific objectives/end results that you feel are not well understood? If so, please describe.
4. Does our list of internal and external clients described in the framework capture the universe of subjects for an effective needs assessment? If not, what changes would you suggest?
5. Will these respondents, have sufficient knowledge and information about the field of waste organics management and the industry to identify and quantify the gaps between “what is” and “what should be”? If not, please describe the issues you see. Where do you think that respondents (or groups of respondents) will lack insight?
6. If you foresee problems, can you think of information, charts or graphics we could provide in the survey that would assist in accurate responses?
7. Are there specific individuals or organizations who we should make sure are surveyed?
8. In your opinion, will we get better data from surveying a prescribed list of respondents or by opening it up to members of industry associations and groups who choose to respond?
 - a. If opening it up – through what key mechanisms do you think we should distribute the survey?
9. What suggestions do you have for assuring a high level of response?
10. Are there any questions or topics that might discourage participation or less than full and valid responses?
11. What is your opinion of asking for respondent’s names and contact information (this helps with effective follow up) versus assigning random numbers to the questionnaires.

12. While our key objective is to define and prioritize needs (i.e., gaps between goals and the current reality), we also hope to identify and prioritize specific research questions that will contribute to progress toward goals. What other specific objectives are worth pursuing in the needs assessment survey?
13. Are there any specific needs that you have identified, that you think are not well understood at this time? If so, what unanswered questions exist for these areas of need?
14. Are there any specific questions you would think we should ask?

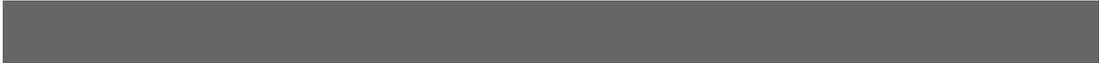
Appendix B. Final Survey, Organics Management in Washington State

WELCOME! Thank you for helping us understand organics management in Washington state. For the purpose of this survey, "organics management" refers to collecting and processing organic residuals and marketing products made from agricultural wastes, manures, food scraps, yard and garden debris, and biosolids.

The survey is designed to take about 10 to 15 minutes to complete or longer, depending on your interest and feedback. Your answers are confidential; only researchers at Washington State University will have access to your answers. The survey report will show summaries of results; any individual comments included will remain anonymous.

If you have any questions about the survey or technical problems with the survey, please contact Jim Jensen at the WSU Energy Program: jensenj@energy.wsu.edu or 360-956-2083.

We know your time is valuable, thank you in advance for your participation.



1. Listed below are some benefits that residents, businesses, and governments might expect from effective organics management. In your opinion, how much of each of these potential benefits has been gained by current organics management systems in Washington? (If you are not sure or have no opinion, choose that option.)

Carbon sequestration in plants, trees or soils

Listed below are some goal statements about organics management in Washington. For each goal, consider how big is the gap between where we are now and where we want to be. (If you are not sure or have no opinion, use that option.)

2. In your opinion, how far is Washington from achieving this goal: "A sufficient network of businesses thrives on collecting and processing residual organic materials into beneficial products."

3. In your opinion, how far is Washington from achieving this goal: "There is robust demand for high-quality organic products in all sectors of the economy, from soil amendments and recycled consumer goods to green energy sources."

4. In your opinion, how far is Washington from achieving this goal: "Economic and regulatory incentives are aligned to support full organics recovery and beneficial use in Washington."

Additional information or comments

5. In your opinion, how far is Washington from achieving this goal: "People in Washington support a sustainable, closed-loop organics management cycle."



6. Listed below are some of the individual parts of Washington's organics management systems. In your opinion how much success has been achieved for each of the different elements? (If you are not sure or have no opinion, use that option.)

s desired for
processing organic
residuals.

This next section asks questions about the scale and complexity of organics management. Considering all the elements of management, such as recovery rates, economics, end product quality, ease of participation, etc, how much do you agree or disagree with the following statements? (If you are not sure or have no opinion, use that option.)

7. How much do you agree or disagree with this statement: “To produce cleaner feedstocks, we need to put greater emphasis on successful source-separation and public participation.”

8. How much do you agree or disagree with this statement: “To reduce materials hauling, we need to put greater emphasis on economically managing organic residuals closer to their source.”

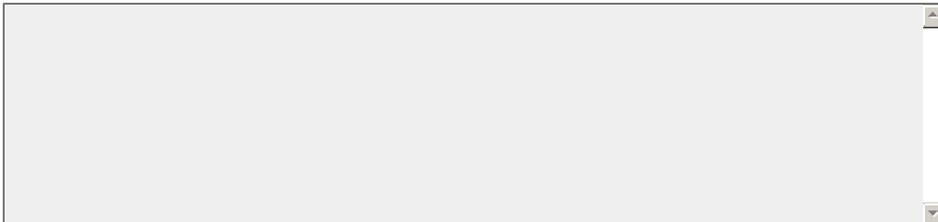
Somewhat Agree

9. How much do you agree or disagree with this statement: “To successfully manage the wide range of organic residuals, we need to put greater emphasis on integrating additional technologies to produce green energy and other products in centralized facilities.”

at Agree

10. Listed below are some issues that people have described as barriers to greater success in organics management. In your opinion, how much is each issue a barrier to more success? The follow-up question will ask you to provide more detail. (If you are not sure or have no opinion, use that option.)

11. System barriers are very important. Please use the box below for additional comments. Are there barriers we missed? For the most important barriers you see, tell us how or why these barriers exist. Can you provide specifics about barriers you have faced in your work?



12. Listed below are several challenges often associated with organics management in Washington. Please indicate in your opinion how much benefit would be gained if we could find the solution to each challenge. (If you are not sure or have no opinion, use that option.)

13. What questions about organics management do you have that you would like research or study to solve? (provide up to 3)

1.

14. Returning to the list of potential benefits from organics management described in Question #1. In your opinion, when deciding how to apply various public resources to improving the organics management system, what is the relative priority of these different benefits? (If you are not sure or have no opinion, choose that option.)

Carbon sequestration in
plants, trees or soils

Please Tell Us About You

15. Which field best describes your involvement with the organics management system in Washington? (Please choose one)

16. What different organics processing technologies are you or have you been actively involved with using, supplying, researching, promoting, etc? (Check all that apply)

17. Please check the box for the number of years you have been involved in work or business in organics management.

 ars

18. What's the zip code at your primary place of work?

ZIP:

19. Please share your contact information if you would be willing to participate in more detailed interviews. Optional.

Appendix C. Demographic analysis of survey respondents

As a whole, survey respondents included individuals across the organics management sector, with the exception of project finance (Figure C-1). The sample included relatively more individuals representing the government perspective, likely as a result of the inclusion of several government list serves in our secondary group (Table C-1). Many respondents had also been involved in work or business in organics management for a number of years, with roughly a third involved for over 20 years (Figure C-2).

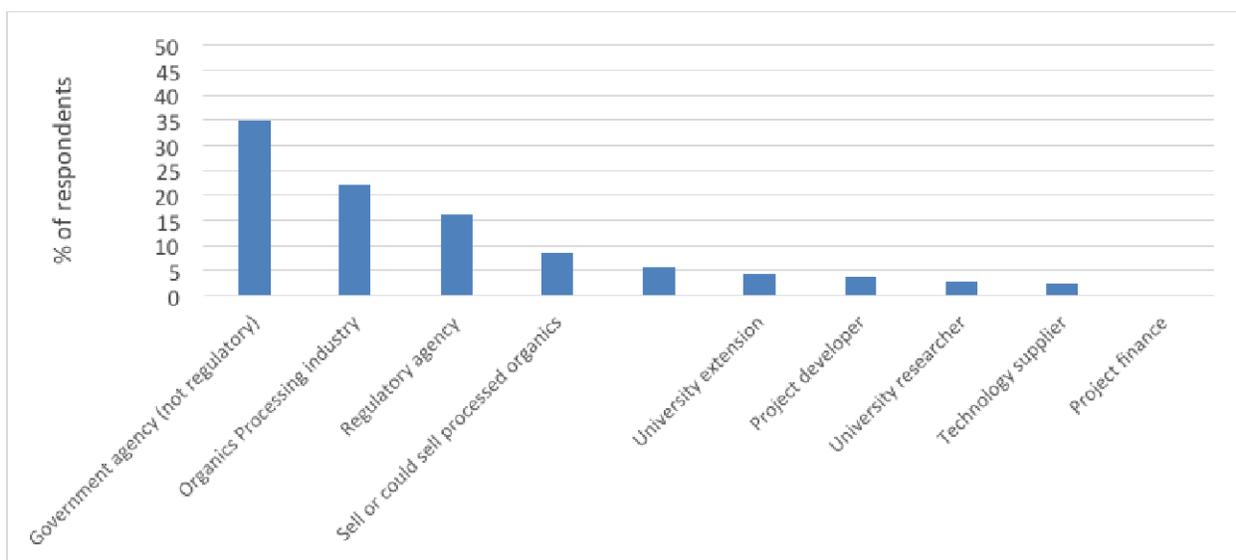


Figure C-1. Survey respondents' self-identified primary role in the organics management system.

Table C-1. Percentage of respondents in each field within our target respondent group, secondary respondent group, and whole sample.

	TARGET (Group 1)	SECONDARY (Groups 2 and 3)	WHOLE SAMPLE
What field?			
Government agency (not regulatory)	24.43	51.16	35.02
Organics processing	25.19	17.44	22.12
Regulatory agency	15.27	17.44	16.13
Sell recycled organics	9.92	5.81	8.29
End user	6.87	3.49	5.53
University extension	5.34	2.33	4.15
Project developer	4.58	2.33	3.69
University researcher	4.58	0	2.76
Technology supplier	3.82	0	2.30
Project finance	0	0	0

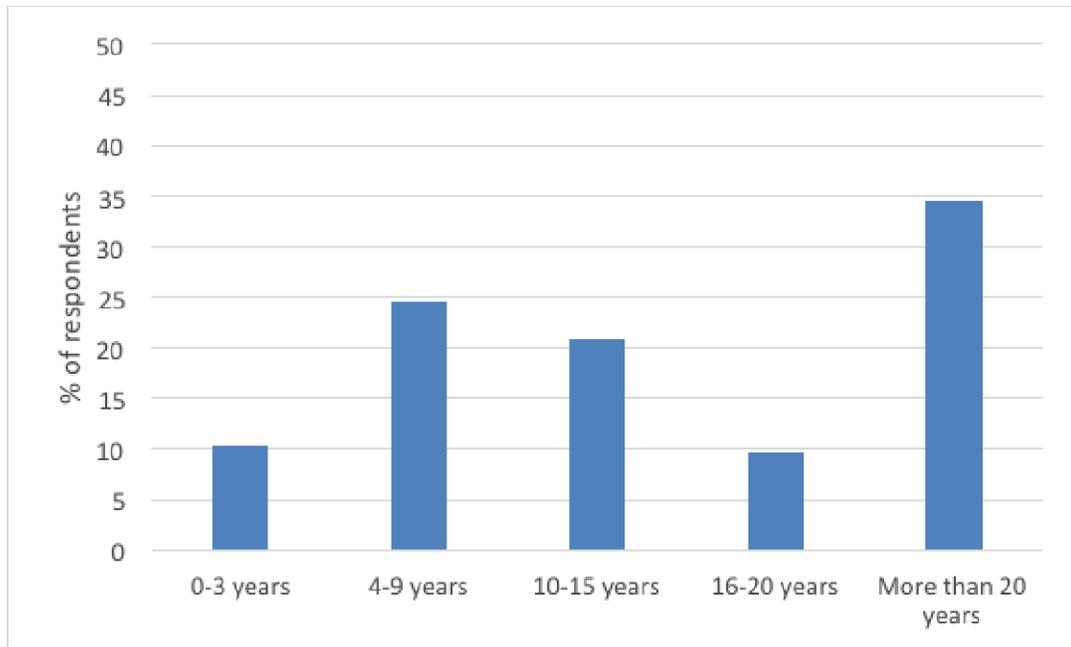


Figure C-2. The number of years that survey respondents have been involved in work or business in organics management.

Respondents were asked which organics processing technologies they have been actively involved with using, supplying, researching or promoting, and they were allowed to choose as many of the different technologies provided applied to them. Respondents were involved with a range of technologies (Figure C-3). While it is a little surprising the number of people involved in anaerobic digestion, this may reflect the inclusion of individuals involved in wastewater treatment, as well as the fact that individuals were allowed to check more than one technology (thus, individuals who are primarily involved with composting, but somewhat involved with anaerobic digestion, are reflected in this number).

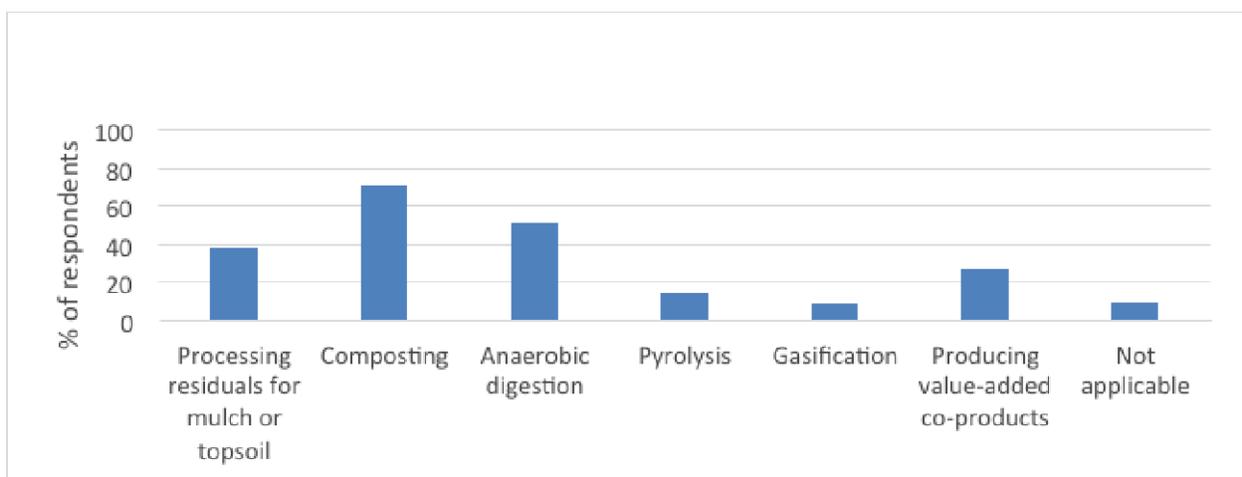


Figure C-3. The organics processing technologies that survey respondents have been actively involved in using, supplying, researching, or promoting. Respondents were permitted to check all that applied.

Of all the total response population of 273, 222 provided zip code data responses. Of these, 11 were identified as from other states or Canada. Two responses were unidentifiable as zip codes. Of the 209 respondents providing in-state zip codes, 31 of Washington’s 39 counties were represented (Table C-2). The secondary group also had a higher percentage of respondents from rural locations.

Table C-2. Geographical locations of respondents (based on analysis of zip codes at primary place of work).

	TARGET (Group 1)	SECONDARY (Groups 2 and 3)	WHOLE SAMPLE
Number of Responses with Valid Zip codes	133 + 11 out of state	89 + 2 out of state	222 + 13 out of state
Number of Washington State Counties Represented	24	27	31
Breakdown of Eastern vs. Western WA	90 Western WA 43 Eastern WA	54 Western WA 35 Eastern WA	144 Western WA 78 Eastern WA

The demographic analysis informed two key decisions about analysis of results:

- We included all responses (from both our target and secondary group) in analysis.
- In addition to analyzing results as a whole, statistical analysis was used to compare results between government and non-government respondents.

Appendix D. The status of organics management in Washington State: full survey results

Survey scope

The survey targeted organics management, defined broadly as the management of biodegradable wastes, in Washington State. This included handling, processing and marketing products made from agricultural wastes, manures, food scraps, yard and garden debris, and biosolids. The focus was on the current timeframe (the last five years) and the future.

The questions asked in the survey were designed to provide insight into four key questions:

- What is the current status of organics management in Washington?
- What are the barriers preventing better management of organics?
- What are the priority areas for action to improve organics management?
- What is the most productive level of scale and complexity for future organics management?
- What research questions would respondents like answered?

Survey design and methodology, along with some key overall insights resulting from the survey, are described in the full report. This appendix provides full results and analysis, organized to reflect the four topic areas above.

Along with analysis of full survey results, statistical analysis examined whether there were differences in the responses of governmental and non-governmental individuals. It is worth noting that there was generally a high level of similarity between the opinions of government and non-government respondents throughout the survey. Therefore, the results are only discussed in the cases where there were statistical differences between the responses of the two groups.

The current status of organics management in Washington State

How successful is the current system?

Respondents were asked to share their opinion on how much success has been achieved for different elements of Washington's organic management systems (Question 6, Appendix B). The overarching result was that respondents considered that all elements of organics management had achieved "some success", with the opinions on different elements differing on being somewhat more positive—leaning towards "big success"—or more negative—leaning towards "little success" (Figure D-1, Table D-1). This overarching pattern was generally true throughout the survey.

The three elements of Washington's organics management systems that were considered to have achieved more success were:

- Recycled organics products being produced were considered to be high quality;
- Collection and recovery programs for residential and commercial organics were considered effective; and
- Companies were successfully developing new technologies for processing organic residuals.

It is worth noting that the success of producing high-quality recycled organic products was perceived to be somewhat greater than the last two elements (Figure D-1).

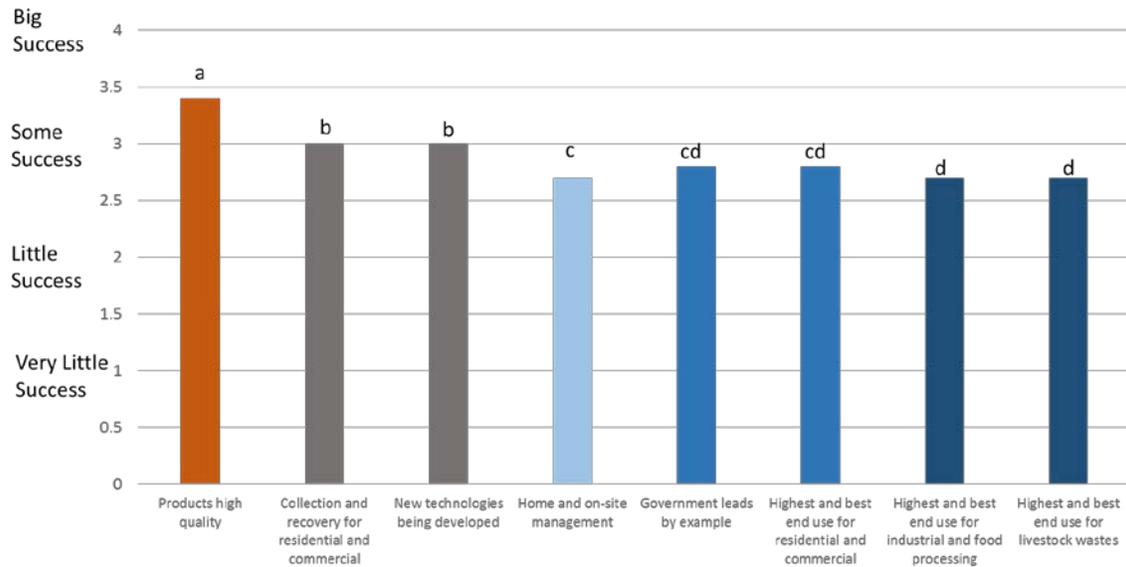


Figure D-1. Level of success achieved by elements of Washington’s organics management system perceived by respondents. Elements labeled with the same letter are not statistically different at the $p < 0.05$ level, as determined using the chi-squared test (if expected values were all equal to or greater than 5) or Fisher’s exact test (if this condition was not met).

Differences between the remaining five elements of the organics management systems (blue bars in Figure D-1) were due mostly to how strongly the responses were centralized on “some success”, or distributed across multiple levels of success above and below “some success” (Table D-1). That is, differences were due to the distribution of responses, rather than to a difference in the overall opinion of respondents.

When responses of government and non-government respondents were compared, results showed almost no statistical differences, highlighting that opinions were very similar between these two groups for most elements of the organics management system in Washington. The only statistical difference was for the statement “Companies are successfully developing new technologies desired for processing organic residuals,” where non-government respondents saw *more* success than government respondents (two-sided Fisher’s Exact test, $p = 0.04986$; Table D-2).

Table D-1. Percentage of respondents who considered Washington’s organics management system elements have achieved each level of success. Elements are organized from those considered most successful (top row) to least successful (bottom row).

Element of Washington’s organics management system	Very Big Success	Big Success	Some Success	Little Success	Very Little Success	Not Sure/No Opinion	Total Responses
	%	%	%	%	%	%	Number
The recycled organic products produced (e.g. soil amendments, composts, biosolids) are high quality (a)	10.3	29.3	39.9	7.4	1.6	11.5	253
There are effective collection and recovery programs for residential and commercial organics (b)	5.1	16.9	48.4	16.5	4.3	8.7	254
Companies are successfully developing new technologies desired for processing organic residuals (b)	2.4	16.4	47.6	12.0	3.2	18.4	250
The system effectively encourages home- or on-site management of organics (c)	0.8	5.9	53.0	21.0	6.3	13.0	253
Government entities (including parks, universities, correction facilities, etc.) lead by example in managing their organic residuals (cd)	1.2	8.8	49.0	21.1	5.6	14.3	251
The system achieves the highest and best end use for residential and commercial organics (cd)	1.2	11.8	44.9	19.7	7.9	14.6	254
The system achieves the highest and best end use for industrial and food processing organics (d)	1.2	10.3	35.2	24.1	7.1	22.1	253
The system achieves the highest and best end use for livestock wastes (d)	2.8	9.6	31.9	19.9	6.8	29.1	251

*Elements followed by the same letter are not statistically different at the $p < 0.05$ level, as determined using the chi-squared test (if expected values were all equal to or greater than 5) or Fisher’s exact test (if this condition was not met).

Table D-2. Comparison of responses between government and non-government to the statement “Companies are successfully developing new technologies desired for processing organic residuals.” Differences between respondent groups were statistically significant (two-sided Fisher’s Exact test, p=0.04986).

Respondent group	Very Big Success %	Big Success %	Some Success %	Little Success %	Very Little Success %	Not Sure/No Opinion %	Total Responses
Non-government	2.9	22.6	46.0	10.2	4.4	13.9	137
Government	1.8	8.8	49.6	14.2	1.8	23.9	113

What benefits are currently being realized?

Respondents were asked their opinion about which known benefits of organics management systems they felt have been realized in Washington (Question 1, Appendix B). The largest number of respondents considered that “some benefit” had been realized for each of the eight known benefits they were asked about, though the distribution of responses differed for different benefits (Figure D-2, Table D-3).

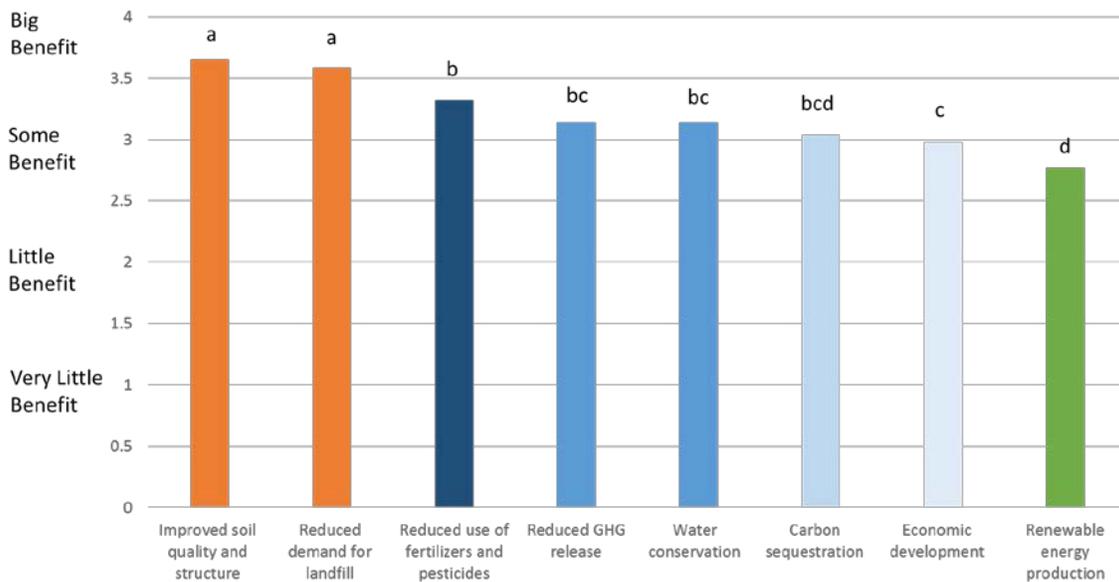


Figure D-2. Extent to which respondents considered each benefit of Washington’s organics management system has been achieved. Elements followed by the same letter are not statistically different at the p<0.05 level, as determined using the chi-squared test (if expected values were all equal to or greater than 5) or Fisher’s exact test (if this condition was not met).

The benefits that respondents felt are currently being realized to the greatest extent are:

- Improved soil quality and structure; and
- Reduced demand for landfill space (Figure D-2).

Meanwhile, respondents thought that renewable energy production benefits are currently being realized to a lesser extent than other benefits (Figure D-2). Among the remaining benefits, there were higher levels of uncertainty about the two benefits related to greenhouse gases—greenhouse gas release and carbon sequestration—are being realized (Figure D-2).

Table D-3. Percentage of respondents who considered benefits of Washington’s organics management system were being achieved at different levels. Benefits are organized from those considered largest (top row) to smallest (bottom row).

Benefit	Very Big Benefit	Big Benefit	Some Benefit	Little Benefit	Very Little Benefit	Not Sure/No Opinion	Total Responses
	%	%	%	%	%	%	Number
Improved soil quality and structure (a)*	22.7	27.5	30.1	7.4	3.0	9.3	269
Reduced demand for landfill space (a)	18.9	28.2	32.2	6.3	3.7	10.7	270
Reduced use of chemical fertilizers and pesticides (b)	16.0	21.3	28.7	13.8	6.0	14.2	268
Reduced release of greenhouse gases (bc)	12.6	14.5	31.6	13.8	7.4	20.1	269
Water conservation (bc)	9.6	20.0	32.6	14.4	6.7	16.7	270
Carbon sequestration in plants, trees, or soils (bcd)	9.4	13.6	28.3	18.1	5.7	24.9	265
Economic development (c)	6.3	14.9	41.0	16.0	6.7	14.9	268
Production of renewable energy (d)	6.7	13.1	31.1	21.4	12.4	15.4	267

*Elements followed by the same letter are not statistically different at the $p < 0.05$ level, as determined using the chi-squared test (if expected values were all equal to or greater than 5) or Fisher’s exact test (if this condition was not met).

When responses of government and non-government respondents were compared, the only statistical difference was for economic development benefits, where non-government respondents saw *more* success than government respondents (Chi-squared test, $\chi^2=19.7097$, degrees of freedom (df)=4, $p=0.0005698$; Table D-4).

Table D-4. Comparison of responses between government and non-government related to the economic development benefits realized by Washington’s organics management system. Differences between respondent groups were statistically significant (Chi-squared test, $\chi^2=19.7097$, degrees of freedom (df)=4, $p=0.0005698$).

Respondent group	Very Big Benefit	Big Benefit	Some Benefit	Little Benefit	Very Little Benefit	Not Sure/No Opinion	Total Responses
	%	%	%	%	%	%	Number
Non-government	9.7	14.8	42.6	8.4	7.1	17.4	155
Government	1.8	15.0	38.9	26.5	6.2	11.5	113

Gaps between current and ideal organics management in Washington State

Respondents were given four goal statements related to the production, demand, regulatory incentives, and public support for closed-loop organics management in Washington (Questions 2 to 5, Appendix B). In each case, they were asked how far Washington was from meeting the goal. For each of the four stated goals, the majority of respondents stated that Washington was “far from meeting this goal” or “halfway toward this goal” (Figure D-3, Table D-5). Statistically, results showed that respondents thought Washington was particularly far from reaching the goal that “Economic and regulatory incentives are aligned to support full organics recovery and beneficial use in Washington” (Figure D-3). Answers for the other three goals were not statistically significantly different from each other (Figure D-3).

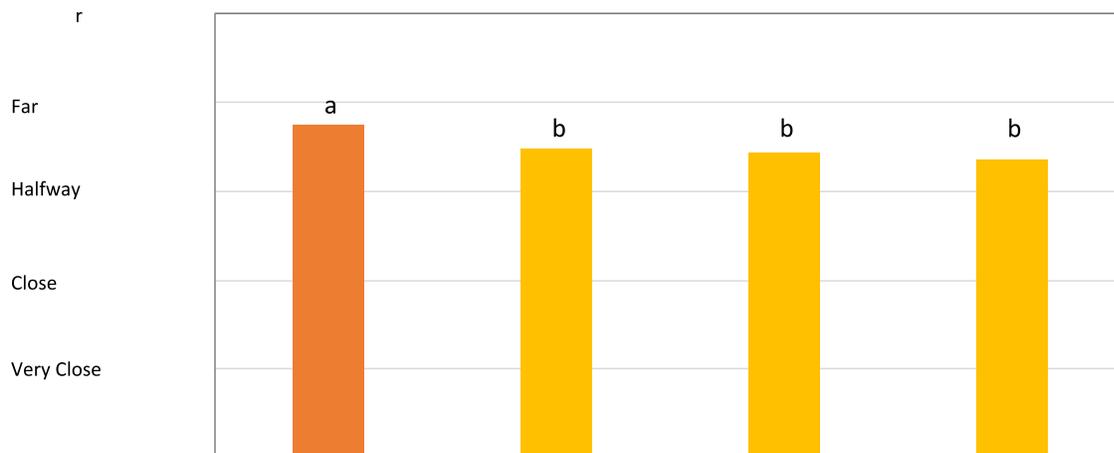


Figure D-3. Distance respondents considered each goal of Washington’s organics management system was from being met. Responses for questions labeled with same letter are not statistically different at the $p < 0.05$ level, as determined using the chi-squared test (if expected values were all equal to or greater than 5) or Fisher’s exact test (if this condition was not met).

When responses of government and non-government respondents were compared, results showed differences between these two groups for two of the four goals:

- Economic and regulatory incentives are aligned to support full organics recovery and beneficial use in Washington (two-sided Fisher’s Exact test, $p=0.00727$; Table D-6); and
- People in Washington support a sustainable, closed-loop organics management cycle (two-sided Fisher’s Exact test, $p=0.04376$; Table D-6).

In both cases, non-government respondents thought the gap to achieve each goal was *smaller* than the gap perceived by government respondents (Table D-6).

Table D-5. Percentage of respondents who considered Washington’s organics management system was at different distances from achieving each stated goal. Goals are organized from those considered to be furthest from being achieved (top row) to closest (bottom row).

Organics management goal	Very Far	Far	Halfway	Close	Very Close	Not Sure/No Opinion	Total Responses
	%	%	%	%	%	%	Number
Economic and regulatory incentives are aligned to support full organics recovery and beneficial use in Washington (a*)	16.7	39.5	22.9	5.8	1.2	14.0	258
A sufficient network of businesses thrives on collecting and processing residual organic materials into beneficial products (b)	7.8	36.1	31.0	9.3	2.3	13.6	258
There is robust demand for high-quality organic products in all sectors of the economy, from soil amendments and recycled consumer goods to green energy sources (b)	5.8	39.9	30.2	8.1	1.2	14.7	258
People in Washington support a sustainable, closed-loop organics management cycle (b)	8.1	30.6	35.3	11.6	1.9	12.4	258

*Responses followed by the same letter are not statistically different at the $p < 0.05$ level, as determined using the chi-squared test (if expected values were all equal to or greater than 5) or Fisher’s exact test (if this condition was not met).

Table D-6. Comparison of responses between government and non-government related to how far Washington’s organics system is from realizing its incentive goal (top two rows) and its support goal (lower two rows). Differences between respondent groups were statistically significant (Incentive goal: two-sided Fisher’s Exact test, $p=0.00727$; Support goal: two-sided Fisher’s Exact test, $p=0.04376$).

Respondent group	Very Far from meeting this goal	Far from meeting this goal	Halfway toward this goal	Close to meeting this goal	Very Close to meeting this goal	Not Sure / No Opinion	Total Responses
	%	%	%	%	%	%	Number
Incentive Goal:							
Non-government	13.9	35.4	24.3	9.7	0.7	16.0	144
Government	20.2	44.7	21.1	0.9	1.8	11.4	114
Support Goal:							
Non-government	6.3	25.0	38.9	11.1	3.5	15.3	100
Government	10.5	37.7	30.7	12.3	0.0	8.8	114

The survey provided space for additional information and comments related to each of the four stated goals. Key comments provided by respondents included:

Production goal: A sufficient network of business thrives on collecting and processing residual organic materials into beneficial products.

- Sufficiency varies by region across the state (working better in urban areas, working better on west side, though one person said east side).
- Definitions of sufficiency vary: does this mean collection and processing of reasonably available/separable organic materials, active competition in processing organics, diversity of methods, capture of significant portion of organics quantified in the WA Biomass Inventory?
- Several issues came up a number of times: issues of product quality and diversity, and not enough demand for products.

Demand goal: There is robust demand for high-quality organic products in all sectors of the economy, from soil amendments and recycled consumer goods to green energy sources.

- Not enough demand, and demand varies depending on location.
- Lack of demand noted by particular users – WSDOT/other public works, big agricultural operations, forestry.
- Cost of products and contamination noted as barriers.
- Several comments about the importance of promoting locally produced organics products.

Incentives goal: Economic and regulatory incentives are aligned to support full organics recovery and beneficial use in Washington.

- Several people questioned whether aligning regulatory and economic incentives is an appropriate goal (given other repercussions of such actions).
- Several people suggested lowering regulations, which would make products less expensive.

Support goal: People in Washington support a sustainable, closed-loop organics management cycle.

- Support for the concept, but are unaware of the specifics of what this means.
- Public has low willingness to pay (whether that's cost, time, or bother) to help achieve the goal.
- People aren't against it, but also aren't aware or actively supporting this goal.

The text of all comments provided by survey respondents is available in Appendix I.

Barriers preventing better management of organics in Washington State

To elicit information about barriers, respondents were provided with a set of issues that have been described as barriers to greater success in organics management, and asked their opinion on how much of a barrier each was to success (Question 10, Appendix B). In general, the largest

number of respondents considered each issue a “major” or “moderate barrier” (Figure D-4, Table D-7). The only exception was in opinions about “lack of private investor support”, where slightly more respondents selected “not sure/no opinion” than those that selected “major barrier” (Table D-7).

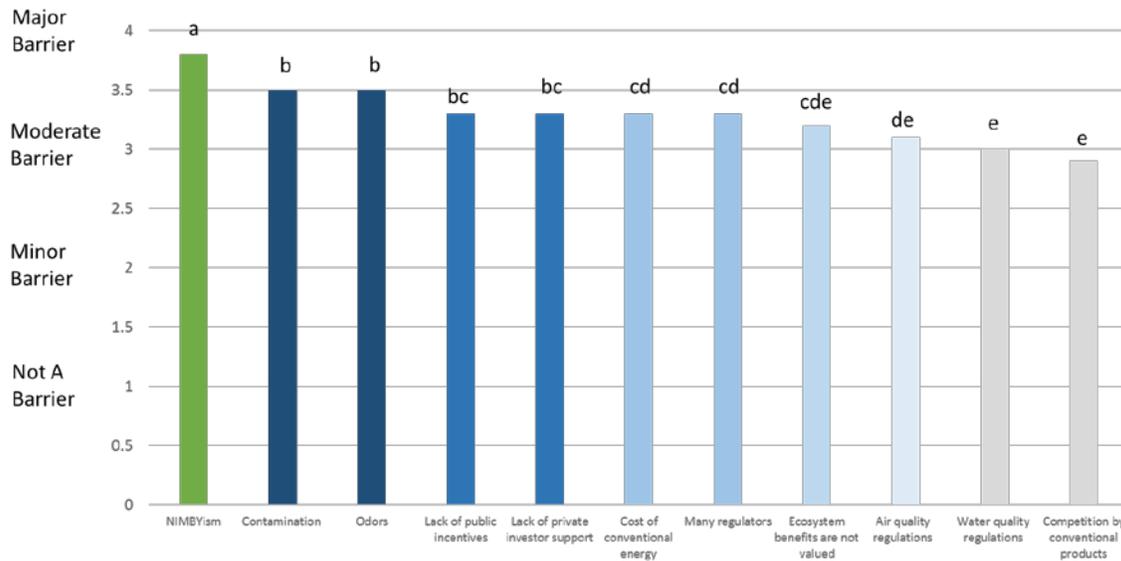


Figure D-4. Extent to which respondents considered each issue a barrier preventing better management of organics in Washington. Elements labeled with the same letter are not statistically different at the $p < 0.05$ level, as determined using the chi-squared test (if expected values were all equal to or greater than 5) or Fisher’s exact test (if this condition was not met).

NIMBYism—which stands for “not in my back yard” and characterizes resistance to an unwanted action in one’s own place, often with the connotation that the action is important to society but should occur further away—was regarded as the most important barrier preventing better management of organics. Other important barriers highlighted by respondents included:

- Contamination in recycled products;
- Odors;
- Lack of public incentives; and
- Lack of private investor support.

Respondents considered that a lack of value for ecosystem benefits, air and water quality regulations, and competition from conventional products were less important barriers (Figure D-4). An important caveat when interpreting this result is to note that end-users of products arising from organics management and processing were under-represented in the survey sample. This under-representation was particularly noticeable in end users in the agricultural community.

Table D-7. Percentage of respondents who considered different issues were barriers preventing better management of organics in Washington. Barriers are organized from those considered biggest (top row) to smallest (bottom row).

Barrier	Extreme Barrier	Major Barrier	Moderate Barrier	Minor Barrier	Not a Barrier	Not Sure/No Opinion	Total Responses
	%	%	%	%	%	%	Number
Neighbor opposition (NIMBYism) (a*)	27.5	35.9	21.5	9.2	1.2	4.8	251
Contamination in recycled organics products (b)	11.2	37.5	28.7	11.6	1.2	10.0	251
Odors associated with managing organic residuals (b)	12.0	39.0	29.5	15.6	1.6	2.4	251
Lack of public incentives (bc)	8.4	30.1	30.5	14.9	2.8	13.3	249
Lack of private investor support (bc)	7.6	25.3	22.9	14.9	3.2	26.1	249
Cost of conventional energy is relatively low (cd)	12.5	24.9	26.1	15.7	4.4	16.5	249
Different agencies of government regulate different organic residuals (cd)	12.5	25.3	30.5	15.7	4.4	11.7	251
Lack of value given to ecosystem benefits (cde)	10.0	24.9	32.9	16.1	6.0	10.0	249
Air quality regulations (de)	11.6	17.5	35.1	20.3	4.0	11.6	251
Water quality regulations (e)	8.4	17.2	34.8	22.0	7.2	10.4	250
Cannot compete with conventional products (e)	6.4	18.0	30.8	24.4	6.4	14.0	250

*Elements followed by the same letter are not statistically different at the $p < 0.05$ level, as determined using the chi-squared test (if expected values were all equal to or greater than 5) or Fisher's exact test (if this condition was not met).

When responses of government and non-government respondents related to perceived barriers were compared, results showed two barriers where there was a difference of opinion between these two groups of respondents:

- Different agencies of government regulate different organic residuals (two-sided Fisher's Exact test, $p = 0.04878$; Table D-8); and
- Air quality regulations (two-sided Fisher's Exact test, $p = 0.01007$; Table D-8).

In both cases, non-government respondents thought these issues were *more of a barrier* than did government respondents (Table D-8).

In addition to asking respondents to identify how much of a barrier certain issues were, respondents were also given space in the survey to identify any barriers that were not considered, as well as root causes for the barriers they perceived as preventing better organics management in Washington State (Question 11, Appendix B). Responses to this open-ended question were

categorized, and the number of times particular categories were mentioned was tallied. A particular response could be tagged as belonging in more than one category.

Table D-8. Comparison of responses between government and non-government related to barriers preventing better organics management in Washington. Opinions of the respondent groups were statistically significant for two statements: “Different agencies of government regulate different organic residues” (top two rows; two-sided Fisher’s Exact test, p=0.04878) and “air quality regulations” (lower two rows; two-sided Fisher’s Exact test, p=0.01007).

Respondent group	Extreme Barrier	Major Barrier	Moderate Barrier	Minor Barrier	Not a Barrier	Not Sure/No Opinion	Total Responses
	%	%	%	%	%	%	Number
Different agencies regulate different organic residues:							
Non-government	14.2	29.1	29.9	12.7	1.5	12.7	134
Government	10.4	20.9	31.3	19.1	7.8	10.4	115
Air quality regulations:							
Non-government	15.4	19.9	33.8	13.2	5.1	12.5	136
Government	7.0	14.8	36.5	28.7	2.6	10.4	115

The new or re-emphasized barriers that were most commonly mentioned by respondents include:

- Regulations (27 mentions);
- Lack of public awareness (24)*;
- Costs and economics (including transportation) (17)*;
- NIMBYism (16);
- Contamination (16);
- Investment or funding incentives (14);
- Low energy costs or competition from conventional products and disposal options (14);
- Scale issues (12)*;
- Innovation and technology development (12)*;
- Odor (7);
- Program direction/focus (5)*;
- Industry problems (5)*;
- Research (4)*;
- Low demand or low product quality (2)*;
- Lack of government leadership (1)*; and
- Nutrient issues (1)*.

Note that many of these categories overlapped—and therefore re-emphasized—barriers included in the multiple-choice question about barriers (Question 10, Appendix B), whose results are summarized above. New barriers that were identified solely by respondents are identified with an asterisk (*) in the list above. The four most commonly identified “new” barriers are the lack of public awareness, the cost and economics of organics management, issues related to the scale of the industry and the development of new technologies.

It is also interesting to note that although air and water regulations were not considered the most important barriers, regulation was still the most commonly mentioned item in the open-ended responses. It is possible that this indicates that while overall, people did not feel this was the most important barrier, those who felt strongly tended to specifically comment on this issue when the opportunity was provided.

The full text of all open-ended comments about barriers is provided in Appendix E.

Priority areas for action to improve organics management in Washington State

Respondents were first asked to give their opinion about how much benefit could be gained if certain pre-identified challenges could be resolved. They were also asked to prioritize known benefits of organics management, based on how they would invest public resources to improve such management (Questions 12 and 14, Appendix B).

How much benefit would be gained?

Four challenges rose to the top as being the most impactful to overcome: respondents felt that overcoming these challenges would lead to greater benefits to organics management (Figure D-5). These four challenges were:

- Getting more products from recycled organics into use, especially by agriculture;
- Eliminating contamination in the recycled organics end products;
- Overcoming neighbor opposition (NIMBYism); and
- Controlling odors and air pollution from organics processing.

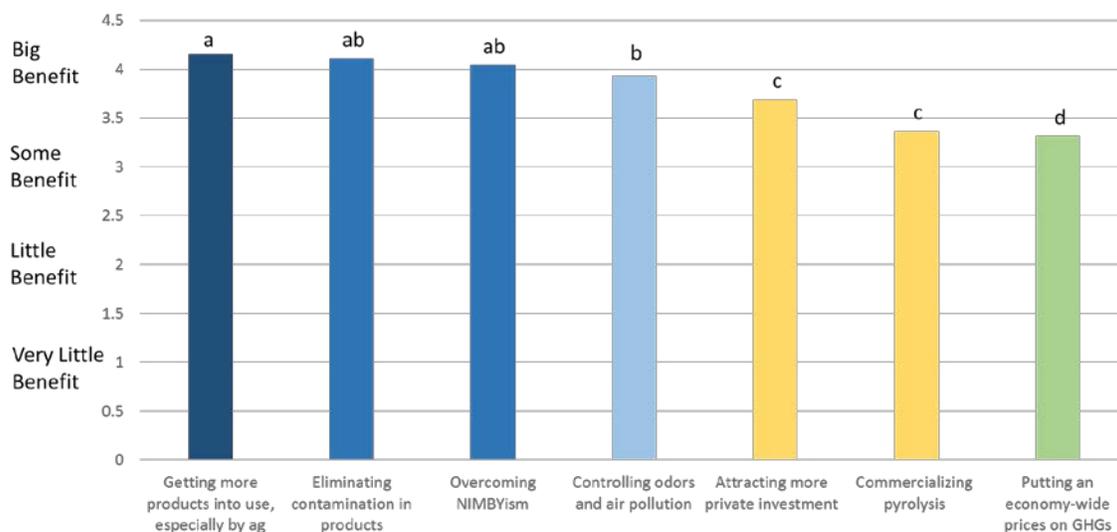


Figure D-5. Extent to which respondents thought benefits could be gained from resolving challenges. Elements labeled with the same letter are not statistically different at the $p < 0.05$ level, as determined using the chi-squared test (if expected values were all equal to or greater than 5) or Fisher's exact test (if this condition was not met).

Among these, eliminating contamination, overcoming NIMBYism, and controlling odors and air pollution, were consistent with the three top barriers (compare Figure D-5 to Figure D-4, above).

However, in some ways this makes it surprising that the most impactful challenge to solve was perceived to be getting more products made from recycled organics into use, especially by agriculture. Overcoming this challenge will likely require additional information (particularly as the survey did not do a good job capturing the opinions of end users of organic products).

Respondents thought that attracting more private investment for organics recovery and processing, commercializing pyrolysis technology for woody materials, and putting an economy-wide price on carbon pollution would be less beneficial, though there were also more “not sure” responses for each of these, perhaps reflecting a lower level of knowledge overall. In particular, opinions about putting a price on carbon pollution were more distributed, perhaps reflecting somewhat politically polarized attitudes towards topics related to climate change (Table D-9).

Table D-9. Percentage of respondents who considered different levels of benefits could be gained from resolving each challenge. Benefits are organized from those considered biggest (top row) to smallest (bottom row).

Benefit	Very Big Benefit %	Big Benefit %	Some Benefit %	Little Benefit %	Very Little Benefit %	Not Sure/No Opinion %	Total Responses
Getting more products made from recycled organics into use, especially by agriculture (a*)	35.1	44.1	14.3	1.2	1.2	4.1	245
Eliminating contamination in the recycled organics and products (ab)	35.1	38.8	18.8	1.6	0.8	4.9	245
Overcoming neighbor opposition (NIMBYism) (ab)	34.7	37.1	20.4	3.7	0.8	3.3	245
Controlling odors/air pollution from organics processing (b)	26.9	43.3	23.3	3.3	1.2	2	245
Attracting more private investment for organics recovery and processing (c)	21.2	28.6	27.4	5.3	3.3	14.3	245
Commercializing pyrolysis (lignocellulosic energy recovery/biochar) technology for woody materials (c)	13.2	21	26.8	7.8	6.2	25.1	243
Putting an economy-wide price on carbon pollution (greenhouse gases) (d)	21.7	20.9	18.0	11.1	13.1	15.2	244

*Elements followed by the same letter are not statistically different at the $p < 0.05$ level, as determined using the chi-squared test (if expected values were all equal to or greater than 5) or Fisher’s exact test (if this condition was not met).

The comparison of the responses from government to non-government respondents indicated that opinions of each group were the same as those described above for the full suite of survey respondents.

What is the relative priority of benefits?

In general, the largest number of respondents considered all eight benefits identified in the survey question as being “high priority”. Half of these eight benefits also had the second largest number of respondents considering it “very high priority”, while the other half had the second largest number of respondents considering it “medium priority” (Table D-10).

Table D-10. Percentage of respondents who ranked each benefit as a certain priority for investment of public resources. Benefits are organized from those considered highest priority (top row) to lowest priority (bottom row).

Benefit	Very High Priority	High Priority	Medium Priority	Low Priority	Very Low Priority	Not Sure/No Opinion	Total Responses
	%	%	%	%	%	%	Number
Improved soil quality and structure (a)	30.7	37.7	24.2	3.7	0.8	2.9	244
Water conservation (a)	24.3	41.6	23.5	4.9	2.1	3.7	243
Reduced use of chemical fertilizers and pesticides (ab)	27.4	35.5	25.7	4.9	3.7	2.9	245
Production of renewable energy (bcde)	20.5	35.3	25.0	10.3	4.9	4.1	244
Economic development (c)	15.6	33.7	32.5	9.1	3.3	5.8	243
Reduced demand for landfill space (cd)	12.3	34.8	29.1	13.5	6.2	4.1	244
Carbon sequestration in plants, trees, or soils (de)	17.8	26.5	22.7	14.5	5.0	13.6	242
Reduced release of greenhouse gases (e)	22.5	30.6	24.1	11.4	6.9	4.5	245

*Elements followed by the same letter are not statistically different at the $p < 0.05$ level, as determined using the chi-squared test (if expected values were all equal to or greater than 5) or Fisher’s exact test (if this condition was not met).

Analysis of the responses about the relative priority of benefits resulted in four benefits being highlighted as being of higher priority (Figure D-6):

- Improved soil quality and structure;
- Water conservation;
- Reduced use of chemical fertilizers and pesticides; and
- Production of renewable energy.

Other benefits were distinguished more by the distribution of responses than by the strength of feeling for a particular priority level: opinions about the priority of reduced release of greenhouse gases and carbon sequestration were more distributed, while those about economic development were more concentrated (Table D-10).

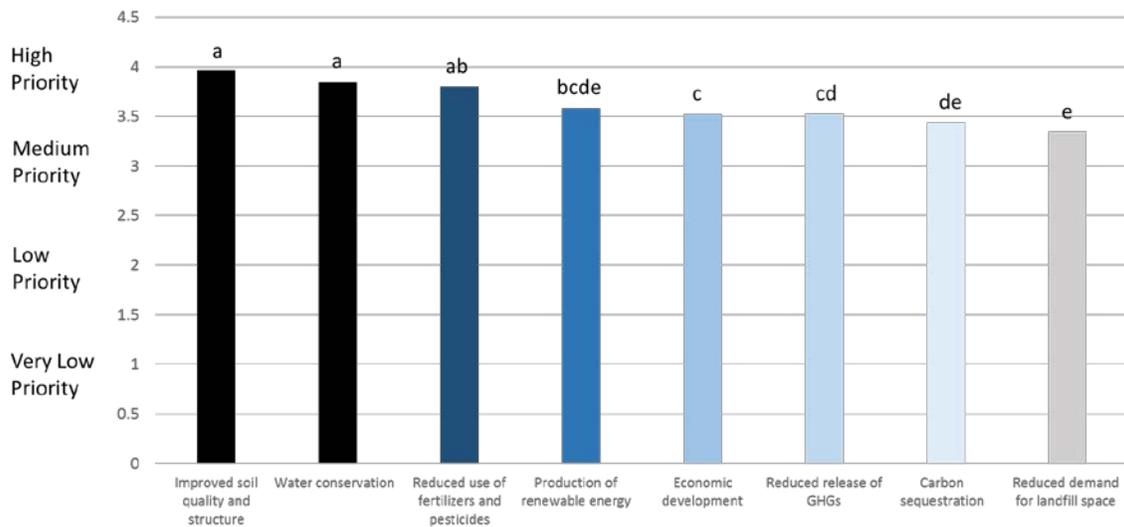


Figure D-6. Extent to which respondents thought each benefit was a priority for investment of public resources. Elements labeled with the same letter are not statistically different at the $p < 0.05$ level, as determined using the chi-squared test (if expected values were all equal to or greater than 5) or Fisher’s exact test (if this condition was not met).

The responses about which benefits were considered highest priorities for achieving through investment of public resources were compared to the responses—summarized earlier—about which benefits of organics management are being realized in Washington State. This comparison led to the following observations:

- Improved soil quality is seen as important, but is also seen as being realized to a greater extent than other benefits of organics management.
- Water conservation is also very important, but is being realized, though to a lesser extent than soil quality.
- Reduced use of chemical fertilizers and pesticides is seen as important, and is also seen as being realized to a good extent, though to a lesser extent than soil quality.
- Reduced demand for landfill space is seen as low priority, but is also seen as being realized to a great extent.

When responses of government and non-government respondents were compared, there was a difference of opinion about the priority of only one of the eight benefits considered: reduced use of chemical fertilizers and pesticides. Non-government respondents thought this item was a *higher* priority than did the government respondents (two-sided Fisher’s Exact test, $p = 0.008074$; Table D-11).

Table D-11. Comparison of responses between government and non-government related to the priority for public investment in research to achieve “reduced use of chemical fertilizers and pesticides.” Differences between respondent groups were statistically significant (Fisher’s Exact test, p=0.008074).

Respondent group	Very High Priority %	High Priority %	Medium Priority %	Low Priority %	Very Low Priority %	Not Sure/No Opinion %	Total Responses
Non-government	33.1	26.9	30.0	3.1	4.6	2.3	130
Government	20.9	45.2	20.9	7.0	2.6	3.5	115

Most productive scale and complexity for future organics management

Respondents were asked to consider all elements of organics management and then asked how much they agreed with the need to put greater emphasis on three different aspects of organics management (Questions 7 to 9, Appendix B). Respondents mostly “strongly agreed” with two of the statements, related to emphasizing successful source-separation and public participation, and to emphasizing economically managing organic residuals closer to their source. Agreement was more muted for the third statement, which was about emphasizing integrating additional technologies to produce green energy and other products in centralized facilities (Figure D-7, Table D-12).

Statistical analysis indicated that government and non-government respondents felt the same about each of these three statements (two-sided Fisher’s Exact test, p=0.4587, p=0.4089, and p=0.964 for statements on source separation and public participation, managing residuals closer to the source, and centralized facilities, respectively).

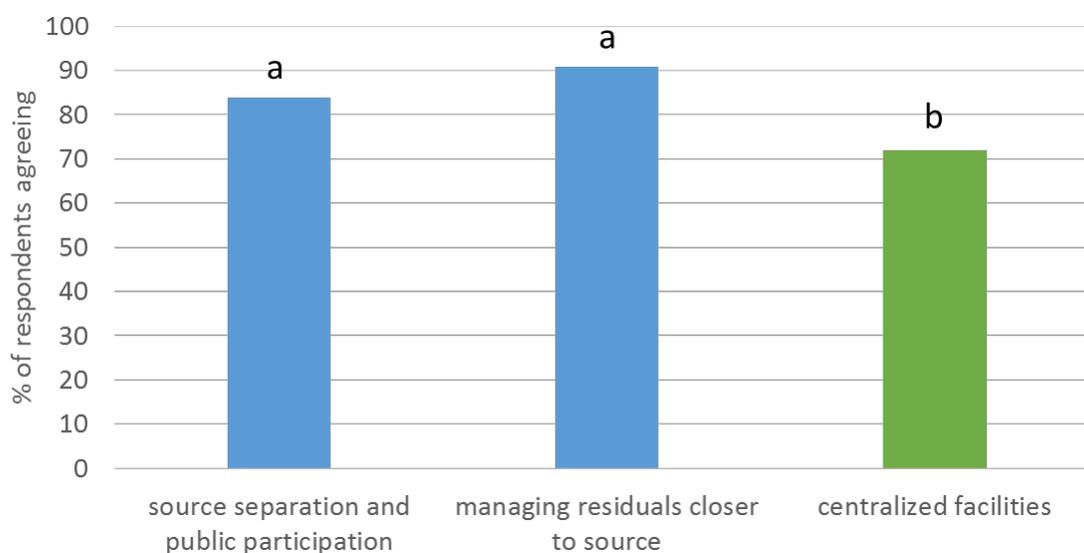


Figure D-7. Extent to which respondents agreed with statements related to the scale and complexity of organics management. Statements labeled with the same letter are not statistically different at the p<0.05 level, as determined using the chi-squared test (if expected values were all equal to or greater than 5) or Fisher’s exact test (if this condition was not met).

Table D-12. Percentage of respondents who agreed to different degrees with statements related to the scale and complexity of organics management. Statements are organized from those for which there was highest agreement (top row) to lowest agreement (bottom row).

Level of scale and complexity	Strongly Agree	Agree	Somewhat Agree	Somewhat Disagree	Disagree	Strongly Disagree	Not Sure/No Opinion	Total Responses
	%	%	%	%	%	%	%	Number
Greater emphasis on successful source-separation and public participation (a)	39.8	30.3	13.6	2.4	2	0	12	251
Greater emphasis on economically managing organic residuals closer to their source (a)	40.9	36.9	13.1	3.2	1.2	2	2.8	252
Greater emphasis on integrating additional technologies to produce green energy and other products in centralized facilities (b)	17.9	30.6	23.4	11.5	7.9	1.6	7.1	252

*Statements followed by the same letter are not statistically different at the $p < 0.05$ level, as determined using the chi-squared test (if expected values were all equal to or greater than 5) or Fisher's exact test (if this condition was not met).

Priority research needs for furthering organics management in Washington State

Respondents were asked to articulate up to three questions about organics management that they would like research to answer (Question 13, Appendix B). Responses were categorized, and then grouped based on the number of times questions in each category were asked. Questions were placed in a single category; thus it is important not to over-interpret the rankings provided here; for example, questions about processing and scale sometimes included mention of specific technologies, but were placed with processing and scale.

Categories of questions with the highest combined mentions (more than 12)

- *Contamination*, including source separation, materials ban (e.g., non-recyclable plastics), physical and chemical contamination, and the fate of organic contaminants in the soil (mentioned 18 times).
- *Scale of technology* and possible benefits of *distributed or decentralized* processing closer to the source (16 mentions).
- *Recycled organic products*, including product economics, market research and development, and the development of advanced products for specialized applications (15 mentions).
- *Economic issues*, with special focus on finished products and the cost of transporting raw feedstocks (14 mentions).
- *Odors*, including odor testing and standards and their impact on neighbors (14 mentions).
- *Benefits* of and the potential for using compost and other recycled organics (e.g., from anaerobic digestion, pyrolysis, biosolids) *in agriculture* (13 mentions). Note that this category is closely related to the recycled organic products category, above.

Categories of questions with moderate combined mentions (between 7 and 12)

- *Life-cycle assessments*, including LCA comparisons of processing methods and technologies, as well as LCA comparisons of different recovery strategies (12 mentions).
- *Anaerobic digestion* and related issues, including co-digestion, biogas utilization, nutrients, waste water treatment plants, and food scrap digesters (11 mentions).
- *Policy*, including carbon taxes, incentives and other policy-related issues (11 mentions).
- *Pyrolysis* and *biochar* (9 mentions).
- *Regulatory issues*, including making improvements to the regulatory system and practice (9 mentions).
- *Composting*, including nutrient retention, economics, compostable plastics, and optimizing process for different environmental conditions and feedstocks (7 mentions).

Categories of questions with lowest combined mentions (less than 7)

- *Concentrated animal feeding operations' (CAFOs) manure management*, including manure nutrient balances, application rates, and improving water quality (6 mentions).
- *Soils*, including valuation and impacts of organic amendments (5 mentions).
- *Promotion* and *public education* (5 mentions).

- *Biorefinery*, including work on anaerobic digestion plus composting, and other combinations of organics technologies or categories (4 mentions).
- *Biosolids* (4 mentions).
- *Financing* and *funding*, including funding for new technologies (4 mentions).
- Waste reduction efforts (4 mentions).
- *NIMBYism*, and how to overcome it (3 mentions).
- *Greenhouse gases* (2 mentions).
- *Bioretention systems* (2 mentions).
- *Carbon sequestration* (2 mentions).
- *Minimal processing* (1 mention).
- *Organics inventory* (1 mention).
- *Incineration* (1 mention).

Among these results, several recurring themes are worth noting. Several of the topic areas receiving a large number of mentions relate to the products from organics technologies (e.g. contamination, recycled organic products, benefits of compost and other products in agriculture). In addition, questions about scale, economics, and transportation/transportation costs were somewhat inter-related, and represent a second area with high levels of interest – including the specific technologies appropriate at various scales.

Responses are provided in their entirety in Appendix F.

Appendix E. Comments about barriers to better organics management

Survey respondents were given the opportunity to provide open-ended responses relating to barriers to greater success in organics management (Question 11, Appendix B). The prompt allowed them to identify barriers that were not specifically identified in the survey (Question 10, Appendix B), as well as to provide further comments about important barriers (how or why these barriers exist, specifics about barriers respondents have faced in their work).

Responses were then categorized, and these results are discussed within Chapter 1 and in Appendix D. This appendix includes all responses in their entirety. Some minor corrections in spelling or grammar have been made to aid clarity.

NIMBYism and anti-organics activism is our #1 problem. Regulations and research are supportive of compost and biosolids use, yet a very small number of individuals with no scientific expertise are able to disrupt projects, prevent facility siting, and spread their opinions and misinformation throughout the cyber world. It is very difficult for public agencies to debunk such a vast number of untrue claims and fears. More support from conservation and climate groups would be very helpful.

The relatively low cost of convention fossil energy affects all aspects of organics recovery, from the value of bioenergy to the value of biofertilizers and soil amendments. To capture the social and economic value of sustainable bioproducts and bioenergy that value has to have a monetary component. That comes from charging polluters for the cost of pollution and for the permission to pollute. Carbon caps and carbon taxes are critical.

Too much plastic mixed in feedstock from fertilizer bags.

Organics that generate odors will always be a challenge because it is human nature to avoid bad odors. While people will express concerns that a foul odor means danger (unhealthy, toxic, spreading disease), I feel that NIMBYISM is more about unpleasant odors than it is about risk. If you can remove the odor barrier, you are well on your way to success. My opinion on this comes from my experience with biosolids. Another barrier for biosolids is the association with human waste and unfounded fears that go with this. A person may be fine with the smell of horse manure, but not biosolids odors.

Neighbor opposition that stems from misinformation about organics recycling.

Investment in management of biosolids and water reuse is expensive and requires full stakeholder support from the facility operators, owners, regulators and public. Any breakdown in these support groups will have a negative result. It takes long term commitment to successfully manage these resources. Poor choices in not looking at the end user to tailor the best technology to the local market have resulted in some projects that fail.

One of our major barriers is we have multiple agencies we deal with and they each think they are the lead agency. They each want different priorities in O&M's, making it somewhat difficult for operators to operate their systems. An example we had DOE approve an operations plan and the clean air regulator wants us to either re-write the plan to fit what they feel they regulate on a Biosolids operation.

Barrier 1: Post-consumer food scraps collection (contamination).

Barrier 2: Major composting operators producing low-quality product.

Barrier 3: Presumption that collecting/processing organics is always (w/o exception) the preferable management strategy.

Barrier 4: Cost of environmental management (e.g. odor control, stormwater) in urbanized Western Washington, among other areas (versus transport costs away from high density pop. centers)

Barrier 5: (often) low cost of alternative management, including disposal, makes investing in sophisticated large scale organics management facilities problematic."

Irrigated agriculture and livestock facilities have extreme barriers when it comes to organics. People love to buy organic products, but don't understand the process that needs to happen first. Perhaps more public education is needed.

Focus on waste management instead of waste avoidance is an extreme barrier to determining how much avoidable waste is actually in the organics waste stream. We should be focusing on where we can prevent the waste in the first place, not just diverting wholesome edible food to compost piles and digesters.

Lack of facilities at a cost that is affordable. Once again land application for biosolids.

Lack of public understanding related to benefits of and opportunities to support sustainable organics management.

Government regulation - Too much.

Public education about the benefits versus actual costs - Be truthful about the benefits and the costs associated with the process. Let the individuals recognize the benefits and chose whether or not to participate.

Large scale recycling/composting efforts often cannot happen close to their sources. Even if a recycling site has been in operation, new neighbors can now bring loss of property value lawsuits.

Organics field is not all-inclusive or supportive of each other - we can be our own worst enemies.

There's also the barrier of "perception versus reality". The reputations of organics management organizations (public and private) have been harmed by a few "bad actors" which sell the message that "anything can be composted." Unfortunately, "anything" cannot be composted in lightly-managed windrows located in near-urban areas in a profit-making timeline. The industry and government need to take a step back and contract what

we deem as acceptable feedstocks; and only after doing an acceptable job, should governments and industry be allowed to expand to more risky feedstocks.

Need greater awareness of the public's role as both a source of organic residuals and as consumers/users of these products.

Public misperception about the quality of recycled organic products, such as composts from manure, yard/food debris, biosolids is a barrier. Scientific consensus supports the quality and safety - fear-mongering based on unfounded perceptions (typically started at a NIMBY level) can prevent production and use of these local, sustainable, and environmentally beneficial products.

Mixed reaction by the public on the value of reducing our carbon footprint.

Air quality regulations in King, Snohomish, Pierce counties (PSCAA) area do not differentiate between the smaller agricultural based organics processing where they want to use their own compost and mulch & the larger organics processing operations that are producing and selling their compost. BACT too expensive for small to moderate size agricultural operations.

Barriers between normal smells and sounds of agriculture and the perception of general homeowners that any smell or equipment noise is perceived as nuisance.

See comments on regulatory processes in question 4 that prohibit use of new products without major investment in time and money to obtain government approval. This is an extreme barrier for small business with great ideas but limited resources. Well financed corporations with the money and staff to meet regulatory requirements dominate "new" product development as a result.

Lack of testing data related to pass through (i.e. effects) of foreign material such as drugs, metals, toxins, etc...

No comment.

There is presently no separation of refuse in Pacific County. We can barely afford a central recycling dump site which always seems to be a mess.

Available \$ for implementation and equipment. Competing alternatives for fuel and open dumping inhibit investment in organics technology.

Kittitas County rejection of Pacificlean based on pressure from a very few people to deny project.

Few seem to want a major residual treatment facility in their back yard. The only incentive for residual recycling right now is that warm feeling of having done the right thing.

Lack of government leading by example!

Air and water quality regulations are important safeguards for organic operations. Meeting the requirements may be a barrier to the particular organics facility, but the contamination that such facilities would create without regulations would be a greater barrier.

Odor control can be accomplished, it just may be an economic barrier.

We have a green space for garden, lawn waste. It is very hard and expensive to get rid of.

In honesty this is simply not a subject that I can say that I am highly informed about. I am intimately familiar with the arena that I operate in, but I really don't have to deal very much with issues like regulatory problems, operation of organics collection etc. I am a waste water treatment plant manager and as such have a professional interest so when an item comes into the news I read about it; odor control issues at composting sites, Northwest Biosolids Management Association (NBMA) emails about biosolids in the news, etc. I have no idea how contaminated the organics waste stream is and energy costs may be so low that recovering organics is not cost competitive, but that does not make it a good thing for energy to cost more. What I can say is that when I want to amend soil, I get biosolids (actually mixed yard waste and biosolids compost) from a local WWTP and I encourage others to do so as well. Of the handful of people that I have talked to about this, two families won't use biosolids due to concerns about contamination, several others are very satisfied customers. I have not studied where there is residual organics pick up and where the stuff gets composted so I don't know how far it is trucked.

Government mistrust is another barrier.

I've seen NIMBYism shut down two major projects in our community. People take a little bit of information, add fear, speculation and mistrust to the mix, then run wild spreading false and negative information which stirs up the community and eventually results in project termination.

Economic barriers are the most important, followed by difficulty working in the regulatory environment.

Businesses need to know what the rule are and have them constantly and fairly enforced. Rules change significantly any time staff changes. Regulatory system has no comprehension of the cost of time taking years to get a decision or process a permit is unacceptable. Should have a 60 day time frame to process permits. Much of the public opinion is generated by the process and the regulatory agencies themselves. We have reached a point of regulatory paralysis where agencies consider it a successful conclusion if they stall and delay long enough to where the proponent goes elsewhere. Here's an actual quote from the lead planner in a Western Washington county: "We need a total rebuilding of the philosophy within the regulatory agencies if we ever want to come close to achieving goals."

Programs are concentrated in populated West, while there is a lack of activity in the East and Central Areas. Promotion could be better around the state.

Transportation, Accessibility, Facility location (zoning and neighbor concerns).

In the greater Seattle area, odor impacts from organics recycling can affect thousands of people.

Methane gas and other biofuels may be produced from the process of organics recycling. These other energy products may make projects for economical that creating electricity.

I believe that the biggest barrier to successful biosolids recycling programs is rampant misinformation about the safety and benefits of using biosolids as a soil amendment. This is something that needs to be addressed in a very big and concerted fashion.

Plastics in finished compost is a big problem for the marketing of the product and for potential detrimental ecosystem effects.

Price of compost doesn't compete well with other agricultural amendments.

Other barriers: Education of consumers. There seems to be misconceptions about how curbside collected organics are handled.

Markets for compost- large stockpiles at sites indicate that demand isn't keeping up with supply. Agricultural land could be an outlet for the material, but the price would have to be subsidized or discounted. I have little knowledge about this but if parks were required to use commercial compost and quality was acceptable for DOT uses, this could potentially help.

Third party law suit barriers.

Need better education to all in benefit versus status quo.

It is all our ""waste"" and we all need to find regional ways to manage them in the most environmentally beneficial way.

Need better regulatory collaboration (currently contradictory) to meet common sense, reasonable goals.

Need more educated regulators that rely on science, not personal feelings or public influence.

I have not personally been associated with organics production on a large scale.

All regulators should be on the same page.

\$\$\$\$\$...it costs \$\$ to comply with air and water quality regulations, it costs \$\$ to market materials, it costs \$\$ to clean up contaminated feedstocks, it costs \$\$ to develop and refine new technologies. State and federal grants should be more equitably distributed to support the development of new technologies (including odor control), education and marketing.

All the incentives and regulatory matters aren't integrated and coordinated.

We really need to move toward one stop regulatory and incentive approaches.

Governments need to get better at cross agency coordination and decision-making.

Growth is continuous. We fail to incorporate these systems as requirements for new

growth. There is limited enforcement or pain to be avoided by bumbling along the way we do now.

The state has limited influence on all the stuff coming in. Banning toxic materials in toys made a huge difference and transformed that market. Why should we have toxics in anything?

Composting is one of the oldest forms of organic recycling and yet it is strongly regulated in Washington State on how the material that is generated can be used. For example, a livestock farmer (cattle producer) who has natural mortality in their herd each year can compost the carcasses without issue. However, they must use the compost on their property. They are not allowed to sell the compost as an income source to help sustain their farm. Many farmers are fine with using their own compost but some would like to offer to compost animals and other organic waste for neighbors then re-distribute the finished compost but can't due to regulations.

The issue of hauling distance and the 'relatively low' cost of fuel make the commercial use and production of products from organic material marginal at best. Facilities that are multiple use where organics and waste in particular could be sorted and processed are likely to be the best bet for commercial product development.

The only barrier not listed is public education about what organics are, how they can be recycled, and why it's important to recycle is one of the most extreme barriers I know about. If I polled the majority of my friends and neighbors most would likely give me a blank stare as the issue isn't in the public lexicon let alone a priority.

Major problem for my beneficial use facility was public misinformation spread by certain groups which clouded the actual benefits from my operation. I pump and maintain septic systems and land apply the septage.

Too many different agencies are involved with organics management without some common program and goals.

Stormwater managers don't understand how compost mitigates pollutants (adsorbs, converts to no-soluble form, breaks down) - they appear to believe that if a "contaminant" or nutrient is present in compost it is polluting runoff. These questions need to be examined scientifically.

The lack of available funding is a large barrier in our ability to provide these services to the public.

Too many government regulations without good scientific justification.

For me the most important barriers are regulation not based on scientific fact, and lack of government assistance financially.

Different agencies of government make it difficult to do business because of lack of consistency or personal opinion and not following regulation or science. Stop the use of local lands or use and makes beneficial use too expensive to be done.

NIMBY is a major problem and most of it is public perception not reality. Companies cannot educate because it appears we just have a financial gain and not a beneficial benefit to the lands or forest areas... This is huge and will stop the success because of political process and cost.

Fear and reluctance of agency personnel to support new innovations.
Research to evaluate appropriateness and efficacy of solutions.
Integration of organic management systems (for example biochar and composting to reduce odors and many other benefits).

NIMBYism is a HUGE problem. We need a media strategy to deal with this if you move out statewide. Contamination is always a problem in any stream. This will increase as more areas adopt the program. Especially if the programs in different areas, accept different items. People are confused and don't pay attention to latest/greatest updates.

"My work involves livestock manure and process waste water. There are several digesters co-located with the livestock operations but there issues that are associate:

- 1- Manure alone does not support digester operation so non-manure feedstock are brought in to boost power generation and maybe more importantly to producer, income from tipping fees collected
- 2- Digester process results in a more plant available form and if not carefully applied to crop land can result in over non-agronomic applications
- 3- Non-manure feed stocks tend to substantially increase nitrogen that will need to be applied in areas already impacted with nitrates in the drinking water (Whatcom and Yakima counties)"

The Department of Ecology is a barrier.

Regulatory agencies are not working together to promote the activity and minor public opposition (25 people) can eliminate projects that support 1 million people.

Education/awareness.

I believe that there should be far more emphasis on on-site composting to nearly eliminate the cost and impact of transporting these materials and to reduce the scale of composting operations and reduce the risk of adverse impacts. Can it be done? Absolutely. How do I know? - visit my website for a wide array of institutional compost systems, all of which are performing efficiently and at very high levels without stinking up the neighborhood. www.o2compost.com.

Also, public education is a significant barrier. People are fear based and hate change.

No comment.

Not enough planning dollars and information on siting and using anaerobic digestion.

"There are macro-economic barriers related to the market valuation of the environment. Capital markets are very poor systems to appropriately value natural resources. There are numerous examples, but degradation of soil and of ground water are certainly among them. Until there is a crisis, markets do not typically place an appropriate valuation of on natural resources. As a result, organic amendments that enhance soil resources are not properly valued. How can it be justified that soil erosion continues at the rates we see? Because short-term economic incentives justify it. How does that occur? Because markets simply don't have the mechanisms to value subtle changes in organic matter, the resultant resistance to erosion, or the contamination of ground water until there are shortages or crisis. So establishing a market value for an organic amendment product, whose value is in-part based upon the value of a natural resource, doesn't work well when the market does not have the mechanism to value the resource.

This country has accepted the false premise that free markets are efficient. That's nonsense with regard to natural resources. Markets actually encourage waste until the point of shortage or crisis. There is a requirement of scarcity before natural resources receive appropriate market value. Even then, it's questionable. Attempting to manage natural resources prior to the crisis point typically means that there is a need to oppose market forces. Commonly this is attained through regulation. Essentially saying, "No, by law you are not allowed to waste this resource", or, "No, you're not allowed to pollute this resource". In the long run of course, those conservation policies are good economics because good natural resource conservation IS good economics.

You ask for specifics. The short term market forces price compost and the application out of reach of many commercial growers. When commercial growers can pour on relatively cheap nitrogen fertilizers (on alfalfa for example) because hay prices are high, the market incentivizes ground water contamination. I've seen the soil test data in the Yakima Valley for example. The market says: if one unit of N addition is less than the value of hay produced, then put it on regardless if half or more of it leaches. Why? Because the return on that last unit of N more than compensates for its cost. That's the real economic equation the grower faces. Inputs versus return. And who is placing the valuation on the groundwater? Who is actually determining whether it leaches and who is responsible and forces the grower to incur the cost of that contamination? Nobody. The market has no real mechanism to value the groundwater. If it did, we wouldn't have the nitrate contamination of the lower Yakima Valley. It's the tragedy of the Commons really. The market needs to assess a fee commensurate with the cost of that alfalfa grower's pollution. What's the cost of the cleanup? To salmon? To drinking water? To the sport fisherman? To the recreationalist? We're not sure because the market doesn't have the mechanism to determine it and we don't put the money behind the infrastructure to measure it. So the barrier is that we need to value the soil resource and the ground water resource sufficiently that the cost of commercial fertilizers become relatively high, and improving soil tilth, reduction of nutrient leaching, and increasing water holding capacity is economical...prior to the crisis point.

Odor clearly gets the public attention. Solutions such as anaerobic digestion of food waste and incorporation of high carbon fly ash in composting to reduce odors should be encouraged.

Most organics recycling or recovery require energy recovery as heat to be economic. We should be ""taxing"" our low cost energy to pay for (or ""incentivize"") developing resource recovery through tax incentives for producers.

With energy relatively inexpensive, there is no real incentive to manage organics more effectively. If the argument could be stated and backed efficiently that organic waste management is 1) important for the environment; 2) profitable if done correctly; 3) good overall and in the long term; and 4) part of the overall scheme of responsible living (e.g., consult Patagonia's Common Threads program at www.patagonia.com), then the whole idea of organics management starts to make sense, and importantly, to make money (or to cost less money). The biggest barrier, thus, is not one that was named above, but our collective attitude toward the places we live. How do we expect to grow food on land that has been robbed of its organic matter, water-holding capacity, and soil structure? [Full disclosure: I am a Ph. D. Soil Scientist, but not working in soils or agronomy presently.]

Many of the barriers have to do with successful communication and proper locating of appropriate composting systems. It would also be helpful to maintain the reduced difficulty of participation by not limiting too much what organic material can be placed in bins (residential and commercial). Finally, finding some direct incentive to property owners nearby sited facilities would be a positive gain.

Washington State Department of Ecology, while seeking industry input, ended up with regulations that are far too tight and do more to insure department employment than it does stimulate organic use, especially in digesters.

Historically, people throw garbage (including organics) "away". They have not known, or cared, where their garbage has gone, but it is out of their house, and does not smell up the kitchen any more. Changing people's habits is extremely difficult, and without some type of incentive to change their behaviors, they will not change them. FREE is always a good word in the waste industry, and unfortunately, some people believe that if this organic material is valuable, they should not have to pay for collection. It's a dilemma.

Lack of readily available scientific data. For example: are prescription medications, personal care products and other molecules typically discharged to wastewater treatment facilities broken down in a heat generating compost process or do they remain relatively intact?

The question is stated as "barriers to greater success in organics management". Some of these barriers may be barriers to only one process, or more for one process than another. What is lacking is clear complete life cycle analysis of each / all technologies and some creative combinations. It is very difficult to make judgments about acceptance of one technology or another without accurate FULL LIFECYCLE analysis of the impacts.

Different regulatory frameworks for different residuals.

Incoming feedstock pricing is often influenced by the local garbage rate. This can be problematic in areas where the garbage tipping fee is lower than the actual cost of doing business for a compost facility.

Too many government entities with associated fees involved in everything we do.

The cost of closed loop recycling is too high relative to other methods.

Some farmers with which I work have stated that compost as a soil amendment is too costly when you combine expenses for purchase, hauling, and incorporation; and there may not be enough available at the few times when applications must be made by most growers based on weather conditions that affect field work.

A lack of research objectives that are attainable within a reasonable timeframe and federal commitments to provide necessary information.

Public at large has a lot of apathy about the environmental issue.

Lack of public information about the values of biosolid compost.

Some of these barriers are interconnected and should be considered together.

Compost facilities in the northwest corner of the state are very large and appear to be larger than the airshed can mitigate. Odors are a significant problem that isn't being addressed adequately. Maybe compost should be addressed in smaller, more local facilities.

Regulations aren't the problem. Facilities violating the regulations appear to be the problem. I do not believe the current regulatory structure is over burdensome.

The rush to get more into the compost stream is self-defeating. Contamination is a real issue. People don't know or understand what they can put into the collection bin for composting. There is no consistent message statewide. The state needs to get off the dime and help develop a consistent message.

We expect the "market" will hurdle barriers, yet, current organic business is not open to innovation and has little incentive to create higher values for climate, carbon, energy outcomes. Businesses have sowed up the market such that new ideas cannot compete with the relics of 1980's- 1990's development. This must change for real progress to occur. WA has leading teams of developers, researchers, scientists and engineers. We need clearly a support network of leading industrialists, and commercialists to come along and support the industry that can be built. However, the most persistent challenge we face is from local govt managers who give lip service to bringing new concepts to the market and consistently undercut the effort by not supporting it with real waste services designed to achieve the numerous potential good outcomes that can be had. Penny wise and pound foolish bean count management is taking a large toll to bring real change to the organics industry.

Current proposed EPA rule changes for the definition of "waters of the United States" is the most dangerous rule change seen in the past 20 years for the organics industry. This will have huge negative impacts on the end use of our products. It could shut the industry down, especially biosolids and manure products. Give them an inch and they take a mile.

Lack of resident awareness about the types of organic material that is accepted. There is a barrier among residents who only divert organic material such as grass clippings, and vegetable peelings and don't understand or refuse to add items like meat and dairy to their organics recycling container. The lack of consistency of what is accepted across areas inhibits wide spread outreach.

Additional barriers:

- 1) Limited types of technologies for processing food and other organics.
- 2) Cost of known technologies (AD).
- 3) Competition with landfills wanting organics for methane creation - which is not likely the highest and best use.

Unincorporated market areas like Snohomish without contracts pay high prices for collection of material and then pay for material at source. It is good that in Snohomish we have companies like Fruhling and Pacific Top Soils.

Some concerns have been raised about weed or grass seeds in Cedar Grove compost leading to problems. Bags sitting out or waiting to be used produce grass and this is a concern that the grass seed is not being killed off in the process.

Ever-changing market of compostable items leads to market use confusion and contamination. Clearer messages from companies like Cedar Grove and regular updates would be helpful.

Sort separation at the home level is cleaner, but generates only low interest. Co-mingling works a bit better as far as participation is concerned, but separation at a sorting table is next to impossible in cold climates. Everything is frozen together and separation is not possible. Collection and separation is a challenge with material generated in some industries and is not yet practicable (i.e. train and river boat industries).

Some government agencies, both municipal and county, compost product. The compost that they sell is in direct competition with private entities' material. This makes it increasingly difficult to market recycled organics and creates a large barrier in the system.

Regulations mean additional expense.

This is fairly complicated to answer in the short time I have available. I think one that might be missed in the lack of state investment in technology assistance to private compost and other organics management facilities. I think public funds should be available to private facilities to help finance advanced technology to address odor and contamination concerns. I also think it would be interesting to look at a means of providing financial subsidy to compost facilities/agriculture for the distribution of compost to agriculture. Overall the system is not managed as a system, but is made up of

many disjointed separate pieces that we then hope will somehow achieve our broader collective goals. But each piece has different drivers, motivations, etc. The private sector is not really providing a robust diverse mix of services and facilities that are necessary to wholly address statewide organics management.

I feel more well-versed in the consumer side of the equation. All of my not sure/no opinions may indicate total ignorance on my part, or it may indicate that it isn't a problem because I haven't heard much about it.

Lack of appropriately zoned land close in to large cities/towns.

The beneficial reuse of organic materials is a very complicated system. This requires multiple systems with many different process to succeed.

The main barrier in our City is the people because I believe that we need to create a different way to present the real benefits of biosolids as a soil amendment.

I do not understand - what kind of "public incentives"? To encourage people to set out cleaner organic material? Lower prices for green energy?

New ideas from the private sector bump against ignorance and suspicion.

Governor talks about reducing GHG and conserving water, but does nothing to support organics recovery and conversion (unless it's to make FUEL) that sequesters carbon, reduces water use and waste, builds soil, captures nutrients, makes energy and bedding substitutes.

Odors, contamination, and NIMBYism for composting are the result of 2-3 bad actors on the west side of the state. Though they are large facilities, I consider their problems minor barriers to the robust statewide array of composters.

The biggest barrier with regard to land clearing debris is that it is currently a lot easier and cheaper to just burn at the jobsite than to recycle it (either on-site or at a facility).

Organic material systems tend to smell when not well operated and neighbors do not want to put up with the potential for odors.

Development of cost effective organic waste management programs should not be based on government incentives. The business model of each project must make economic sense in the absence of government incentives. If it makes sense then the private investment should occur.

Transportation costs.

Population densities vs. scale/economic sweet spot of a given technology.

Lack of affordable electricity storage capacity/technology.

I think the biggest barrier is that few individuals or enterprises have the goals of the program as one of their priority goals. For example, I think it would be good if I put my household food waste into the compostables to be picked up along with my yard waste,

instead of throwing it into the garbage. However, it would mean I would have to store it in a container that I would put into the refrigerator and then have to remember to dump it into compostables each week, and then probably have to rinse/clean it. I would also have to take out the compostables container to the curb each week, even when I don't have yard waste. Even though this sounds like small time/effort, it is large compared with the quite small amount of food waste I have each week, and certainly pales in comparison with other household tasks (keeping up with garden/landscaping, housecleaning, laundry, paying bills, etc.). The same thing happens with enterprises and with many households, I think.

Regulations do not scale with facility size. For instance, a 20,000 ton per year facility has the same air permit requirements as a large facility. Smaller facilities have lower impacts and the regulations should take that into account.

The huge stockpiles of composted material in Western Washington at the facilities that are processing residential and commercial food waste that allow containers and service wear attest to the problems with end product contamination. Many farmers in Snohomish County will not even take this material for free anymore because of contamination. WSDOT, the largest user of compost in the state, will no longer purchase coarse compost from these producers due to contamination. Yard waste only composters continue to have good markets for their material and have not acquired these stockpiles. Contamination is a huge problem.

No one is being held accountable for contamination in organics but the compost producer.

I think government regulation could be streamlined. It doesn't make sense for projects to be regulated by multiple agencies who all request the same or similar information. This is the case, for example, for a dairy farm with an anaerobic digester that accepts off site organic waste.

Air quality regulations are an issue for anaerobic digesters who produce electricity from a generator set. It would be nice if regulators could look at projects as a whole and take into account the amount of greenhouse gas reductions when permitting/regulating digesters.

Politics and conservative attitudes toward environmental policies - even when the economic benefits to the citizens are provided. Garbage collectors, whether public or private, contracted or Washington Utilities and Transportation Commission operations - make their money from hauling. Organics hauling is not regulated, so any Jane or Joe can cut into a garbage hauler's revenue stream by skimming away organics collection accounts one business at a time. Because of garbage collectors' direct contractual relationships with cities and counties, they can exert direct pressure on local and state policies to discourage or minimize source separation programs and funding.

Regulatory processes and multi-jurisdictional overlaps prevent and discourage the private sector from actively pursuing investment opportunities related to organics management. That plus the over-riding issues of NIMBY will continue to prevent localized successes and thus maintain costs associated with organics management. Energy production from

organics processing requires substantial investments against use of more conventional resources and reductions in expenses by simple efficiency improvements.

Culture is a large barrier - a significant number of ideas to implement are not easy and our culture needs easy if we want to make things happen in the majority of the population.

Government regulation biggest barrier. You touched on them above in separate lines.

We could, with sponsorship of the State make a huge impact. We need to have Economic Development Grants just to publicize the finest quality products we produce. We need media attention. We need representation. We need some larger scale equipment that could be purchased so that we could make even higher value products from waste diversion. We have created demand and designed products all self-financed.

We are contributing to the greater good, not only by waste diversion, but by soil quality enhancement and carbon sequestration. Additionally, our products are excellent for remediation and filtration and reduction of the toxic loads in ground water, stormwater, and in situ landfill contaminants. But, if we could be sponsored or supported by Washington State to take our knowledge and have help in financing some additional equipment we could do this on a very large scale, and we could contribute to the economic development of the State in ways that have been overlooked. We would be a net exporter of our industrial waste and we would contribute a large amount of reduction in the toxic sites in our State and elsewhere.

Moreover, we know the technology, which could be replicated to expand this, over a several State area greatly increasing our capacity and the State's revenues.

Appendix F. Research questions that survey respondents would like answered

Respondents were asked to identify up to three research questions that they would like answered (Question 13, Appendix B). Responses were then categorized, and these results are discussed within Chapter 1 and in Appendix D. This appendix includes all responses in their entirety. Some minor corrections in spelling or grammar have been made to aid clarity.

Successfully showcase how organics management can be a win-win for agricultural operators, public and economy.

Compost and other organics benefits to both conventional and organic or sustainable farm systems.

What are the demands from the agricultural soils market that could be met by the organics industry--the forms and quantities of nutrients and microbiology needed for crops?

Successful incentives for landowners and agricultural producers.

Impact of price supports for agricultural users of compost on market development.

Compost use in low or no till direct seed applications; economic and soil quality analysis (dryland).

We need research on how to finance the use of organic materials such as compost in the agricultural sector.

More documentation of benefits to agriculture, both economic and other.

Economic cost/benefit analysis for using compost on farms. What is the price farmers could afford, while staying profitable? Would that price point also work for composters?

Comparison of benefits to agriculture (conventional vs. organic).

Economic agricultural application rates of compost for improving soil health over time.

Compost use in cover crop applications; economic and soil health analysis (dryland and irrigated).

Increases in plant available water (in table form) by organic amendment, soil texture, and crop. The return on investment needs to be calculated.

Increased production of biochar and heat.

Can source material contamination, such as heavy metals be successfully immobilized in pyrolyzed products, such as biochar?

Use of combustion residues - high carbon wood ash and carbonized urban wood waste – in stormwater and remediation applications.

Biochar engineered for agricultural use benefits need better documentation. Some poor research has been done.

Methods for making and uses for biochar.

Biochar benefits for odor management, compost quality, and field cropping systems outcomes of biochar admixed composts.

How do we get a large scale (mobile?) pyrolysis pilot project (primarily for biochar) implemented (so we have TONS of char to apply to fields and compost piles)?

Are there economically viable pyrolysis technologies which produce acceptably low levels of particulate matter nano-particles?

How can we make pyrolysis into a working technology?

Can methane be used to create biodiesel?

Improving the affordability of biogas purification technology.

What can we do to develop community-scale anaerobic digesters to process waste, produce compost and produce energy?

What portion of energy from landfilled organics is captured as opposed to anaerobic digested organics?

By what percentage are anaerobic digesters more efficient in producing green energy and capturing greenhouse gases than bio reactors in landfills?

What organic materials can be mixed in anaerobic digestion?

We need to develop more effective/less costly processes for concentrating nutrients from anaerobic digesters.

Why do engineers say digesters are not profitable in waste water treatment plants under 5 million gallons per day?

Implement a working anaerobic digester-to-energy front end with composting of solid residuals in Washington, as a model.

Benefits of anaerobic digestion followed by composting

Develop lower tech/lower costs high solids (post-consumer food waste) digestion technologies.

Build out and test a biorefinery concept facility, or modify processes at several compost facilities to evaluate individual additional process system such as anaerobic digestion, nut recovery, combined heat and power, compressed natural gas/renewable natural gas, and biochar.

Carbon and energy LCA benefits for a combined system biorefinery.

Working together across organics categories to find solutions.

Improving technology so a variety of feedstocks can be handled at the same time in a non-sterile environment.

Nutrient and metals reduction or release of actual installed bioretention facilities.

Bioretention systems- LCA of benefits, quantifiable guidance on feedstocks

Why is incineration of biosolids a bad option?

For communities that refuse to allow application of municipal biosolids in their regions, where do they want their OWN biosolids (that they themselves are generating) to be applied?

Class A Biosolids facilities in Washington State - successes and failures. What worked and what didn't and why?

When will private businesses become interested in free biosolids and how to access them?

How can animal feeding operation and confined animal feeding operation manure application be monitored more effectively to ENSURE that manure is applied at agronomic rates and during the right time of the growing season?

Research and publicize nutrient mass balances in confined animal feeding operations.

Need to develop drainage systems for agriculture that filter out the nutrients before water discharges into streams and rivers.

How can animal feeding operation and confined animal feeding operation manures be better managed and tracked to reduce threats to human health and environment?

Improving water quality in industrial milk production operations.

Effective and wide-spread manure management.

Carbon sequestration.

Ecosystem benefits per ton of carbon returned to the soil, i.e. constructed peat bogs or wetlands.

Pros and cons of including manufactured "compostables" in organics collection programs.

Compostable materials need to break down much faster, they are impacting compost markets.

Consistent standards for compostable materials.

Better retention of nutrients in finished compost.

Differences in organics processing Western Washington climate versus Eastern Washington climate.

Is there a model for alternatives to composting that doesn't rely on a tipping fee for financial success?

Identify optimum formulas/systems for composting food waste (managing acidity, optimum temps, etc.).

What type of education, materials or signage would help people keep contaminants out of organics?

Will accepting only compostable products clearly identified with a unified symbol lower or remove contamination from compost?

Simplified methods for source separation of wastes that homeowners will implement.

More conversations on contaminants and how to effectively change this.

Have there been any thoughts to impose financial penalties on generators for contamination?

What type of pre-processing and/or screening would be necessary to get a clean, marketable material?

Sort separation.

We need to clearly understand how to effectively remove contaminants at the facilities themselves and provide the funding to implement those technologies.

What do we need to do to get contamination out of organics at the source (not after it's gone through the composting process)?

Has there been any thought to show the public what they are contributing to when they don't pay attention to what they put in the organics recycling receptacle/bin? What about a video to be produced for local television showing the impact of negligence?

What are the best management practices to reduce contamination in compost and create stable end markets?

Preventing mad cow disease.

Could we restrict packaging to recyclable or compostables that would reduce separation requirements?

Could we ban non-recyclable plastics?

How do we make sure that pharmaceuticals and other chemicals that are used in commercial dairy, meat, and egg industries do not persist through nutrient management and adversely affect human health and environment?

Personal care products, and pharmaceutical products – are they a risk for biosolids?

Pharmaceuticals.

Eliminating the use of clopyralids in agriculture would be helpful.

Effect of heat composting on breakdown of pharmaceuticals and other personal care products.

Fate of organic contaminants in the environment following beneficial use/land application.

Options for organics management for rural communities where the transportation costs exceed the value of feedstocks or end product.

How can smaller scale composting operations better comply with regulations that seem to be intended for very large scale operations?

How to advance more close-to-source management - on-site, smaller scale facilities?

Small scale production of class "A" biosolids that is affordable.

Technical hurdles and cost of small onsite digesters for small organics business users. I'd like to see more small digesters across the state.

Small scale modular affordable anaerobic digestion.

Cost reduction in small scale/micro scale localized organics management systems (mini digesters).

Develop public support for local solutions; hauling organics hundreds of miles in not the answer.

Best application of onsite technologies (for large organics generators).

Funding for collection and processing of organics in small rural communities.

Scaling biogas technology so it is not always a go big proposition.

Cost reduction in small scale/micro scale combined heat and power systems that could tie into mini digesters.

What is the public or ecosystem subsidy necessary to incentivize organics recovery at different scales?

Focus on neighborhood scale integrated approaches.

Have the state sponsor some demonstration projects for local community-based organics management.

Are small scale composters and digesters feasible in urban settings?

How can we make green energy affordable without subsidies or new taxes?

Economic analysis of impact of grant funding on the entire infrastructure - i.e. what are long term impacts of various types of funding? What are the financial implications of processing with various size / technology / types of waste stream?

Willingness to pay for a more sustainable system.

How to decide whether a particular type of organic has greater value as energy source or as recycled material.

"Bioreactors" are similar are similar to incinerators: Once the investment is made, to make economic sense, you must continue to feed them, but do they make long term environmental sense?

Industry collection development.

Concentrate nutrient sources for economical transport.

Improve understanding of benefits/costs of large centralized facilities vs. smaller decentralized facilities.

Whether total costs to society are greater when sorting of organics occurs at the generation point or at a central management point.

How can we encourage more competition so there are more processor options to choose from?

Economically feasible options for transporting organic waste out of Western Washington into Central Washington.

Transportation and organics density mapping.

Development of creative logistics – we will always have the need to move materials around.

Research that helps us get over the transportation issue - nutrients and OM return to the food production systems (land) outside of urban areas.

Price impact on commercial fertilizer were there a carbon tax.

Why hitch the wagon to a carbon tax concept? This should be the frosting on the cake. Failure is assured if new technology requires a public subsidy for success.

Public benefit of subsidies vs. the effect of additional fees on economic productivity (carbon tax).

Effect of carbon market on business.

What combination of government/private industry will it take to turn organic wastes into resources (energy, nutrients, products), and distribute them to the places that will use them.

What incentives do business and industry need to up-cycle organic waste streams?

Reduce taxes.

Consider a progress landfill tax like the UK uses to help build organics diversion facilities.

What are the emerging options in the latest carbon management policy announce by President Obama and to be regulated by the Environmental Protection Agency?

West coast-wide cooperation on laws, regulations and incentives promoting sustainable development and combatting climate change

Washington has a lofty goal as part of the new carbon policy. How can Washington lead the nation in showing how carbon emissions can be reduced?

Financing for those of us who would make a significant contributions to all of the goals outlined.

Where are the funding sources?

Funding sources available.

Funding pre-commercial development of proven technologies and products.

How can we expose the lie that carbon dioxide is a pollutant?

What about greenhouse credits for landfill bioreactor? Encourage though use of reduction of post-closure time period.

What is the role of modern high-tech incineration?

More research/involvement on economics/value of organics in ecosystem recovery and greenhouse gas mitigation.

A comparison of GHG emissions from garbage can to landfill entombment versus composting with anaerobic digestion.

Perform full lifecycle analysis of all impacts of each technology and organic waste stream.

What are the highest and best uses for organics - a organics management hierarchy with a life cycle look?

Why is there not clearer public data on the life-cycle costs of AD systems?

Carbon footprint of the organic management value chain - right now relies on a lot of fossil fuel input.

What is the most preferable organics management solution on a lifecycle basis (Pete Pasterz is doing some of this research for Oregon DEQ)?

Identify the most effective and appropriate technologies for each type of organic waste stream.

Whole life cost of publicly subsidized processes.

Comparative economic and greenhouse gas emissions benefits of reducing organics generation in the first place rather than consuming resources to process it.

Evaluation of the infrastructure existing compared with different models of infrastructure for Washington - should we have lots of small facilities, everyone home compost, several huge facilities, what type of diversity of facilities best accomplishes the goal of maximum environmental, economic and societal sustainability, etc.

Comparing and contrasting existing organics management systems and comparing contamination rates, processes, and economic viability. It seems like every city/county is doing something a little bit different and experiencing varying levels of success. It would be great to compare them all in one document.

Are there ways to use organics materials productively with minimal processing?

How to market establishing a new location to neighborhood.

NIMBYism is killing us.

Overcoming NIMBYism.

How to create fair and effective odor standards.

Control of production odors.

Odor.

Possible impact of odor issues.

Odor issues may help overcome NIMBYism.

Odors seems to be a driving force in keeping organics management on the hot seat. How do we solve these odor issues?

Odor issues.

We need to clearly understand factors related to odors and the technology/etc. necessary to control them. Odor issues are killing potential.

Develop and implement cost effective, simple to operate and effective odor management processes.

Is there a critical threshold (volume) of material above which a compost facility cannot expect normal odors to remain on site, i.e. dispersal to the greater airshed is inevitable?

Effects of odors associated with organics processing.

Need to develop better methods for odor control from composting facilities.

Odors are less significant in heat dried class A biosolids if digested prior to drying. How can the odors be reduced more?

Generic odor modelling for different scale facilities at 20,50,100,250 ton per annum scales.

What is the percentage of each sector of organic generator to the total generated?

More information on use of products, in order to close the loop.

Need market development to encourage purchase and use of products.

Blended products, e.g. topsoil blends.

Maintaining consistency of product.

Applied demonstrations of use of recycled organics.

Using organics to solve environmental challenges.

What are effective marketing plans for organic products derived from waste streams?

How do we convince local government that more isn't necessarily better? That quality is far more important than quantity.

Some enhanced benefit for specification of use of the products of the quality we produce as best management, and certification by WSDOT and Ecology for use of products and incentives to utilize them.

The development of weed and pest control materials from organics.

Cost per ton of finished products.

Why is the cost of recycled materials still so high and the price for recycling materials so low?

Economic analysis of the use of recycled organic material.

What is the realistic availability of organics at local, state and regional levels to support commercialization?

Comparison of costs of commercial fertilizer (with C tax) and equivalent fertilizer made from local organics waste streams.

Media coverage for those of us doing the work, and showing it works.

Educating public on process, location, benefits etc. to promote advancement of these types of businesses, whether public or private.

How is research information of organics management provided to the general public to gain support?

Why don't we educate the public/elected officials more?

Opportunities for public participation.

Regulations associated with sending green yard waste for fuel in hog fuel boilers? Is this legal?

Find ways to make the regulatory system function.

Rigid regulation for air and water even when [facilities are] located on good sites.

Cost of permits and permitting time frames for new organic facilities.

Required monitoring.

Improving regulatory processes.

Develop a regulatory system that the average farmer could understand and navigate.

Why do we need so damn many regulations?

Regulatory issues and consistency and response to needs, permits, update or upgrades etc.

Soil quality (living biology and fertility) and nutrient density of food compared to the health of the plant, animal, ecosystem and humans.

The forest soils are being mined and will soon be unable to grow the trees desired. Using the Base Cation Saturation Ratio (not SLAN), re-mineralize Washington soils while studying the living systems with biochar from forest waste.

Valuation of soil benefits.

Soil mineral balancing and its relationship to food, forest, and range land nutrient density. Ban herbicides from forests. Find alternatives as ecosystem is collapsing in disease.

Soil enhancement beyond fertility - moisture retention, structure.

Support for waste reduction and recycling prior to composting.

How can a system of accountability be created so that trash doesn't go to compost sites in the first place?

Policy which encourages hierarchy - PAY AS YOU THROW.

How much edible or preventable food waste is currently in the Washington waste stream and how does that compare with inedible food and agricultural waste (bones, peels, scraps) in the state?

Appendix G. Questions for post-survey follow up interviews

1. Respondents to our survey suggested that improved soil quality and structure was one of the most important benefits being gained by current management of organics in Washington. Can you elaborate on this? Specifically,
 - a. What evidence is there that we are currently achieving soil quality and structure?
 - b. What product qualities are desirable?
 - c. Are there important needs in terms of ongoing research into product development or in other technical areas?
2. Our survey found conflicting results around product quality. On the one hand respondents said that the current system makes high quality products. On the other they said that contamination is a barrier and that if we solved the contamination issue (whether chemicals or plastics or undigested compostable plastics) we would realize big benefits. Is this issue something that technology research and development can do something about? If so, what research is most likely to make a difference?
3. Many survey respondents noted that scale and transportation (of wastes and products) were important issues in organics management.
 - a. The survey found support both for distributed facilities to manage residuals closer to the source, and for centralized facilities. In your opinion, should we be aiming for more centralized facilities (near either generation, or near end use), or more distributed facilities? Why do you feel this way?
 - b. Are scale and transportation something that technology research and development could provide some insight into? If so, what research is most likely to make a difference?
4. There's some indication in the survey that we may be achieving less success in managing organic wastes in rural areas, compared to those in more urban areas.
 - a. That intuitively indicates that it would be important to invest effort to help them catch up. Is this wishful thinking, or is it something that should now be a priority?
 - b. Are there technical barriers that have contributed to rural areas achieving less success? If so, what?
 - c. One persistent challenge that was noted in the survey responses was that economics do not allow for widespread use of compost in agricultural operations. Is this something that academic research and development could do something about? If so, what?
5. As part of the survey, we asked people to tell us what research questions they would like answered. When we grouped these questions, certain patterns emerged. Can you look at this grouped list, and reflect on which of these areas would be most impactful to answer (in terms of furthering organics management in WA State)? Why do you feel this way?

HIGHEST COMBINED MENTIONS (>12)

- 17 combined mentions - Research needs about contamination, including chemical contamination and the fate of organic contaminants in the soil

- 16 combined mentions - Research needs about the scale of technology and possible benefits of distributed or decentralized processing closer to the source
- 15 combined mentions - Research needs about recycled organic products, including product economics, market research and development, and the development of advanced products for specialized applications
- 14 combined mentions - Research needs about economic issues, with special focus on the cost of transporting raw feedstocks and finished products
- 14 combined mentions - Research needs about odors, including odor testing and standards and their impact on neighbors
- 13 combined mentions - Research needs about the benefits of and the potential for using compost and other recycled organics in agriculture

MEDIUM COMBINED MENTIONS (8-12)

- 12 combined mentions - Research needs about life-cycle assessments, including LCA comparisons of processing methods and technologies, as well as LCA comparisons of different recovery strategies
- 11 combined mentions – Research about taxes, including carbon taxes, incentives and other policy-related issues
- 9 combined mentions - Research needs about pyrolysis and biochar
- 9 combined mentions - Research needs about regulatory issues, including making improvements to the regulatory system and practice
- 8 combined mentions - Research needs about issues related to anaerobic digestion, including co-digestion, biogas utilization and nutrients

Appendix H. Results from follow-up interviews

As analysis of the survey results progressed, the team carried out follow-up interviews with a few key individuals representing a range of interests and involvement in organics management. This was done to probe at some of the questions raised by the survey results, and provide additional qualitative information. Additional information on methodology is provided in Chapter 1. Full results are summarized below, with highlights in Chapter 1.

Improved soil quality and structure

Survey respondents generally suggested that improved soil quality and structure was one of the most important benefits being gained by current management of organics in Washington. We asked the post-survey interview group what evidence supports the idea that we are currently achieving soil quality and structure.

Interviewees pointed to research showing that compost improves soil quality from WSU and WSU Extension, Soils for Salmon, WSDOT and the Western Washington Stormwater Manual. There have also been efforts to get this message out to the public and to professionals (see: www.buildingsoil.com). One interviewee described compost use in soil trials by WSU Snohomish County Extension, in which upwards of 80% of the participants the trials report improved soil quality. More specifically, analyses show increased soil organic matter and plant available nitrogen from compost additions. Other observations include improved tilth and workability and increased water retention. Another person felt the survey respondents may be reflecting on multiple improvements, including improvements in microbial activity, water retention, and soil organic matter.

One interviewee wrote that our survey results may reflect a general trend in knowledge that compost use is known to provide soil quality improvements on a site basis more than any proof that we have achieved soil structure or quality improvements on a regional or statewide basis. “The more organics use – especially on agricultural soils – becomes commonplace and talked about, the more realization [there is] of how depleted our soils have become, the more compost and organics will be used.”

Another noted that as the acreage of organic and natural production systems has increased, so has demand for valuable and unique inputs. (note: around Prosser, National Fert Co/Simplot has a separate dry shed just for organic fertilizer inputs).

We also asked the interviewees about what needs they see for ongoing research into product development. Research topics mentioned by interviewees included (in no particular order):

- What amount of organics would be needed to attain various levels of soil quality in various applications?
- Compost leachate – What are range of components and characteristics based on feedstocks? Process? Is there a better use than waste water treatment plants? Research is needed to develop standard land application practices for certain crops, soil types, seasons, etc.

- Agricultural use – How to produce compost at a cost that farmers will accept? Does it need to be subsidized to protect soil quality? Is there a cheaper method of producing the product? Should production be subsidized as environmental protection of land, air, and carbon benefits, etc. compared to landfilling?
- Stormwater low impact development use – Develop specifications to encourage development of blends that will behave as desired rather than limits on feedstocks.
- Research into microbiologic population dynamics during composting, curing, and application, especially as it relates to plant pathogen reduction and nutrient optimization. What methods / feedstocks can be used to develop a compost with high pathogen reduction qualities for particular pathogens for particular crops?
- Research into biochar and compost blends
- Investigate beliefs that transporting organics spreads disease and pathogens.
- Research that supports reduction of regulatory hurdles that discourage business investment, suppress prices, and create obstacles to local solutions (e.g., flat bans on outdoor furnaces that could produce biochar, heat and energy; and bans on industrial hemp that would encourage the agricultural economy, soil improvement, income streams, and feedstocks for biochar and mulch).
- Compost leachability, specifically phosphorus.
- Research different soil types for various compost applications; organic growers especially need this data. Then look at moisture holding capacity.
- Much of the research on compost use and improvements is from the urban horticulture world; more research dollars for agriculturally-related work would be good.

Product quality and contamination

The survey results contained what might be interpreted as conflicting indications around the issue of product quality. On the one hand respondents said that the current system makes high quality products. On the other they said that contamination is a barrier and that if we solved the contamination issue (whether chemicals or plastics or undigested compostable plastics) we would realize big benefits.

Our post-survey interview subjects said these results were not inconsistent, arguing that compost is of excellent quality IF it is processed and screened to remove contaminants. These apparent conflicting results appear consistent with findings from a survey of Snohomish County farmers using compost, carried out in June 2014 by WSU – Snohomish Extension. In that survey, 93% of the 44 farmers who responded said the compost was high quality, but around 9 mentioned that there were plastics in the compost and 15 selected "Reduce plastic contamination in finished compost " when asked how composters could help address challenges farmers have to using compost.

Another interviewee pointed out that the system is creating multiple types of compost, only some of which have contamination issues. For example, composts from feedstocks without food wastes (e.g. agricultural manure composts) tend to have lower contamination, while other composts that include food waste feedstocks are screened to a

very small size. On the other hand, for composts derived from municipal solid wastes, several interviewees said the contamination issue is quite real.

More than one interviewee felt the current emphasis on downstream treatments (expensive new equipment and triple screening) may be insufficient. Several felt that resources would be better spent upstream by keeping contaminants out of the organic material in the first place. Specific strategies mentioned included more education and training for voluntary compliance on the front end, rejecting unsatisfactory loads at the processing plant, requiring drivers to clean loads, and using other technologies to process food waste streams, separate from or before composting. Said one interviewee, "I don't believe that technology research and development is going to have much effect on keeping the contaminants out of the organics."

For research initiatives to address this issue, one interviewee thought that an economic analysis of potential new contamination reduction protocols could be implemented and funded would be useful. "A couple of examples of contamination reduction procedures that are cost prohibitive include cart screening and tagging before the waste is picked up. This has proved successful, but having the staff and time to check individual carts at residential or commercial facilities is expensive. Perhaps a study could evaluate whether a fine imposed on contaminated carts could potentially pay for the extra staff time needed to check carts. Also on the compost facility side, pick lines with workers physically removing contamination from feedstock before materials are ground has proven effective, but composters say this is too expensive to employ all of the time. On the flip side, some composters are paying hundreds of thousands of dollars for high-tech screening equipment for finished compost and "overs". I'd be curious if the effectiveness of each of these practices and subsequent costs (and gains) could be compared against each other."

Because contamination is a serious issue, not only about physical contaminants, but also about persistent chemistries, one important research topic would be about chemical contaminants (or disease contaminants), that is, what are the acceptable background levels, compare and contrast natural occurrences with that added by recycled organic products.

Economics of agricultural use of compost

Agricultural use of compost also came up in the survey results a number of times, both as a challenge in that economics do not allow for widespread use of compost in agricultural operations, and as a key opportunity that might improve organics management in Washington. We thus asked interviewees to reflect on whether this was something that academic research and development could do something about.

The following research topics were specifically mentioned:

- Research showing the costs and benefits of moving urban organics back to rural agricultural production. This could include valuations of the improvements to soil quality and moisture retention, as well as other factors.
- Research into possible policies and price supports that might support wider use. Possible specific approaches that could be investigated include (but are not

limited to) clarifying what price supports already exist for farmers or for chemical fertilizers and how might they be applied to organics, and investigations of whether the solid waste tax could be used to subsidize the use of compost on farms.

- A multi-year compost trial and significant work to evaluate the nutrient release of compost over the short term and long term. This work could build upon (and coordinate with) existing research trials being carried out by WSU Snohomish County Extension.
- Trials specifically examining the nutrient implications of fall compost applications, including questions about nutrient needs, use of cover crops, and whether compost positively or negatively impacts existing concerns about water quality and nutrient leaching.
- Research examining the impacts of compost application on pesticides and fungicide practices.
- Research on compost teas, which have the potential to be incorporated into irrigation systems, potentially at a lower cost (though also potentially with smaller benefits) than compost.

Processing scale and transportation of wastes and products

Another topic of interest that emerged in the survey was about the scale of processing and the transportation of wastes and products. The survey data showed support both for distributed facilities to manage residuals closer to the source and for centralized facilities. In the post-survey interview, we asked “In your opinion, should we be aiming for more centralized facilities (near either generation, or near end use), or more distributed facilities?”

Several people indicated that they think both are important. An Eastside interviewee said we need both. “Promote the unique, synergistic combinations of waste and resource availability with local needs, e.g., the Othello-based, Perfect Blend Fertilizer with a poultry manure operation a short distance away.” Meanwhile, a Westside interviewee said we should be aiming for “a blend of big and small, centralized and distributed, and of various technologies....That seems strongest, most resilient.”

Not all interviewees agreed, however. “I always opt in favor of decentralization where possible,” said one interviewee. Reasons for this included a lower carbon footprint; more direct community engagement, support, and ownership; and enhanced resilience of the system as a whole (if a large, centralized facility has to shut down, a large number of communities are impacted – whereas closure of a small facility is problematic but only for a few communities and a neighboring facility might be able to pick up the slack). “Redundancy in the system is better than all eggs in one basket.”

Interviewees also mentioned several more specific issues related to scale and complexity. One interviewee said distribution needs to be closer to agricultural end users. Farm access to compost is hindered by the centralized location of the resource and the resulting transportation costs. Additionally, composters face significant challenges in

transportation in trucking the materials to the farms when they need it (usually during a small 2 month or so window of time in the spring).

Additionally, an interviewee discussed the need to figure out how to have larger-scale urban compost facilities in urban, industrial areas that are fully enclosed, perhaps combined with smaller-scale urban anaerobic digesters. This might necessitate collection systems that separate food scraps from coarser yard debris to achieve higher level best use.

We also asked interviewees whether scale and transportation were topics that technology research and development could provide some insight into (and if so, what areas would be most likely to make a difference). While some respondents felt that there was likely little that technology research could do, others mentioned:

- Research odor issues: seafood, fish offal, poultry manure, agricultural wastes.
- Research distribution systems, such as the possibility of satellite sites where finished compost would be stockpiled on a farm or other decentralized site.
- Perform full / large system boundary life cycle analyses of combined organics processing options such as composting, AD-composting, biochar-AD-composting – looking at all aspects, including the environmental, economic, resource, and social.
- Tools and technology to improve handling, transporting and processing.

Success in rural compared to urban areas

Some of the comments received from the survey suggested that Washington may be achieving less success in managing organic wastes in rural areas, compared to more urban areas. To follow up on this, we proposed to interviewees during in depth interviews if true, this conclusion would intuitively indicate that effort should be invested to help them catch up. We then asked interviewees whether they thought this was wishful thinking, or whether it was something that should now be a priority.

Several interviewees indicated that there are reasons to think that rural areas may not actually be significantly less successful – or at least that this conclusion would be premature. Among the reasons cited are that rural areas have a variety of ways of handling organic materials without resorting to landfills. Another noted that many people in rural areas process with their own organic waste. Still another noted that given the number of differences, it would be important to give this question some attention, though there may be existing research or information that could contribute to an answer. “The questions remain: if rural areas are less served for management of organics – are they less served with availability of compost or other soil amendments? And are the quantities of organics available for ‘management’ worth worrying about – i.e. are they less or more than more urban areas per square foot? Are rural areas a problem or an opportunity for both collection and sales / application?”

Several interviewees also noted potential technical barriers that could be contributing to rural areas achieving less success:

- The amount of money available per capita,

- The cost, given the availability of land for cheaper land-disposal options,
- Restrictions within agencies, and
- A lack of creativity as much as economics.

Appendix I. Comments about gaps in organics management

Survey respondents were allowed the opportunity to provide additional information and comments about a series of questions focusing on how far Washington is from achieving a series of goals; Questions 2-5, Appendix B). These comments are reproduced in their entirety below. Minor corrections in spelling or grammar have been made to aid clarity.

Comments related to Q2: In your opinion, how far is Washington from achieving this goal: "A sufficient network of businesses thrives on collecting and processing residual organic materials into beneficial products."

Sufficient means there are significant levels of competition by businesses for feedstocks and finished products.

More information needs to be given to the general public about benefits

Sufficiency varies substantially by region across the state. And sufficient for me does not mean capturing 'all ' (or perhaps nearly all) residual organics...it means collecting/processing reasonably available/separable organic materials.

In Asotin County we have to haul Bio-Solids to a Compost facility in Lewiston Id. at a Cost of 500.00 per Truck load. And it must only be 12 to 15 % Solids the rest is water that we are paying to dispose of it for beneficial use. Yet Clearwater Tech or Roto Rooter can haul septic bio-solids and land apply. How is the possible all Bio-solids should be going on farmland.

If by "sufficient network" you mean qualified, regulated companies which legally participate in a managed system, we're doing well.

Need more combined yard waste & food waste composting.

We have been asked to participate in this survey although we are in British Columbia, Canada and so are not participants in Washington other than the Roosevelt Landfill is taking some of our biosolids

Most is sent to non-agricultural and non-beneficial sites

Not sure if I believe we are half way but we are way ahead of many other states.

I'm sure this works well in the urban areas, but very few programs in rural Western or Eastern WA.

The City of Moses Lake has a network of businesses that collect, haul, and process our organic and recyclable materials. This divert roughly 50% of our collected waste material to other locations than the landfill.

The regulatory system just cannot function in a timely and constant manner needed for businesses to thrive

East and Central Areas of Washington have transportation logistics to overcome.

Based on City of Seattle collection of organics and availability of compost from organics processing. Other parts of Washington? Other organic streams?

Community must be willing to invest in the management - not cost effective.

I see areas of the state where we are essentially at this goal and other areas where there is still a ways to go.

For commercial food and yard waste compost- stockpiles at compost sites indicate that the demand for compost isn't meeting the supply. Compost use in agriculture could be vastly expanded. I believe a large contributor to this is plastics in the compost which shows a need for education and enforcement for the purpose of collecting clean materials at the curb.

Puget Sound area is further developed than other parts of the state.

Agency action or inactions are inhibiting this process.

A big part of achieving this goal is having state and local government recognize that it should be achieved.

Achieved in pockets, but far from ubiquitous. Little progress on moving toward universal compostable, recyclable materials

City and county managers of green waste have other priorities.

The east side of the mountain is far ahead of this side, we are too politically correct.

System falls apart in remote/rural areas.

I think I'm being generous saying 1/2 way.

We need more facilities statewide to achieve this goal.

I see "pockets" of progress across the state but very hard to qualify. I think it would be helpful to target watersheds impacted by too much volume of organic materials that can be a utilized in other areas in a beneficial manner, such as Whatcom County.

There is a conflict of interest at the State (and therefore the County) level regarding 1) regulating organic wastes and 2) promoting the recycling of these materials.

Appears there is not much diversity in collecting or processing.

Organic waste is not fully being utilized for energy recovery prior to composting. More dry anaerobic Digesters should be used at Composting facilities. One energy produced in with this technology is more efficient than the use of capturing energy from landfills, and is better for the environment by trapping greenhouse gases.

We have developed a considerable infrastructure, but still landfill substantial amounts of organic material

Important infrastructure has been developed. More can be done to use the infrastructure and branch out from just compost and some biosolids use.

This is a great idea, and I am one to help lead these efforts, but WA has a long way to go before residual organics and beneficial products are synonymous.

Commercial organics and multifamily organics are still disposed. Many single family households do not have organics services across the state.

The market for finished compost is weak, and there is a mountain of finished compost sitting on the West Side of the state.

Organics end up west of the Cascades - The material needs to end up east of the Cascades. We are short organics management facilities in agricultural lands. The network is incomplete.

I think there is still a ton of work to be done on this, as many communities have little infrastructure or are severely underserved by their processing capacity. Additionally, end-use markets need major growth before the processing market grows.

Further along in Western Washington than Eastern.

Facilities in rural areas need help getting permits, etc. Most do not have but operate anyway.

We have the collection side pretty well down. Residents and businesses are participating. However, it seems like collection has outstripped capacity in the west side of the state, and governments are looking to truck their compostable materials to central/eastern Washington. There also are growing concerns about human caused contamination of compostables, primarily through residential and commercial food waste collection

Composting is a first stage industry. It needs a substantial technical / capacity improvement to achieve anywhere near the capability it can represent for creating business and beneficial products. We have several co-digestion AD projects, but no commercial municipal organics AD. We don't have nutrient recovery for municipal

organics, or CHP, CNG/RNG, or pyrolysis/gassifiers. Composting is only one component that needs the benefits of the added processing capabilities of these processes.

The network is small and not very influential.

We need more competitors and more understanding for the public regarding the cost of doing this.

I'm not sure if it is halfway, but there is a lot of interest and progress in this area.

There is phenomenal unmet opportunity but many risks to this business sector. Compost facilities for instance are struggling in a variety of ways.

In percentage terms, I'd be surprised if we were half way to achieving diversion of all economically viable organic waste, but the first steps are often the hardest, so I'll call it half way.

Some counties and facilities are doing better than others. This is somewhat related to geographic location but not entirely. Some products have more developed systems for making beneficial products.

Current composting infrastructure is overwhelmed. Need more, smaller ("neighborhood") facilities as well as more use of AD and pyrolysis to manage food and wood residuals.

There seems to be a monopoly in many counties.

More incentives for anaerobic digestion of mixed residuals. Much better management of manures and animal wastes needed.

Depends on where you are in the state.

Large swathes of the state have no compost facility available.

The businesses for collection and processing are in place in the major urban areas and could be in place in more rural areas with local policy and program support to divert organics. The program and policy support to promote organics diversion is significantly lacking, and if anything, is being reduced: funding for outreach and education, local and state policies to include organics (and recycling) collection within a package of garbage collection service

I would suggest that at best the network needed is perhaps only one third of the way developed.

There are too many different collection methods needs to be consistent throughout the State.

I believe this is a small sector of industry where market penetration of collection and processing of all source separated and other organics as measured by the WSU Bioenergy Inventory and Assessment for Eastern WA which shows over 4.3 million bone dry tons per year of biomass capable of being diverted to these applications. It is my estimation that the current level of diversion may be about 500,000 wet tons per year (est. of 250,000 bone dry tons) which shows a market capture of less than 6%- thus far from meeting the goal of a sufficient business network.

Comments related to Q3: In your opinion, how far is Washington from achieving this goal: "There is robust demand for high-quality organic products in all sectors of the economy, from soil amendments and recycled consumer goods to green energy sources."

There is a large demand for these products but a low cost production issue.

More focus on market development needed to match the level of processing capacity.

The main thing holding back the full acceptance and use of recycled organics, i.e. compost, is the amount of contamination in the feedstocks and the end products. One of the main things holding back green energy projects is the lack of willingness of our utility companies to pay for green energy at rates that will make the capital investments worthwhile.

Biosolids are not viewed as green as other recycled materials.

'Across all sectors' is the challenging part. Robust demand in some sectors, and in some sectors in some regions of the state...but all sectors across the state--no.

We don't do a very good job closing the loop with residents or businesses. It is too easy to purchase competing compost or "organic" products in the marketplace rather than locally-produced material.

Given the huge stockpiles of compost, it would appear there is a need for greater consumer awareness, marketing of such products. Supply seems greater than demand, so far.

Need more outlets/uses for processed organics. We have a lot more compost than what can be marketed. Not enough customers willing to pay for the finished product.

This demand exists in certain areas of the state, but not in others. Market is over-saturated or product quality is insufficient from some operations to achieve this goal.

Regulations are far too complicated to allow more beneficial use. Most ends up in landfills.

We have a long ways to go before EVERYONE recognizes the importance of using organic soil amendments.

Many organics that have been composted are loaded down with plastic and other contaminants that come in when yard waste is mixed with food waste from commercial and residential sources.

The public and commercial gardens want this product. I think some are concerned about chemical residuals and their impact on the new users/use.

I'm not informed on the demand for the finished product. I know the City still has to pay for someone to take our yard waste/organic material.

There is a fair demand but way too many road blocks in the way.

Household compost collection - Seattle area. What about other parts of state or other organic streams?

There is significant potential demand - however many compost facilities are unable to distribute their final product for end use. Expansive outreach/educational efforts will be needed to expand the demand.

This question lumps a few things together that I don't find completely cohesive. My experience is with commercial food and yard waste compost and tells me that there is a robust demand for high quality finished compost in agriculture and residential uses. Compost price is currently too high for farmers to afford, residents need to focus on buying local compost versus all the many competitor bagged (and to a lesser degree bulk) brands, WDOT could use the compost. All these uses would require clean compost.

I don't feel that people in general are very close to be being educated on organics. There is way too much effort put into the unhealthy foods that we eat and not near enough into the great benefits of organics in every sense of the word.

Many gardeners, yes. Growing in agriculture, but mostly small. Limited change in big ag and forestry.

I have heard that California has made much more progress in this area by utilizing much of the product in road construction, meridians, etc. My understanding is that current use of product in WA by WSDOT and in other construction projects is very restricted and limited.

The demand is high. The incentives are low.

Is most compost used by farmers? No? Mostly used by landscapers and road builders? Yes? Then we're far from meeting the goal.

Outside of urban areas, we do not see this happening.

The current costs of such products are oftentimes barriers to making people switch. Organic products are still not embraced by many folks because the benefits of their use doesn't necessary mean more profit or food production.

There is a HUGE disconnect for the consumer regarding this "final" chasing arrow step. In my opinion people do not understand the dire need to buy products made from the post-consumer "recycling" stream. The "re-use" arrow is very weak....This MUST be strengthened NOW for robust-ness to really get a foot-hold.

We are not half-way there yet, but we are more than "far from meeting this goal". There should be a mid-choice or the bullets should be reworded.

Not enough people know where there organics go and what they are used for.

Compost supplies in some areas of the state exceed demand, in others demand exceeds supply. I think this optimizes where we're at generally. The "robust demand ...in all sectors.." has certainly not been achieved. To provide a more accurate response I would have to look at a variety of recent data which I have not done lately.

I don't think that the WA capacity for organics recycling is clearly understood. Demand should increase.

Again, a great idea and I am a practitioner. I would like to be pushing businesses in this direction, but things like operational costs of providing organic products are always stated as too high and prohibit adoption. We (practitioners) need to be able to show that those costs are met in the long term.

Still problems with weeds, smell, plastic, etc. in the products for sale. Demand could be higher with better education and promotion. Public works should use more product.

Contamination in compost is a huge problem which has a negative impact on demand.

We still have about 1/2 of the material being landfilled. What would it take to move to 70%?

Little demand for products - supply exceeds demand. Poor system to enable product development and use.

It's very much a niche market at this point.

Baby steps toward this. Excessive costs are the main problem.

People still buy compost shipped in from out of state. Should buy compost produced within 50 miles.

Large piles of compost sit at some facilities in the state. They are either not marketable, or the demand isn't there. WSDOT seems to be buying a lot less compost these days. The Green energy sources for organics seems to be buoyed more by the tip fee they collect than the energy they produce. Without the tip fee would these operations be financially viable.

A substantial floor is in in the market, however, compared to where we could go, we have a lot we can yet do.

Green energy is a waste of tax money. They can never be stand-alone businesses.

Robust is not the word that fits this activity generally. While there are areas that this is true, the majority are still working to develop this. There is too much concern over residual herbicides for some to take a chance on this application.

Washington is a very green state; good or bad.

Some areas are doing a great job and other are doing nothing at all

Stop forcing us to drink industrial waste fluoride as a toxic additive to products and public water. Oregon passed an initiative with a two-thirds majority, despite outsized chemical company expenditures.

No "robust demand" but compost is being used. Green energy is still in pockets - not SOP.

Again incentives, poor recent rules from WA DOE on bioretention system composts

I see building out and improving anaerobic digestion capacities at existing WWTPs and dairies -- to add ability to process food waste to generate combined heat and power, RNG for refueling CNG vehicles, or purified biomethane (pipeline quality) -- as potential areas for improvement for WA's urban areas.

Compost not being used in large scale soil amendment?

There is robust and unfilled demand for high quality solid amendments. Unsure what organic products constitute recycled consumer goods. The current state of anaerobic digestion is young and may be plausible, especially in on-farm and dairy situations. But the promotion of landfilling organics as a beneficial method of methane generation is counterproductive because of the amount of methane released before a landfill cell can be capped for methane capture.

Robust demand would suggest that it is the 'first' go to resource used by consumers state-wide. Not enough product out there due to other constraints for access to be robust. Cost barriers are still a consumer/end user factor.

Costs remain too high for robust demand

Comments related to Q4: In your opinion, how far is Washington from achieving this goal: "Economic and regulatory incentives are aligned to support full organics recovery and beneficial use in Washington."

Funding and grants for co-generation, class A Biosolids processes, and effluent reuse projects

I don't know that economic and regulatory incentives need to be 'aligned to support full organics recovery'. Such an aspirational and unconditional goal is unreasonable. Economic incentives to reach this goal would necessarily have repercussions elsewhere in the larger system. And regulatory incentives to that extent could result in other unintended consequences.

Manure from AFOs and CAFOs is not well regulated or managed.

Small organics collectors (small farmers) undercut municipal organics collection programs, but the small farmers do not get proper permits to accept organics.

Achieving recognition for carbon & nutrients would be beneficial for this field.

Current regulatory ideology inhibits adoption of new green products that cost the public less than traditional composts and produce better results. Case in point: tens of thousands of cubic yards of compost are specified and required on WA DOT projects when at least two biotic soil amendments are commercially available at a fraction of the cost, a fraction of the time to install and a significantly more predictable and enhanced result. Why? Government has colluded with big business using its regulatory process (TAPE and others) to prevent new product use on publicly funded projects. The barrier to entry for new products is the cost and time of going through the regulatory adoption process. Break down the regulatory mechanism if you want truly progressive green solutions.

There is no incentive at all for applying biosolids to say, wheat fallow fields. There are plenty of incentives to just dump at landfills. ie, regulatory complications.

Big Ag interests have not yet figured out how to profit from organic agriculture. Their paid minions in the legislature are not supportive either.

If this is an actual stated goal no one in the regulatory system has ever seen it.

I think regulatory should not be considered a solution to this issue. Voluntary groups such as RCO, Conservation Districts, and extension agencies should be used. Fund them for outreach and implementation.

Economic and regulatory incentives should be promoted to local businesses, community partners and local government agencies.

For biosolids, in some many we are close to meeting this goal. It is wonderful that Ecology defines land application as a beneficial use of biosolids and that Ecology really supports this recycling program. On the other hand we see some barriers from local health departments, and some problems with biosolids composting being regulated under WAC 173-308 while all other compost feedstocks are regulated under WAC 173-350. For example, on occasion we will see code or specs saying that compost must comply with WAC 173-350 and by default biosolids compost is omitted, even though that was not the intent.

I agree that the regulatory incentives are there and composters seem to be profiting, however we need to balance the goal of waste diversion with the need to produce quality compost. Requiring organics collections at commercial, residential, and multifamily locations can lead to contamination and should potentially be scaled back.

System is cumbersome and not well integrated. Too much hand holding is needed to make something work. Modest change by incumbents

The Department of Ecology has explicitly barred local governments from using Coordinated Prevention Grants for support of additional organics recovery - this is clearly not helping to increase recovery!

Too many incentives.

The costs (financial) of using commercial fertilizers needs to be higher to discourage use. Recycling should be better rewarded through reduction of the cost of doing so.

From Dairy Nutrient Management Program perspective, I think that the regulatory structure (RCW 90.64) and the economics do not fully support moving manure off the farm. Transportation cost, food safety issues, producer interest, and clear regulatory language are just a few issues that come to mind.

See my comments in 2 above regarding a conflict of interest.

Politics over other issues can get in the way of using advanced technologies in order to get the best and highest uses out of organic residuals.

There are macro-economic issues that oppose natural resource use efficiency. See narrative in System barriers, #11

My understanding is that there is far to go on many regulatory issues.

We are not as far off as "Far from" but we are not "Halfway toward this goal" either. Economic incentives will likely come if/when cap and trade is allowed to run as a market.

Regulatory incentives might help if they could kick start the market based economic incentives.

No capital or operating subsidy. How about a UK system with a progressive landfill tax?

We have large areas of the state which cannot support full organics recovery due to distances between small agricultural, poor, municipalities on the East side of the state.

Organics management budgets have been cut in recent years. There is no Best Management Practices guidebook for organics management facilities for Washington

I'm a little cautious of this goal as stated because as currently (or near past) done, economic / regulatory incentives have interfered with "free market" of some existing composters. Incentives must be carefully analyzed to ensure throwing money in one direction isn't hurting existing infrastructure. In my opinion, the regulatory structure (individual regulatory departments and county by county differences -especially air agencies) actively dis-incentivizes composting. Additionally, while grants are often used to help emerging innovations, they also unbalance the playing field. Consider the amount of \$ given to AD facilities relative to existing privately-funded compost facilities.

Regulations are not enabling.

Composting remains a tough business to be in and rate-payers aren't always seeing cost savings. Still much work to be done here to make the composting industry more hospitable on the regulatory side, thus reducing operating costs. The more efficient we can make the processing of organics, the more the savings can be passed down to the rate payer.

Currently regulatory management of organics production makes compliance very difficult. When I pointed this out to one of the regulators, she reminded me we didn't have to be in the organics program if we didn't like the way she worked.

Too many regulations for rural producers, especially those who do not use food waste as a feedstock or who use biosolids.

Regulations seemed to be well balanced in the state. I'm not sure economic incentives should be pushing organics management. If it can't stand on its own merits, why should it be subsidized?

Economic incentives are needed in the waste recovery for energy/fuels/pipeline gas etc. Economic incentives are needed to support stable carbon for soils that improve the benefits for using compost, char digestate for improving soil productivity.

We could always use less regulation, as less regulation equals improved economics.

Recently, Cedar Grove and Waste Management are pursuing rate increases to cities they service. They are stating this is due to WA DOE policies they are mandated by but not all the local haulers are participating who have contracts with Cedar Grove. Policies like this create a negative impact. A consumer pays for collection and then pays to purchase soil. Double whammy in a limited competition market.

Once again there are pockets where this may be true, but there needs to be more teeth in this to have it work.

There are few regulatory or economic incentives that support organics recovery - just bans and lower tip fees, grants for local governments.

We need to put pressure on the utilities to adopt and/or refine rules that enable projects to come on-line with more financial and technical incentives. Such as removing caps on biogas generating capacity and paying better rates for distributed gas and electrons generated from renewable energy projects.

Most monetary and contract support goes to haulers, processors, and operators. Policy development support and outreach and education are either unsupported, or the support has been significantly reduced. These are the programs that make sure that the material collected is correct, does not damage equipment, promotes the all of the benefits of source reduction and diversion to residential, business and institutional generators so they will incorporate those practices as a normal part of their day.

Let's be honest here! If the State loosens up the regulatory rules the industry would have no problem meeting every goal the state wants to achieve and then some. Also the costs would be lower and then more companies could operate and the average citizen could afford these products and the organics industry would be self-sustaining. What a concept!

Both types of incentives are crucial to the success of this nascent industry. Economic incentives need to include elements to support all portions of a projects revenue stack as well as align and complement federal incentives as well as speed project development. Permitting approval cycles need to be measured in days or weeks versus the current cycle of months or years. As well these incentives need to support stable long term investment through a combination of revenue enhancements and cost reductions.

Comments related to Q5: In your opinion, how far is Washington from achieving this goal: "People in Washington support a sustainable, closed-loop organics management cycle."

Washington is well behind the rest of the West Coast in effectively mining our organic waste stream and utilizing our great biomass resources. In my view, there is a whole host of reasons for this- from the antiquated limitations embedded in our State Constitution to lukewarm support for sustainable development from the leading environmental organizations. But I cannot help but think all of these real barriers could have been overcome if we had enjoyed strong and visionary leadership.

Most Washington residents wouldn't understand the question. If the question is understood, I suspect that most would support (in principle), but in practice likely wouldn't be willing to support or make required investments.

People have not been educated on the costs and benefits associated with this goal.

This seems like only a partial statement - 'people' support this, but what is the goal, i.e., a percentage of people, all people? People mostly think about what they send off for recycling, such as yard waste, but not about using the products, like compost, that are created from them. The loop isn't really closed.

Conceptually, yes. But the reality is that society doesn't support the bad compost operators that continue to create nuisance conditions in their host communities. If operations can be done in such a manner so that the public doesn't have to see, smell or hear the operation, people will support "a sustainable, closed loop organics management cycle".

Here in Pacific County, we have no idea what is going on in the Washington State Organics program. Never heard of it, and I consider myself a leader in the sustainable farming movement.

Some but not all. Not sure what percentage actually participates in using organic soil amendment products.

Most people do not really care.

The people of Washington love the idea of recycling but only if it is done somewhere else. King County citizens do not want to have organic recycling take place anywhere in the County.

Half way may be extreme, but exceeds "far from".

Hard to say for WA as a whole vs. King County.

People support it - but they do not understand the concept. Efforts for education of youth and through the schools will be the best way to accomplish this.

On a theoretical basis I've never come across a person who doesn't support closed-loop recycling of organics. However, many people are adverse to various products whether from manure, biosolids, or yard, or food waste. I also come across people who have food waste recycling available to them, but still put their food scraps in the solid waste bin.

In Snohomish and King Counties, significant educational efforts and marketing are being utilized to promote this support. More education is still needed to clean up organic waste

streams and education people about what happens to food and yard waste when it leaves the curb.

Question 5 is not a good question.

I don't think the average citizen understands what a sustainable closed loop organics management cycle is. They do understand if that put material in a cart at the curb for recycling it's good for the environment.

Depending on how close one lives to a compost facility...emphasizes the need to move beyond compost

Lip service is halfway, but taking action is slow. Few nurseries or big box stores are striving to get there. People don't demand it.

My perception is the majority of Washington State residents don't know anything about organics management let alone closed-loop organics management cycle.

I think many people agree with the principle in theory, but the dirty work of separating organics at home and on the go (especially food scraps and food soiled compostable paper/packaging) requires a level of commitment and engagement that many people still lack, even in places where the supporting infrastructure and incentives are fully in place.

Most people do not understand what it takes to achieve such goals.

Other half of the Mountain.

Not enough people are aware of this.

Western Washington does embrace recycling and environmental protection, I feel that more work needs to be done in Eastern Washington.

This is in part, geographic. Ask a grower in eastern Washington this question and I bet that the answer will commonly be "Sure, and I do". All the while the organic matter in their soils are decreasing. In general, what people think they support, and what they actually support by both action and regulation, are two different things.

That would be desirable. Realistically most people don't appreciate what is being done in Washington.

My observations so far are that people will say this and support it until it costs them something to close the loop on organics (i.e., it takes something away from profits). My observations are also consistent with the idea of most people wanting to be socially responsible because it sounds great, but when it costs something to be socially responsible the shine fades quickly.

Public is supportive.

Although I believe we are far from meeting the above goals, I do believe we are on the right path and that the will of the people of Washington State is leading the actions of our government and business community.

Small communities need funding to construct organic management facilities and systems. They can't do it on their own, even with some state funding.

The rise in demand for organic food in recent years helps to strengthen broader support .

More accurate "People in Washington support a sustainable, closed-loop organics management cycle as long as it doesn't cost them anything, require any effort, or exist in their view or neighborhood."

I think most people want to do the right thing, but this is not a front and center issue in most communities. Organics collection is voluntary or not available in most communities, and often experiences mediocre to low participation rates.

I don't think this is important to most people. They are motivated by cost and better environment. This goal is detrimental to the first motivation and they don't understand how closed loop management relates to the latter.

There is too much competition among local governments to recycle at any cost. The recycle number (percentage of wastes recycled) has become the holy grail. A lot more emphasis needs to be placed on the quality of materials collected, not the quantity. Until we have a clean final product that consumers accept, we won't have a sustainable market.

On a generic basis people support this. In fact they have not been provided correct and targeted information on how to act on their beliefs.

So long as it is economical/cost effective.

People that truly influence agriculture and waste management do not yet support it.

The west side folks are more in tune with this concept. The Washington Organics Recycling Council (WORC) is promoting this at every avenue.

I suppose there is a semantics argument to be had about the word "support" in this context. Vocally, we are probably past half way. Support in practice however, perhaps somewhat less.

Even so-called "well-informed" consumers are blind to their own wastefulness and unnecessary use of unnecessary products, mostly made of plastic it seems.

... Just as long as the organics management facility is not near them.... I wonder if they understand that buying local compost is closing the loop?

More public outreach for wastewater

People support domestic production of energy and fuel. The issue is how to build the regulatory and financial environment so there is capital available to make the projects possible and ensure there is an acceptable level of return on investment. Using recovered organics as the feedstock for renewable energy projects is generally more favorable than using cropland or fresh forest products.

There is a difference of attitude across the Cascades in terms of diversion. The west generates the material but east needs the compost for agriculture but does not support organics diversion or processing.

They'd support it if they knew anything about it. But as long as dollars are prioritized to operators/collectors with direct sales and lobbying connections through contract relationships, outreach and education will be at the bottom of the funding priorities.

If you could have all the collection methods collect the same products and keep the costs low enough, then you can have a cohesive Washington state and its citizens come together and support it Statewide.

I note that this question does not inquire regarding the number of people or the quality of the endorsement. These factors would be best addressed by conducting a thorough high quality survey of Washington residents.

Most people would not know what you are talking about.

This depends on the demographic. The well-educated, people without a vested interest in doing things the usual way, people that understand that there are sometimes non-monetized costs associated with doing things— these people are on board. The rest don't understand or have an economic interest in keeping things the same or cheap and destructive.

Appendix J. Construction of the baseline compost model

This appendix details the information used to create the 160,000 wet tons per year hypothetical composting facility.

Inputs and Assumptions

Incoming Feedstock: Commercial waste collection companies and municipalities supply the incoming feedstock. Delivery trucks bring the feedstock between 9 am and 11 am, and 2 pm and 4 pm, taking about 4 hours per day. Material is delivered to the facility 240 days per year Monday through Friday. This is about 667 wet ton per day, 5 days per week. This means the facility should get 167 tons per hour during the 4 hour period. Assuming a twelve-wheeler semi-truck can carry 16-21 tons (Desert Trucking, 2014) then about 10 trucks should be arriving at the facility per hour during the 4 hour period.

Incoming materials will undergo a pH test in the tipping building. Feedstocks high in nitrogen measuring with a pH above 8 may release too much nitrogen and ammonia. Feedstocks high in nitrogen measuring with a pH below 5.5 may create too many organic acids. pH is balanced by either mixing neutral or basic materials with the feedstocks, or the piles will be aerate more often.

About 100 tons of a bulking agent will need to be on hand at all times for the feedstocks. Wood chips are good material to use. The wood chips should be between one and four inches long. When processing the wood chips, a screening must be performed in order to sort out any pieces larger than two inches. The smaller pieces will be used for mixing, and the larger pieces will undergo a secondary screening to remove any contaminants. Both wood chips and an inoculate, a pile also about 100 tons, will be kept close to the tipping building so creating the initial compost blend will be a easier.

The composting material will be in the facility for approximately 10 weeks. The feedstock breaks down during four weeks of active composting, two weeks each for maturing and curing, and two final weeks of storage. The facility will then have to store about 60,000 tons of material.

Tipping building: The trucks used to bring in the feedstocks will use a negative air pressure building which will help dispose of the odor with the use of a biofilter. If the tipping building has a volume of 6,000 m³, measuring 40 m x 30 m x 5 m, an odor control system can be utilized. This system sucks out all of the air in the mixing room four times every hour, replacing it with fresh air. The odor control air flow was 24,000 m³ per hour (Levis and Barlaz, 2013).

Blending and/or grinding: Once inside the tipping building, bulking agent (wood chips) and inoculate (brown material) are mixed with feedstock using a front-end loader. The goal is to achieve the proper mix of carbon (woody) and nitrogen (food, leafy). It is vital for the composting process to maintain a proper balance between carbon and nitrogen. This is the primary processing phase that helps build the correct mix of feedstock for managing odors during compost. The quantity of bulking agent (wood chip) should be enough to reach a porosity

of more than 30 % free air space in the blend. Another criterion for preparing a good blend is to reach an optimal range of carbon to nitrogen ratio (30:1) to increase microorganism growth. A low initial C:N mixture has a greater potential to generate odors, but excessively high C:N mixture may not necessarily generate many odors, but will be very slow to compost. The right moisture and optimum porosity are controlled at the tipping building.

The capacity of a front-end loader bucket will be assumed to be close to 3.0 cubic yards (1 cubic yard is approximately 1 ton) (Volvo-Model L90; Michigan, 1991). To calculate the number of front-end loaders needed for transporting feedstock between the tipping building and the mixer (Figure J-1), we will suppose that the front-end loader can make 21 loads per hour. To move the 670 ton in 8 hours we will need four front-end loaders working between the tipping building and the grinder and one front-end loader preparing the blends of waste materials, wood chips and the inoculate. Most waste is received in the morning and then processed and ground within a couple hours of being received, before 2 pm. The waste that is received in the afternoon will be mixed early the next day. In the afternoon, (between 3 pm and midnight) these four front-end loaders are moved to the curing final product sections. The mixture is loaded into the mixer by four loaders that take the combined raw matter (waste, wood + brown material) from the tipping building. The product from the grinder is discharged onto the conveyer that then brings the mixture to the active composting section.



Figure J-1. Mixer in a composting facility (Ecology, 2011).

A misting system, located on top of the grinder, disperses odor control agent and water to reduce the release of odors and dust. The misting system is regulated to help provide the optimum moisture for the composting process.

Grinding decreases the size of the individual pieces of feedstock so that bacteria can act on it efficiently while simultaneously providing texture and porosity to facilitate air movement. The material then passes beneath a huge magnet to remove metal contaminants.

Material is moved via an enclosed conveyor from the grinder to the middle of the phase I cells of the GORE cover system. Moisture is added, as needed, in the form of leachate (collected from under the GORE Cover pads and treated in a tank); storm water or fresh water is sprayed onto the material as it is moved on the conveyor. The moisture content of the mixed material headed for compost should be 55% by weight.

Composting piles: A front-end loader will collect compostable waste mixture at a drop at the end of a conveyor and move it to a previously cleaned cell location. The GORE cover has been rolled up on a winder rig in preparation and relocated at the head of the new row. The heap is built one-bucket load at a time. Phase I heaps are built while the grinder is operating, from about 6 am to about 2 pm (8 h). Phase I heaps are then taken apart and the phase II heaps are built from about 3 pm to about midnight (8 h). In order to manage the 667 ton/day that is processed in Phase I (between 6 am and 2 pm) and the volumes going to phase II, we need 4 front-end loaders working between 6 am and midnight in the active compost section.

A biofilm like layer of wood chips or a blend of chips and coarse compost (between six inches and a foot thick) will be placed over the entire top of the aerated static pile of compost.

After a heap is constructed, the GORE cover is pulled over the pile. The cover is a specially developed membrane, laminated between two polyester layers. The cover protects the pile from the elements, while still allowing the release of CO₂ and moisture. These controlled conditions reduce the risk of damp pockets that create anaerobic conditions while allowing a consistent product to be produced. This synthetic material also ensures simultaneously that the reduction temperatures for pathogens are reached and vectors are controlled. The covers last 8 to 9 years and sandbags placed on the sides help protect the cover from high winds.

The material spends its first 28 days (active composting) in 32 long, narrow heaps. The dimension of the stacks (windrows) is: 50 x 8 x 3 m (165 x 26 x 12 ft). The capacity of each of these heaps is approximately 450 tons.

Air is forced through pressurized channels below the compost. Oxygen probes control the air pressure inside the pile to help balance the biodegradation rate. Oxygen and temperature probes monitor the system 24 hours a day. Odors will be kept in check as long as sufficient oxygen levels are supplied over 10%, which will also speed the composting process. The temperature in active composting should be maintained at 55°C or higher for three consecutive days. Cooler temperatures mark the end of the active composting phase in the composting pile.

The pile is moved to the maturation area (second composting phase) after 4 weeks in active composting. This pile is operated very similar to the active composting phase (using same dimensions as the covered stacks under forced aeration) but the material will stay in this phase for two weeks. This section is formed by 16 covered windrows. Next the mulch is moved into 16 uncovered, curing piles, where after two weeks it's again moved into the final product section.

Curing: After the compost has met pathogen-killing requirements and started to cool down to mesophilic temperatures (below 55°C, 113°F), it enters the curing phase. The products of the maturation phase are then moved to a 3rd phase "open pile curing" for the final two weeks where

they will dry out some. Construction and disassembly of the Phase III heaps will occur in the same way as Phase I and Phase II, except that a GORE cover is not utilized. Most of the odorous compounds in the material have been broken down by the composting process in phase I and II. An active air supply is provided to each heap during its composting period.

In this phase, the level of compost biological activity is measured as the main parameter to identify the moment where a final product is obtained. This is accomplished with a microbial respiration test kit (Solvita Test Kit). The curing and finished piles will be kept on forced air to maintain aerobic conditions.

Finished compost: After the curing step, compost is added to a 35-foot tall mountain. This mountain holds the equivalent of 1,000 tractor-trailer loads (around 20,000 tons of finished product, more than a week of production). As with active and curing compost, moisture and oxygen levels should be managed to protect finished product quality as this continues to cure. The piles of finished compost will be covered with a semi permeable blanket that sheds water but allows the pile to breathe. The finished piles will be kept on forced air to maintain aerobic conditions and turned every month to evenly distribute moisture.

Screening: The contaminants in the final compost are screened out by size in two separate steps and then used in a final product (compost, mulch, for mix with soil blends, etc.). Oversized material (biggest compost chunks) (overs of first screen > 3 inch) is returned to the beginning of the compost process where it is blended with unprocessed material in the tipping building. This helps inoculate the incoming material thereby accelerating the onset of the composting process. A final sifting removes more plastic contaminants.

The second screening step will be scheduled based off of consumer requirements and when they want the product. In our design case, we will consider a sieve with openings of ½ inch. The materials that pass through this sieve will be sold as garden product. The screening should be conducted at least one week before the delivery of the product because the compost could briefly re-heat for up to a week due to microbes being re-energized. The product between 2 inch and ½ inch is used as packing for the biofilter.

Compost material testing: A representative sample of compost material will be collected for analysis from each pile for every 5,000 cubic yards produced. The following tests will be done for the sample tested: arsenic, cadmium, copper, lead, mercury, molybdenum, nickel, selenium, zinc, physical contaminants, pH, biological stability, fecal coliforms, and salmonella. Finished compost will be tested to meet the limits of Fecal Coliform or Salmonella using an accredited laboratory that can test compost and agricultural samples. The compost produced should not have more than 0.25% plastic film by weight.

The current criteria for evaluating compost quality can be divided in three major groups: (1) physical, (2) chemical and (3) biological. The physical criteria are associated with the odor, color, particle size and inert materials in the compost. The chemical characteristics are associated with the carbon and nitrogen contents (C:N ratio), water content, cation exchange capacity (CEC), water soluble extracts (pH, EC organic-C), mineral nitrogen (NH₄-N content, NH₄-N:NO₃-N ratio), pollutants (heavy metals and organics), organic matter composition (content of

lignin, complex hydrocarbons, lipids, sugars, etc.), humidification (humidification indices, humic like substances characterization: elemental and functional group analysis, molecular weight distribution, E4:E6 ratio, Py-GC/MS, spectroscopic analyses (NMR, FTIR, Fluorescence, etc.)). The biological characterization is typically associated with the following measurements: respiration (O₂ uptake, consumption, CO₂ production, self-heating test, biodegradable constituents), enzyme activity (phosphatases, dehydrogenases, etc.), ATP content, nitrogen mineralization-immobilization potential, nitrification, (microbial biomass), phototoxicity (germination and plant growth tests), others (viable weed seed, pathogen and ecotoxicity tests).

Storm Water and Leachate handling system: The hypothetical compost facility as proposed, will manage storm water and leachates separately, to meet Washington State standards established by local water and air quality permits. In order to minimize the production of leachates and runoff, the storm water management system will include run-on prevention systems, covered area (roofs), diversion swale, ditches and other features to divert storm water from areas of feedstock preparation, active composting and curing. The leachate will also be collected from areas of feedstock storage and preparation, active composting, and curing. It is then converged to the leachate storage and treatment system.

The storm water and leachate collection system were calculated based on the volume of water resulting from a twenty-five-year storm event as defined by WAC 173-350-100. It will also take into account the evaporation data. The leachate storage structures were calculated with a capacity to store the normal maximum volume of leachate generated by the facility (taking into account the normal leachate reuse and removal). The leachate tank will have a freeboard (distance between the liquid level and the top of the pond) equal to 20 inches to avoid overtopping from wave action, overflowing or precipitation.

Any leachate generated will be drained through surface ducts and treated. Some leachate will be used as an inoculant for the process and be kept separate from the storm water. Leachate is the liquid that is contaminated with dissolved or suspended materials after it has been in contact with solid waste such as incoming feedstock. The facility will have a leachate tank according to WAC 173-350-220(3)(e).

Leachate can be a source of odors when liquid has accumulated and should be taken into account when it comes to reducing potential odors. The leachate will be drained and accumulated sediments removed every month. The sediments will be blended with other feedstocks in the primary composting phase. The leachate can be used to moisten incoming feedstock. The leachate tank is prevented from going anaerobic and producing odors with the addition of air through aeration. Daily visual inspection of the leachate tank will be employed to confirm that the air diffusers are working properly inside the tank. In addition, the leachate collection and handling systems will be cleaned daily.

The facility will build and utilize two large retention ponds that will capture and settle rainwater. The aeration system for the storm water detention pond is checked daily to maintain an aerobic state in the pond.

Odors control (biofilters): The odors in the receiving building are controlled through the use of a biofilter. Biofilters host microbes that live on odor compounds as the air gets evenly distributed through the shredded woodchip biofilter. If the microbial population in the biofilter is healthy and the air being treated has sufficient lag time in the wood chips, then most odors will be consumed before they are released to the atmosphere.

The biofilter will be maintained at moisture content between 50 and 65%. A gauge measuring backpressure will determine wood-chip replacement requirements. Wood chip filters are generally replaced at around 14 to 18 months.

There are four potential odor sources at an active green waste/food composting facility. The first two sources can be from incoming material being received for processing or later develop as it waits on-site. Third, compostable materials that may be deposited on the ground around the site will develop odors when it becomes wet and decays. Fourth, leachate and storm water on-site may accumulate in puddles, ponds or tanks and develop odors as the nutrients in the liquid decay. The biofilter of the installation studied will only manage the odors generated in the tipping building.

Operators: The unit will be operated by 32 workers: (1) general/technical manager, (3), two engineers, (4) secretary, (5) balance and feedstock odor controller (monitoring incoming feedstock and identification of excessive odors) (9 am – 4 pm), (7) two operators in charge of preparing the blends (9 am – 4 pm), (11) four end loader operators feeding the grinder (6 am – 2 pm), (15) four end loader operators building the active composting piles (6 am – 2 pm), (19) four end loader operators in charge of building the maturation heaps (3 pm – mid night), (23) four end loader operators in charge of the curing and final products piles (3 pm – mid night), (25) two operators controlling and sampling the active composting phase, the maturation step and the curing step, (26) odor specialist (monitor odor complains in the surrounding community and investigating and documenting odors), (28) two workers in charge of cleaning and maintenance, (29) laboratory quality controller, (31) two marketing and commercialization, and (32) one public relations specialist.

Properly trained workers will supervise the operation of the facility. The operators controlling each step of the process will maintain representative operational records of daily temperatures and oxygen content of each composting pile. The operator will also document and respond to nuisance odor controls as they arise. All the operators will receive training in safety, compost basis and good management practices according to WAC 173-350-220(4)(a)(vi)(A). Operators will also receive the training offered by the Washington Organic Recycling Council. The unit will have a “sanitary station” and locker room space for staff to conveniently wash up and change clothes in the office building.

The operators will maintain a Plan of Operations that have specific details, such as a list of feedstocks and how they will be handled, a pathogen reduction plan, fire and emergency plans and an odor management plan. The temperature of the active compost pile will be maintained at 55°C or higher for at least three consecutive days while continuously monitoring the temperature and oxygen content of the composting pile. The carbon to nitrogen ratio, moisture and porosity

of all the piles will be determined at the beginning as the pile is being formed. The moisture content of the pile should not exceed 60% by weight.

The operators will also record the backpressure to the biofilter. A drop in pressure is an indication of biofilter deterioration due to channeling but an increase in pressure may indicate clogging.

The monitor and Control Room: The temperature of each covered pile is recorded by remote thermistors. All data will be available to regulators so that they can monitor the process. Regulations require temperature exposures of three days at 131°F (most of the process, 30 days, is at 131°F). Raws typically achieve 154°F, while a new pile is seen rising to 138°F.

Main Equipment: The main equipment is shown in **Table J-1**.

Table J-1. Main equipment needed for the composting facility

Equipment	Number of Units	Function
Scale	1	Weight the material received
Front-end loaders	10	Mixing, transport of material and formation of windrows
Pre-Trommel	1	Separate the small and big particles in the organic material received
Tub Grinder	1	Reduce size of incoming feedstock and mix the material
GORE covering system	2	Cover and uncover the windrows
Aeration systems	64	One aeration system per windrow
Belt conveyers	4	Transport materials between steps
Miscellaneous truck	1	For transport materials inside the installation
Water truck	1	For cleaning the system and providing water when needed
Excavator	1	To remove materials from large compacted piles
Trommel screens (post screeners)	2	To separate materials by sizes
Bobcat	1	Move materials
Odor control system	1	Control odor in Tipping building
Leachate collection tank	1	Collect the leachate produced in the composting facility

Mass and energy balances of composting facility

For the mass and energy balances, we will use the scheme shown in **Figure J-2** and parameters of the model developed by Levis and Barlaz (2013). The (SWOLF) Solid Waste Optimization Life-cycle Framework model developed by Levis and Barlaz (2013) was designed to perform an analysis of solids waste management (SWM) as an integrated system for rigorous analysis of system response under changing policies. The LCA is a framework for estimating the environmental impacts associated with products, processes and systems. The SWOLF model estimates the environmental impacts of waste management processes and systems and can facilitate “what if” scenario analysis to quantify the environmental effects while making incremental changes to the integrated biorefinery systems. Ultimately, a series of process models are linked together to build a life cycle assessment (LCA) model for an entire solid waste system, by integrating unit processes from waste collection through treatment, final disposal and beneficial recovery of material (Levis and Barlaz, 2013). A generic process model is presented in **Figure J-2**.

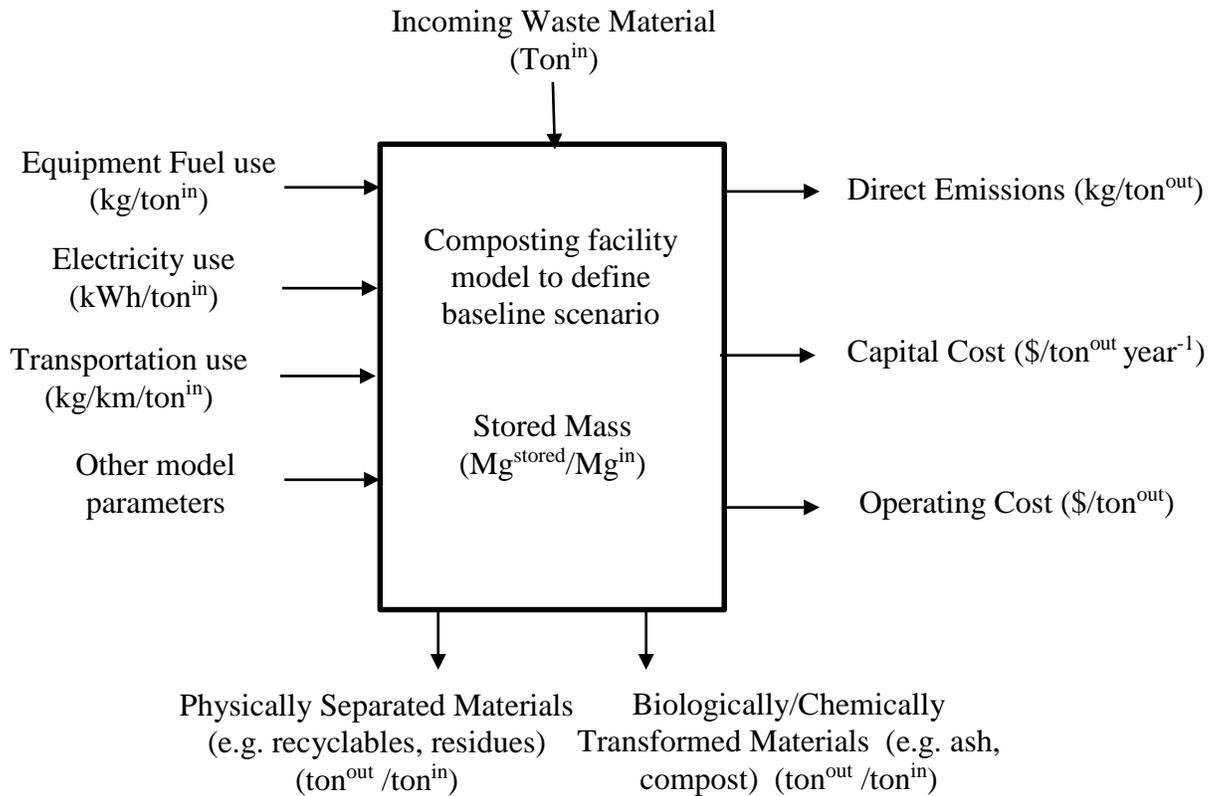


Figure J-2. Inputs and outputs for the baseline scenario created for a composting facility (Levis and Barlaz, 2013)

The functional unit for each process model is 1 metric ton of mixed material arriving at the gate. For each process model, default model parameters are provided, but can also be manipulated by the user in the MS excel files annexed. Each process model calculates the masses output waste materials, emissions, fuel used, electricity use, capital costs and operational costs based on incoming waste composition and model parameter values. All of the information used to create the baseline scenario was obtained from Levis and Barlaz (2013). In this report, emission factors have been developed using emission data associated with equipment fuel use, transportation, chemical and biological transformations, and electricity use in each process. Life cycle impact factors can then be used with the life-cycle inventory (LCI) results to calculate environmental impacts from the emissions (e.g. global warming potential, acidification potential or human toxicity). The sections that follow describe the information used to create the baseline case for our study.

Feedstock: The composition of the feedstock used is shown in **Table J-2**. Our calculations only consider 13 of the 26 compounds in the SWOLF model developed by Levis and Barlaz (2013). The SWOLF composting process model calculates stream composition, emissions and processing costs for each of the waste components. The model can consider any potential

incoming waste composition, but an assumed composition is used to allocate costs and emissions to the individual materials (Levis and Barlaz, 2013).

Table J-2. Composition of municipal solid wastes to be processed in the baseline scenario

Nº	Fraction	Mass Fraction (mass %)	Moisture content (wt. %)	C (dry basis wt. %)	N (dry basis wt. %)
1	Yard Trimmings, Leaves	30.3	38.2	41.1	1.0
2	Yard Trimmings, Grass	25.5	82.0	43.4	1.8
3	Yard Trimmings, Branches	21.0	15.9	45.1	0.3
4	Food Waste- Vegetable	5.2	77.0	38.5	3.0
5	Food Waste – Non-Vegetable	14.0	57.0	45.0	6.0
6	Wood	3.0	16.0	50.0	0.3
7	Newsprint	0.1	13.0	43.7	0.2
8	Corr. Cardboard	0.2	17.0	36.9	0.2
9	Bags and Sacks	0.2	22.0	42.2	0.1
10	PET – Containers	0.2	10.0	61.4	0.052
11	Plastic Film	0.2	14.0	79.1	0.42
12	Ferrous Cans	0.05	13.0	0	0
13	Ferrous Metal – Other	0.05	13.0	0	0

Composting design: Four composting alternatives were considered by the model developed by Levis and Barlaz (2013). These are 1) windrows, 2) aerated static piles (ASP), 3) the GORE cover system and 4) the in vessel system. We will be looking at the parameters of the GORE cover system for this study. Piles of compost are covered with a breathable expanded polytetrafluoroethylene fabric and use positive pressure for aeration but are controlled based on the concentration of oxygen. The only mechanical odor control is at the tipping floor and above the conveyors. Instead, odor is controlled by dissolving into a layer of condensation on the inside of the cover. This system reduces volatile emissions by over 90% compared to windrow composting.

Tipping building (mixing): The C:N ratio is usually what defines the nutritional balance. The microorganisms in the compost need an energy source to sustain them (degradable organic-C) and N for development and activity. The ideal range for this C:N ratio is 25-35 because these microorganisms need about 30 parts of C per a single unit of N. High ratios slow the entire process because of the extra degradable substrate. Low ratios mean there is extra N per C. Too much inorganic N is produced and lost through ammonia volatilization or leaching. These low ratios can be balanced by mixing in a bulking agent, providing more C.

The main operational criteria for the mixing step is to achieve a C:N ratio (wt:wt) over 30 and a water content of at least 50%. The water and amendment added will be calculated such that these parameters are achieved.

Based on the data shown in **Table J-2** we can estimate the moisture content of our feedstock was **48.15%** and the C:N ratio was: **30.86**. The dry material is equivalent to **0.5156 ton per wet ton** of waste material. It means out of the **667 tn day⁻¹** processed, **345.66 tn day⁻¹** corresponds to dry material and **320.99 tn day⁻¹** corresponds to water.

The level of water and the C:N ratio in the feedstock were very close to the optimal conditions for composting. The content of yard trimmings and wood in the feedstock considered is such that we will not need to add more wood to increase the porosity of the windrow.

Compost pile (active composting): The parameters used to describe the outcome of the composting step were obtained from the work of Levis and Barlaz (2013) and are shown in **Table J-3**. A more detailed description of the volatile organic compounds produced during composting has been reported by Komilis et al. (2004).

Table J-3. Indexes to calculate the quantities of solid stream produced (Levis and Barlaz, 2013)

	C-loss (mass %)	N-loss (mass %)	VS losses (kg VS lost per kg C losses)	VOC emissions (mg VOC per kg VS loss)	Overs on First Screener (3 inch) (wt. %)	Overs in Second Screener (1/2 inch) (wt. %)
Yard Trimmings, Leaves	26.9	45.8	2.3	4.5	2	1
Yard Trimmings, Grass	54.7	78.7	2	4.5	2	1
Yard Trimmings, Branches	18	37.5	2.1	4.5	5	80
Food Waste- Vegetable	65.7	83.9	1.9	4.7	2	1
Food Waste – Non-Vegetable	65.7	83.9	1.9	4.7	2	1
Wood	18	37.5	2.1	4.5	5	80
Newsprint	37.9	31.6	2.1	17.3	80	5
Corr. Cardboard	37.9	48.5	2.1	17.3	80	5
Bags and Sacks	37.9	31.6	2.1	17.3	90	90
PET – Containers	0	0	0	0	90	90
Plastic Film	0	0	0	0	90	90
Ferrous Cans	0	0	0	0	0	0
Ferrous Metal – Other	0	0	0	0	0	0

We will consider that 60% of the aerobic decomposition will happen in the active composting, 30% will happen in the maturation step and that 10% will happen in the curing step. The total metals removed was only 0.75 ton day⁻¹; the mass balance for the organics and ash are listed in **Table J-4**. In total we will produce 0.2226 dry tons per ton of wet biomass process (or 0.446 tons of wet compost per ton). It means we have converted close to 43.17% of the dry material into the final composted product.

Table J-4. Flow of different compounds (tons ton⁻¹ of waste processed)

	Organic solid leaving active composting (ton ton ⁻¹ of waste)	Ash leaving the active composting phase (ton ton ⁻¹ of waste)	Organic solid leaving the maturation step (ton ton ⁻¹ of waste)	Ash leaving the maturation phase (ton ton ⁻¹ of waste)	Organics leaving the curing step (ton ton ⁻¹)	Ash leaving the curing phase (ton ton ⁻¹ of waste)
Yard Trimmings, Leaves	0.1403	0.0183	0.1260	0.0183	0.1213	0.0183
Yard Trimmings, Grass	0.0266	0.0062	0.0200	0.0062	0.0179	0.0062
Yard Trimmings, Branches	0.1525	0.0060	0.1435	0.0060	0.1405	0.0060
Food Waste- Vegetable	0.0078	0.0007	0.0061	0.0007	0.0055	0.0007
Food Waste – Non-Vegetable	0.0363	0.0035	0.0262	0.0035	0.0228	0.0035
Wood	0.0199	0.0024	0.0185	0.0024	0.0181	0.0024
Newsprint	0.0006	0.0001	0.0005	0.0001	0.0005	0.0001
Corr. Cardboard	0.0012	0.0002	0.0010	0.0002	0.0010	0.0002
Bags and Sacks	0.0010	0.0002	0.0009	0.0002	0.0009	0.0002
PET – Containers	0.0017	0.0001	0.0017	0.0001	0.0017	0.0001
Plastic Film	0.0016	0.0001	0.0016	0.0001	0.0016	0.0001
Ferrous Cans	0	0	0	0	0	0
Ferrous Metal – Other	0	0	0	0	0	0
Total (ton per ton of waste)	0.3898	0.0377	0.3463	0.0378	0.3317	0.0378
Total (ton day ⁻¹)	260	25	231	25	221	25
Total (ton per ton of waste)	0.4276		0.3841		0.3696	
Total moisture (tons ton ⁻¹)	0.4276		0.3841		0.3696	
Total (Tons day ⁻¹)	570.13		512.13		492.8	
	Oversized Organic material in first screen (ton per ton of waste)	Oversized Ash material in first screen (ton per ton of waste)	Fibers (organics) Over in second screen (ton per ton of waste)	Fibers (ash) (ton per ton of waste)	Composted Product (Organics) (ton per ton of waste)	Composted Product (ash) (ton per ton of waste)
Yard Trimmings, Leaves	0.0024	0.0004	0.0012	0.0002	0.1176	0.0178
Yard Trimmings, Grass	0.0036	0.0001	0.0002	6.11x10 ⁻⁵	0.0173	0.0060
Yard Trimmings, Branches	0.0070	0.0003	0.1067	0.0045	0.0267	0.0011
Food Waste- Vegetable	0.0001	0.00001	0.00005	6.56x10 ⁻⁶	0.0053	0.0006
Food Waste – Non-Vegetable	0.0004	0.0001	0.0002	3.48x10 ⁻⁵	0.0221	0.0034
Wood	0.0009	0.0001	0.0137	0.0018	0.0034	0.0004
Newsprint	0.0004	0.0001	0.00005	6.35x10 ⁻⁷	9.57x10 ⁻⁵	1.20x10 ⁻⁵
Corr. Cardboard	0.0008	0.0001	0.00001	0.000002	0.0002	0.00003
Bags and Sacks	0.0008	0.0001	0.00008	1.57x10 ⁻⁵	8.61x10 ⁻⁶	1.74x10 ⁻⁶
PET – Containers	0.0015	0.0001	0.00015	0.00001	0.00001	0.000001
Plastic Film	0.0015	0.0001	0.00014	6.50x10 ⁻⁶	1.64x10 ⁻⁵	7.22x10 ⁻⁷
Ferrous Cans	0	0	0	0	0	0
Ferrous Metal – Other	0	0	0	0	0	0
Total (ton per ton of waste)	0.0162	0.0015	0.1225	0.0067	0.1930	0.0296
Total (ton day ⁻¹)	11	1.0005	81.5	4.5	128.7	19.7
Total (ton per ton of waste)	0.0178		0.1292		0.2226	
Total moisture (ton ton ⁻¹)	0.0178		0.1292		0.2226	
Total (ton day ⁻¹)	23.7		172.3		296.8	

Emissions during composting

The main products of the composting process are fully mineralized materials such as CO₂, H₂O, NH₄, and stabilized organic matter (mostly humic substances) heavily populated with competitive microbial biomass and ash. To model the active composting phase, Levis and Barlaz (2013) propose indexes to calculate CO₂, CH₄ and VOCs. In this study we will consider that 98.3% of the C converts to CO₂ and the remaining 1.7% is released as CH₄ (Levis and Barlaz, 2013). In the case of nitrogen, 4% is emitted as NH₃, 0.4% as N₂O and the rest (95.6%) as N₂. The compost model allows the use of an odor control system (Levis and Barlaz, 2013; Beck-Friss et al., 2001; Boldrin et al., 2009). An estimate of gases released is shown in **Table J-5**.

Table J-5. Emissions from composting facility

Molecule	Total released (tons day ⁻¹)
VOCs	0.000452
CO ₂	167.4
CH ₄	1.0
NH ₃	0.164
N ₂ O	0.042
N ₂	6.461

Emissions due to combustion of diesel fuel

Diesel is used by the tub grinders, front-end loaders in the composting facility. **Table J-6** shows the indicators used to estimate the gases released.

Table J-6. Diesel fuel combustion material flows from selected diesel powered equipment (Komilis and Ham 2004)

Type of vehicle	Diesel Consumption (L tn ⁻¹ MSW)	HC (kg kJ ⁻¹)	CO (kg kJ ⁻¹)	NO _x (kg kJ ⁻¹)	PM _{total} (kg kJ ⁻¹)	SO _x (kg kJ ⁻¹)	CO ₂ (kg L ⁻¹ diesel)
Front-end loader (value refer to a tracked loader)	0.40	2.6E-7	8.9E-7	3.6E-6	2.5E-7	3.1E-7	2.8
Tub grinder (value refer to a chopper/stump)	1.3	4.7E-7	1.9E-6	3.1E-6	3.1E-7	3.6E-7	2.8

Tube grinders: Tube grinders are used to grind down the size of the over passing through the secondary pre-screen. The grinder energy requirement was estimated with a consumption of 10.6 kWh ton⁻¹ and fuel consumption of 0.25 L kWh⁻¹ (Levis and Barlaz, 2013) for the GORE system. In our case, we will be processing 667 wet tons day⁻¹. While Komilis and Ham (2004) recommend an indicator of 1.3 L ton⁻¹ MSW, the parameters recommended by Levis and Barlaz (2013) result in a 2.6 L ton⁻¹. Using the highest parameter, we can estimate a diesel consumption of **1,767 L day⁻¹**.

Front loader: The fuel consumption for this equipment was estimated at 0.33 kWh ton⁻¹ transported (Komilis and Ham, 2004; Levis and Barlaz, 2013). This equipment consumes 0.26 L kWh⁻¹ (Levis and Barlaz 2013). Every day the front loaders move 667 wet tons of biomass and its composting products from: (1) the tipping building to the grinder, (2) from the drop to build the active composting windrow, (3) from the active compost windrow to the maturation step, (4)

from the maturation step to the curing step, and (5) from the curing step to the screening step. So in our calculations we will consider that every day the loaders transport 3004 tons with a diesel consumption of: **1,202 L day⁻¹**.

In total we will suppose that 2,968 L day⁻¹ of diesel are consumed in the installation. The estimation of the amount of contaminants released by the combustion of diesel was done using the parameters shown in **Table J-7** and considering that the density of the diesel is: 0.85 kg L⁻¹ and its low heating value: 42.5x10³ kJ kg⁻¹.

Table J-7. Consumption of diesel and associated emissions (Komilis and Ham, 2004, Levis and Barlaz 2013)

Type of vehicle	Diesel Consumption L day ⁻¹	HC (kg day ⁻¹)	CO (kg day ⁻¹)	NOx (kg day ⁻¹)	PMtotal (kg day ⁻¹)	SOx (kg day ⁻¹)	CO ₂ (kg day ⁻¹)
Front-end loader (value refer to a tracked loader)	1,202	11.3	38.6	15.6	10.9	13.5	3,360
Tub grinder (value refer to a chopper/stump)	1,767	30.0	121.3	197.9	19.8	23.0	4,948
Total	2,968	41.3	160	213	30.6	36.4	8,308

Leachate and other waterborne material flows

Leachate from compost appears yellow to dark-brown in color due to the presence of dissolved and particulate organic matter. Characterization of the amount and type of organic material (both dissolved and particulate) in compost leachate indicate that, in the early stages of composting, the leached organic matter contains oxidized functional groups and then in later stages of composting, there is an increase in phenolic functional groups. The increase of phenolic groups indicates degradation of lignin in the maturing compost (Chatterjee et al., 2013). Generally, varying amounts of leachate can be produced in MSW and yard waste composting facilities starting from 0 (Krogmann and Woycechowski, 2000) to approximately 490 L ton⁻¹. The limited data on leachable material mass loadings presented in Cole (1994) and Krogmann and Woycechowski (2000) cannot be transformed to the more desirable format for mass and energy balances (kg of material per ton of MSW entering the facility).

Figure J-3 shows a scheme on how to conduct the water balance in a composting facility. The water that enters the composting process includes water from the waste itself, reaction water that is generated during the composting process, rain water in open facilities without a roof and tar that is added to adjust the moisture of the feedstock. An additional part of the water balance equation is the loss of evaporated water from open windrows directly to the ambient air or through biofilters.

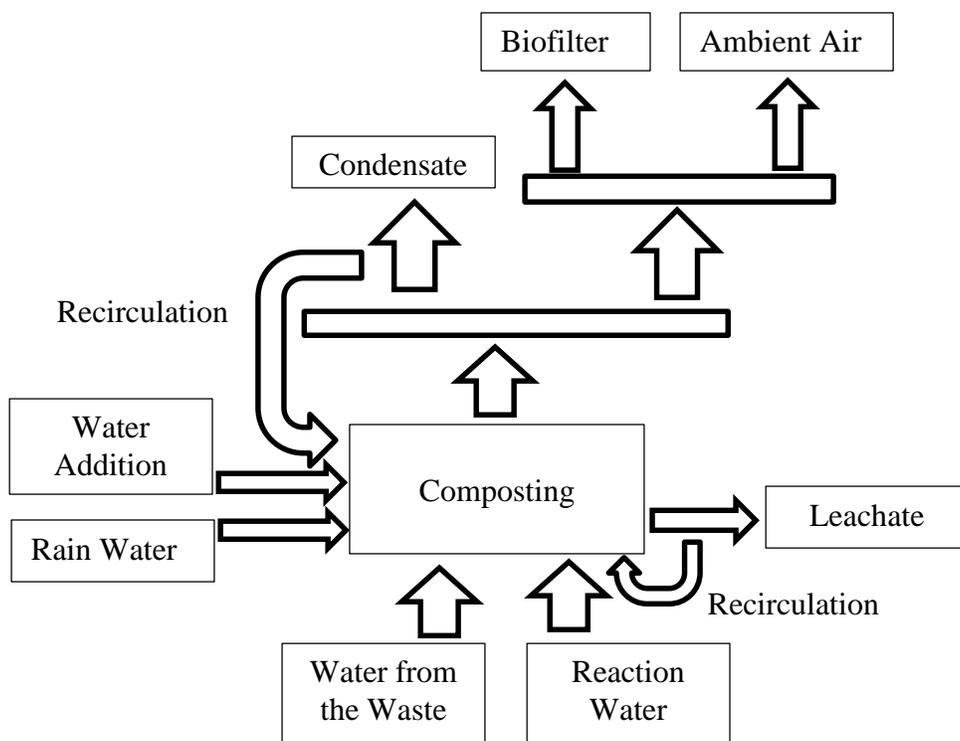


Figure J-3. Schematic water balance during composting (Krogmann and Woycechowski, 2000)

Leachate mass balance: Mass balance calculations predict that an initial waste with a moisture content of 40% and final compost target moisture content of 45% would theoretically not release any liquid by-product (Krogmann and Woycechowski, 2000). On the other hand, a waste with initial moisture and volatile solid content of 70%, a degradation rate of the organic matter of 50% and final compost target moisture content of 35% would release 600 L ton⁻¹ (including the evaporated condensate that is not collected) (Krogmann and Woycechowski, 2000). According to manufacturers of in-vessel and enclosed composting facilities, the amount of collected leachate and condensate ranges between 0 (open rotating drum) and 300 L ton⁻¹ (box composting). In most composting piles, water moves through the pile and towards the bottom under the influence of gravity. This action creates leachate if the moisture content of the compost exceeds its water holding capacity. The authors were not able to find a reliable source for estimating the yield of leachates. In this study, we will suppose that 300 L ton⁻¹ of organic material leachate are produced in our installation (Krogmann and Woycechowski, 2000). The composition of the leachate can be found elsewhere (Krogmann and Woycechowski, 2000).

In our case, the yield of leachate produced will be closely estimated to be: $150 \times 666.666 = 100,000 \text{ L day}^{-1}$, if we suppose a density close to 1000 L ton⁻¹ the leachate will be around 100 ton day⁻¹.

We will consider that the contents of organics that will go into the leachate will be 5% of the solids. So we will be producing 5 ton day⁻¹ of soluble organic materials being released as leachate.

Water mass balance: To conduct the water balance in the installation, we estimate that: (1) the water content of the material entering the active composting pile is 55%, (2) the water content of the material after active composting is 50%, (3) the water content of the material after maturation is 50%, (4) and that the water content of the material after curing is 50%.

In order to achieve the 55% needed in the composting pile we need to add 96.5 ton day⁻¹ of water. This amount of water is similar to the water that could leach out of the composting piles. So we do not expect to use much fresh water to reach the moisture content for the active composting step. The material entering the active composting pile will be approximately 762.6 ton day⁻¹.

A big loss in water mass happens in the active composting step. The product leaving this step has 50% moisture. The wet product of this step is close to 570 ton day⁻¹. It means that in the active composting step, we see a reduction in mass (through leaching, drying or through aerobic degradation) close to 192 tons day⁻¹. The material leaving the maturation step will have 50% of water. The mass flow out of this stream will be close to 512 ton day⁻¹. So in the maturation step, 58 tons day⁻¹ are removed from the solid either through leaching, drying or anaerobic degradation. The material leaving the curing step will also have 50% of water. The mass flow out of this step will be 493 ton day⁻¹. Consequently, the material removed in this step will be 19 ton day⁻¹.

For the overall water balance we will suppose:

Water in: 323 ton day⁻¹

Water out: 246 ton day⁻¹

Water evaporated - water formed by reactions = 323 – 246 = 77 ton day⁻¹

Electricity usage

Electricity is extensively used during material processing, odor control and aeration in the GORE Cover System. Electricity is also used in the office for all other facility types. Some of the indicators associated with the energy use are shown in **Table J-8**.

Table J-8. Equipment fuel and electricity use parameters for GORE systems (Levis and Barlaz, 2013; Komolis and Ham, 2004; US DOE, 2003)

Parameter	Units	GORE
Motor efficiency for forced aeration system	%	65
Blower power	kW	5.6
Blower required per dry mass component	1 ton ⁻¹	0.004
Proportion of the time that the blowers are on	Fraction	0.25
Screens	kWh ton ⁻¹	1
Office area	m ² per ton per day	1.7
Electricity use	kWh m ⁻² year ⁻¹	290
Blower power requirements	kW m ⁻³ min ⁻¹	0.06
Effective motor efficiency	%	64

Electricity consumed by the fan in the tipping floor: The flow of area that needs to be removed was estimated in 24,000 m³ per hour (400 m³ min⁻¹) (removal of the air of the tipping building

four times per hour). Electricity requirement: $0.06 \times 400/0.64 = 37.5$ kW (Motor of 50.28 hp) (The fan to remove the air system will operate 24 hours every). The Electricity consumed everyday will be: **900 kWh**.

Electricity consumed in the composting facility for forced aeration of windrows: Number of blowers required: Every windrow will have 450 tons of material, consequently each windrow will have: $450 \times 0.004 = 1.8$ fans (so each windrow will need 2 fans). In total 64 windrows will need 128 fans. The power of the fans will be 5.6 kW and the efficiency of the fans will be 65%. So the electricity consumed by the fans will be: 1102.7 kW. The fans will only operate 25% of the time. So in total the system will only work 6 hours per day. The electricity consumed will be: **6,617 kWh**.

Electricity consumed by the two screens: 1 kWh per ton processed. The material leaving the curing step and passing for each screen will be: 493 ton day^{-1} , so in total we will be consuming 493 kWh per screen. In total (2 screens) we will be consuming everyday: **986 kWh**.

Electricity consumed in the office area: Surface area: $1.7 \text{ m}^2 \text{ ton}^{-1} \text{ day}^{-1} \times 667 \text{ ton day}^{-1} = 1133.9 \text{ m}^2$
Energy consumed: $1133.9 \times 290 = 328,831$ kWh (every year). So every day the consumption will be: $328,831/360 =$ **913 kWh**.

Total Electricity Consumed: The electricity consumption every day will be **9,415 kWh**. The electricity consumed will be equivalent to 211 kWh per ton-wet material processed. This value is very close to the estimates of Zhang and Matsuto (2011).

Economic analysis

Cost coefficients include both capital C and operation and maintenance (O&M) costs (Komilis et al., 2004). Capital cost includes the land purchase, facility preparation and construction, equipment purchase.

Capital cost estimation: The capital costs primarily consist of land acquisition, construction, engineering, and equipment installation. The direct project costs (DPC) are those directly associated with the construction of the facility. Engineering and management costs are estimated as a percent of the DPC to estimate the installed project costs (IPC). Commissioning, contingency, and contractor's fees are calculated as a percent of the IPC to obtain the total plant costs (TPC). The final capital costs are then calculated as the sum of TPC and land acquisition costs. Land acquisition costs will vary depending on the location of the facility. Site-specific values should be used when available. The primary construction costs are shown in **Table J-9**.

The land required for the installation we calculated using the parameter proposed by Levis and Barlaz (2013) ($0.4 \text{ ha ton}^{-1} \text{ day}^{-1}$). In our case we are processing 667 ton day^{-1} consequently the area required should be: 266.8 hectares (660 acres). The cost of the land will be: $266.8 \times 2,500 =$ **\$666,667** (2013 estimate). An alternative method to calculate the fence requirements is using the parameter given by (Levis and Barlaz 2013) (13 m per ton of biomass processed) ($1.3 * 667 = 8,671$ m). The cost of facing for this installation will be: $8,671 \times 30 =$ **\$260,180** (2013 estimate).

Table J-9. Capital and construction cost parameters (Levis and Barlaz, 2013)

Parameters	Units	GORE
Facility useful life	Years	20
Land requirement	ha ton ⁻¹ day ⁻¹	0.4
Land acquisition cost	\$ ha ⁻¹	2,500
Grading requirement	ha ton ⁻¹ day ⁻¹	0.03
Grading cost	\$ ha ⁻¹	31,400
Paving required	ha ton ⁻¹ day ⁻¹	0.02
Paving cost	\$ ha ⁻¹	123,000
Fencing requirement	m ton ⁻¹ day ⁻¹	13
Fencing cost	\$ m ⁻¹	30
Office requirement	m ² ton ⁻¹ day ⁻¹	1.7
Office cost	\$ m ⁻²	430

Cost of Grading: $0.03 \times 667 \times 31,400 = \mathbf{\$ 628,000}$ (2013 estimate).

Paving cost: $0.02 \times 667 \times 123,000 = \mathbf{\$ 1,640,000}$ (2013 estimate).

Cost of offices: The area of offices was calculated using the parameter recommended by Levis and Barlaz (2013): $1.7 \text{ m}^2 \text{ ton}^{-1} \text{ day}^{-1}$. In our case we will process 667 ton day^{-1} so the area needed is: 1133.3 m^2 . The cost of building the office will be: $1,133.9 \times 430 = \mathbf{\$ 487,333}$ (2013 estimate).

Tipping building: $\mathbf{\$800,000}$ (Wolken, 2007), $\mathbf{\$908,003}$ (2013 estimate).

Total land and construction estimated for 2013 was $\mathbf{\$4,590,003}$. Correcting the costs for inflation using the Marshall & Swift Index we obtain a total land and construction cost for April 2015 of: $\mathbf{\$4,699,842}$.

The total cost of equipment (2015) will be: $\mathbf{\$14,050,134}$ (Table J-10).

Other Engineering costs were calculated as a % of the construction costs:

Engineering, design and supervision: $0.15 * \text{DPC} = \$2,107,520$

Management overheads: $0.1 * \text{DPC} = 0.1 * \text{DPC} = \$1,405,013$

Total Cost of Installed facility (IPC) = $\mathbf{\$17,562,668}$

Commissioning: $0.05 * \text{IPC} = 0.05 * 17,562,668 = \$878,133$

Contingency: $0.1 * \text{IPC} = 0.1 * 17,562,668 = \$1,756,266$

Contractor Fee: $0.1 * \text{IPC} = 0.1 * 17,562,668 = \$1,756,266$

Interest during construction: $0.1 * \text{IPC} = 0.1 * 17,562,668 = \$1,756,266$

TOTAL PLANT COSTS: $\mathbf{\$23,709,602}$

LAND + CONSTRUCTION COST: $\mathbf{\$4,699,842}$

The total capital cost is: $\mathbf{\$28,409,444}$

Table J-10. Main equipment and cost per equipment

Equipment	Number of Units	Cost per Unit	Equipment Life (years)	2007 Total Cost for (20 years of operation)	2015 Costs (Corrected with Marshall & Swift Index)
Scale	1	50,000	10	100,000	116,216
Front-end loaders	10	222,506	10	4,005,162	5,171,770
Pre-trommel	1	148,337*	10	296,674	344,784
Tube Grinder	1	370,843**	10	741,686	861,960
GORE covering system	1	500,000	20	500,000	581,082
Aeration system	64	50,000	20	3,200,000	3,718,925
Cover equipment	2	75,000	20	150,000	174,325
Bell conveyers	4	45,000	10	360,000	418,379
Miscellaneous truck	1	50,000	10	100,000	116,216
Water truck	1	150,000	20	150,000	174,324
Excavator	1	230,000	10	460,000	534,595
Trommel screens (post-screeners)	2	148,337*	10	593,348	689,567
Bobcat	1	44,501	10	89,002	103,434
Odor control system (Biofilter + fan)	1	748,800	20	748,800	870,228
Leachate collection tank*	1	150,000	20	150,000	174,324
Total cost				12,089,630	14,050,134

*Wolken (2007) used a price for the Trommel screens equal to \$ 325,000.

**Wolken (2007) estimated the cost of the grinder in \$ 700,000 and this system will operate for 10 years.

Other sources of information not used in our analysis: Cost of the Volvo Model L90 Front-End Loader: \$ 178,000/loader, Morbark Model 1100 Tub Grinder: \$ 475,000, 6' diameter, 12 feet long, 3/8" opening Trommel Screening Machine (McCloskey): \$ 140,000 (Michigan, 1991)

The facility will be paid in 20 years. We will borrow this money from the bank at a 5.12% interest rate. The annual payment will be: **\$2,302,899 per year.**

Operation and maintenance costs

Operating costs are the costs associated with processing a mass of material through the composting facility and are reported in units \$ ton⁻¹. The model is capable of calculating these costs for the user, or the user may directly enter the capital and operating cost coefficients, if these costs are known. The primary operating costs are fuel and electricity, personnel, and equipment maintenance. Diesel costs are calculated by multiplying the total diesel use calculated in previous sections by the current price of diesel. Electricity costs are calculated similarly.

Cost of diesel: For our estimates we will consider a retail price of \$3 gallon⁻¹ or (\$0.8 L⁻¹). The annual cost of diesel will then be: 2,968 x 240 x 0.8 = **\$569,931**. Our estimate of the diesel cost (**\$569,931**) is close to the estimate given by Larry Condon for a 75,000 tons year⁻¹ plant (\$360,000 year⁻¹). If we suppose that our capacity is 2.1 bigger that the design presented by Larry Condon the fuel consumption should be **\$756,000**).

Cost of Electricity: Cost of kWh: **\$ 0.052**. The annual cost of electricity (360 days) will be: **\$176,250 per year**. This value is very close to the estimate of Larry Condon for a 75,000 ton

year⁻¹ plan they expect to pay close to \$80,000 year⁻¹, a unit 2.1 times that could be paying **\$168,000**. The total operating cost associated to diesel and electricity consumption was: \$746,182 year⁻¹. This is equivalent to \$4.66 ton⁻¹ of material processed. This cost indicator is comparable to the operating cost for electricity, fuel, water and bulking materials reported by Zhang and Matsuto (2011).

Cost of Water, Bulking agent and Chemicals: Using the data provided by Zhang and Matsuto (2011) we will consider that the cost of Water, Bulking agent and Chemicals will be considered 50% to the cost of electricity + diesel: $\$746,181 \text{ year}^{-1} * 0.5 = \mathbf{\$373,090 \text{ per year}}$.

The total cost of electricity, diesel, water, bulking agent, + chemicals will be **\$1,119,272 per year**. According to Zhang and Matsuto (2011) the cost of electricity, fuel, water, bulking materials and chemicals is typically between 1 and 10 thousand JPY ton⁻¹-wet processed (8 and 80 \$ ton⁻¹). Our estimate is **\$7 ton⁻¹**.

Maintenance: Each front-end loader (10 in total) will be operated between 6 am and 12 pm (5 days a week). They will operate 18 hour day⁻¹ x 5 day week⁻¹ = 90 hour week⁻¹ (Levis and Barlaz, 2013). The life of a front-end loader tire is 2,100 hours. It means we will need to change tires every: 23.33 week, so we assume tires are changed twice a year. Total cost of tires for front-end loaders is: $10 * 2 * 4 * 1,000 = \mathbf{\$80,000 \text{ per year}}$.

The bobcat will also work (90 hour week⁻¹), so we will need to change its tires also twice a year (Tire Life: 2,000 hours). The cost of the tires for Bobcat is \$600. Total cost of Tires for Bobcat: $2*4*600 = \mathbf{\$4,800 \text{ per year}}$.

Front-end loader: \$3,000 year⁻¹ per unit: Total: **\$30,000 per year**.

Tub grinder: **\$5000 per year**.

Screens: $\$2000 \text{ year}^{-1} * 3 = \mathbf{\$6000 \text{ per year}}$.

Odor control system: **\$10,000 per year**.

Fans of Windrows: \$3,000 year⁻¹ per windrow (Total = $64 * 3,000 = \mathbf{\$192,000 \text{ per year}}$).

Contingency: **\$32,780 per year**.

Total maintenance cost: **\$360,580 per year**.

Labor: For the estimation of labors we will suppose that the unit hires 32 workers as indicated in **Table J-11** and assumed benefits corresponding to 29% of their base salary.

The total labor expenses will be: **\$1,907,136 per year**. The biggest expense is labor.

Property Taxes and Insurance: The property taxes will be considered 3% of the Capital Investment (Seider et al., 2009). In our case it will be: **\$852,283 per year**.

Operating Overhead: The operating overhead will be considered as 22.8% of the maintenance and labor costs: **\$517,039**.

Total operation and maintenance cost: **\$4,756,311 per year**.

Table J-11. Estimation of labor costs on a composting facility

Appointment	Number of workers	Number of hours day ⁻¹	Salary (\$ h ⁻¹)	Annual salary (\$ year ⁻¹)	Total salary and benefits (\$ year ⁻¹)
General Manager	1	8	60	115,200	148,608
Engineers	2	8	50	96,000	247,680
Secretary	1	8	20	38,400	49,536
Balance and feedstock odor controller	1	8	20	38,400	49,536
Blends preparation	2	8	20	38,400	99,072
Front-end loader operators	16	8	20	38,400	792,576
Operators controlling and sampling composting piles	2	8	20	38,400	99,072
Odor specialist	1	8	20	38,400	49,536
Cleaning and Maintenance	2	8	20	38,400	99,072
Laboratory quality control	1	8	30	57,600	74,304
Marketing and commercialization	2	8	40	76,800	99,072
Public relations	1	8	40	76,800	99,072

Table J-12 shows the composting costs at different facilities in US. Composting costs approximately \$80 to \$200 per ton per day. Within that range, container composters would appear at the lower price range, while agricultural-type static digesters and tunnel composters are in the midpoint. Large, auger-unloaded static digesters and drum composters typically lie in the high end of the price range, but produce higher quality compost (Manser and Keeling, 1996).

Table J-12. Composting Costs of Different Facilities (Diaz, 1993)

Facility	Year Opened	System	Capacity (TPD)	Capital Cost (\$)	O & M Costs (\$ year ⁻¹)	Tipping Fee (\$ ton ⁻¹)
Lake of the Woods County, Minnesota	1989	TW	10	500,000	150,000	0
Fillmore County, Minnesota	1987	A-SP	15-20	1,310,000	N/A	40
Swift County, Minnesota	1990	A-SP	30	1,400,000	266,000	69
Portage, Wisconsin	1986	Drum-TW	30	850,000	N/A	0
St. Cloud, Minnesota	1988	Drum-TW	100	N/A	N/A	50
Portland, Oregon	*	Drum-A-SP	600	20,000,000	5,000,000	42
Pembroke Pines, Florida	†	A-SP	667	48,500,000	N/A	N/A
Dade County, Florida	1990	TW	800	25,000,000	N/A	24

TW – Turned Windrow

A-SP – Aerated Static Pile

* - Closed in mid-1993.

† - Undergoing modifications at time information was published.

Our capital cost of \$28.4M for a 667 ton day⁻¹ facility is comparable to the capital cost for a Portland facility of similar capacity 600 ton day⁻¹ which cost in 1998, \$20M. Correcting for capacity and inflation the cost of this facility in 2015 will be:

$$\text{Cost}_{2015} = \text{Cost}_{1998} * (\text{MS}_{2015}/\text{MS}_{1998}) * (1596/1075)^{0.6} = \mathbf{\$29.7M}$$

For the inflation we considered the Marshall & Swift Index (MS₂₀₁₅ = 1,596, MS₁₉₉₈ = 1,075). Our operational and maintenance costs (\$4.8M year⁻¹) is lower than those of the facility in Oregon (costs for 2015: \$7.4M).

Earnings

Revenue from product sales is also included in the operating costs. The value of the produced soil amendment will vary significantly based on quality and availability of markets. Bagged compost demands the highest price, but if markets are not available, facilities may rely solely on bulk sales. The default sales price is \$20 ton⁻¹, which assumes mostly bulk sales. If most sales are bagged compost, then the price could be greater than \$100 ton⁻¹.

For concept of tipping feeds the composting plant will receive \$60 ton⁻¹ processed. So the revenues for concept of tipping fees will be: 160,000 x 60 = **\$9,600,000** per year. The unit will produce 71,226 ton year⁻¹ of compost (50% moisture). The selling of composted product will be: \$20 ton⁻¹. So the revenue will be: 71,226 x 20 = \$1,424,538 year⁻¹. Total earnings: \$11,024,538 year⁻¹. Capital cost is \$2.3M year⁻¹, operation and maintenance costs are \$4.7M year⁻¹, and annual earnings are \$11,024,538 year⁻¹. The gross earnings of the plant (before taxes) will be: \$3.9M year⁻¹.

Case 1: All the capital obtained from the bank at 5.12% interest per year. Because the gross earning is between \$300,000 and \$10M, we will consider the federal taxes as 113,900 + 34 % (Over 335,000) (Seider et al., 2009). The Federal taxes will be: \$1.3 M year⁻¹.

Case 2: Capital provided by the owner of the facility. In this case the Gross Earnings will be the same: \$11,024,538 year⁻¹ but the production cost will be lower. The gross earnings of the plant (before taxes) will be: \$6.3M year⁻¹. The federal taxes will be \$2.2M year⁻¹. The net earnings in this case will be \$4.0M year⁻¹. This results in a return on investment (ROI) of 14.3 % per year. This ROI is considered acceptable and competitive with current commercial interest rates.

References

- Beck-Friis, B., Smars, S., Jonsson, H., and Kirchmann, H. 2001. Gaseous Emissions of Carbon Dioxide, Ammonia, and Nitrous Oxide from Organic Household Waste in a Compost Reactor Under Different Temperature Regimes. *J. Agric. Eng. Res.*, 78(4), 423–430.
- Boldrin, A., Andersen, J.K., Moller, J., Christensen, T.H., and Favoino, E. 2009. Composting and Compost Utilization: Accounting of Greenhouse Gases and Global Warming Contributions. *Waste Manage. Res.*, 27(8), 800–812.
- Cole MA (1994) Assessing the impact of composting yard trimmings. *BioCycle*, 35(4), 92-96.

- Chatterjee N, Flury M, Hinman C, Cogger CG: Chemical and Physical Characteristics of Compost Leachates. A Review. Report prepared for the Washington State Department of Transportation. August 22, 2013.
- Desert Trucking. 2014. Retrieved from <http://www.deserttrucking.com/rentaltrucks.html>.
- Diaz, L. 1993. Composting and Recycling Municipal Solid Waste. p. 263.
- Ecology. 2011. Siting and Operating Composting Facilities in Washington State. Good Management Practices. Washington State Department of Ecology, Olympia, WA.
- Komilis, D.P., and Ham, R.K. 2004. Life-Cycle Inventory of Municipal Solid Waste and Yard Waste Composting in the United States. *J. Env Eng*, 130 (11), 1390–1400.
- Komilis, D.P., Ham, R.K., and Park, J.K. 2004. Emission of Volatile Organic Compounds during Composting of Municipal Solid Wastes. *Water Res.* 38(7), 1707–1714.
- Krogmann, U., and Woyzechowski, H. 2000. Selected Characteristics of Leachate, Condensate and Runoff Release during Composting of Bio-Genic Waste. *Waste Manage. Res.*, 18, 235–248
- Levis, J.W., and Barlaz, M.A. 2013. Composting Process Model Documentation. North Carolina State University. NC 27695-7908.
- Manser, A.G.R., and Keeling, A.A. 1996. Practical Handbook of Processing and Recycling Municipal Waste. CRC Lewis Publishers.
- Michigan. 1991. Michigan L90. Form No. L-528. VME Americas Inc., Cleveland, OH. Retrieved from volvoce.com.
- Seider, W.D., Seader, J.D., Lewin, D.R., and Widagdo, S. 2009. Product and Process Design Principles. Synthesis, Analysis, and Evaluation. Third Edition. John Wiley & Sons, Inc. pp 534–597.
- US DOE. 2003. Commercial Building Energy Consumption and Expenditure. Energy Information Administration, US Department of Energy.
- Wolken, M. 2007. Alternative analysis. Cedar Grove Composting Everett, Washington Facility Expansion. Report Prepared in May 2007.
- Zhang, H., and Matsuto, T. 2011. Comparison of Mass Balance, Energy Consumption and Cost of Composting Facilities for Different Types of Organic Waste. *Waste Manage.*, 31, 416–422.

Appendix K. Construction of the pyrolysis and pelletization models

This appendix details the information used to model the hypothetical pyrolysis and pelletization processes.

Case I: Production of biochar and hot air

The scheme for a pyrolysis system for the production of biochar and hot air is shown in **Figure K-1**. The capacity is 100 ton day^{-1} ($4.17 \text{ ton hour}^{-1}$). The woody biomass will have 50% moisture. The properties of the different process streams are listed in **Table K-1**.

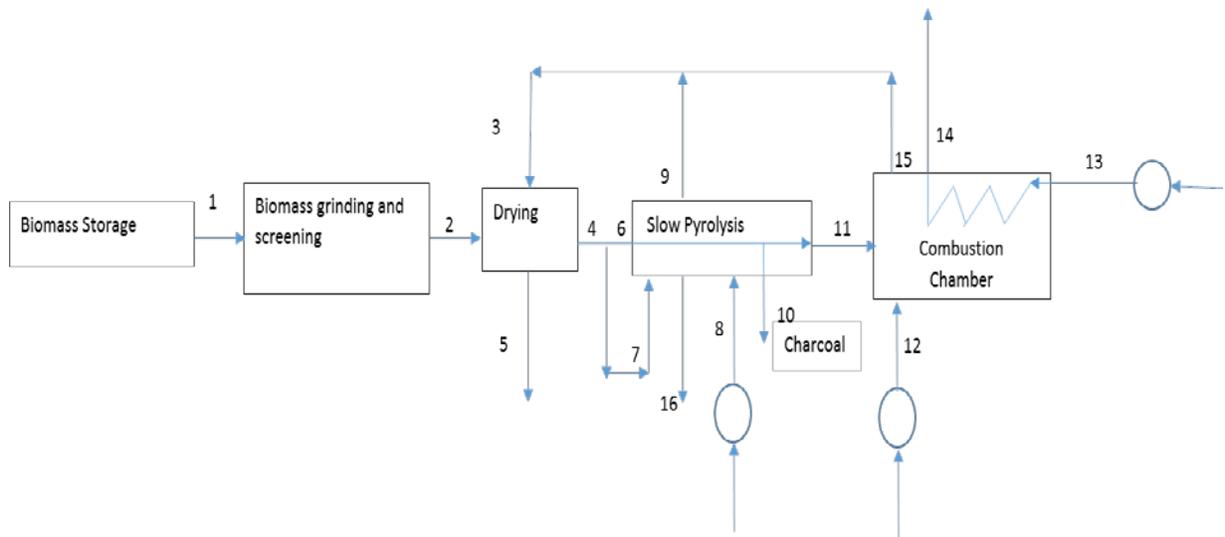


Figure K-1. Scheme of the pyrolysis unit with heat recovery

Mass and energy balances

In our analysis we will consider that the feedstock is a wood waste sized between 10 and 100 mm (3/8-4 in) and mostly free of ferrous and non-ferrous metals. The biomass pretreatment step will be formed by the same system in operation at the composting facility.

Incoming Feedstock: The design capacity of the pyrolysis unit will be 100 wet tons per day. We will try to make use of the same grinding facility used for the composting unit. In the base line scenario of the composting facility it receives trucks with biomass between 9 am and 11 am and between 2 pm to about 4 pm (4 hours per day). So as an average the facility should receive $167 \text{ tons hour}^{-1}$ of mixed materials (during four hours). The woody biomass rich materials will be received between 4 pm and 6 pm and will be stored in the stockpile that after grinding (typical size 1-4 inches) will be blended with the stockpile of bulking agents (wood chips). The first

processing step is screening and sorting out large materials (>2”), and send the unders to mixing while the overs are sent to a secondary screen to remove contaminants.

Table K-1. Properties of main streams

N°	Description	Flow rate (ton day ⁻¹)	Temperature (°C)	Pressure (atm)	Composition
1	Biomass	100	25	1	50 wt. % moisture
2	Biomass	100	25	1	50 wt. % moisture
3	Combustion gases	-	-	1	
4	Biomass	-	80	1	10 wt. % moisture
5	Exhaust combustion gases	-	120	1	-
6	Biomass for pyrolysis	-	80	1	10 wt. % moisture
7	Biomass for combustion	-	80	1	10 wt. % moisture
8	Combustion air	30 % excess	25	1	-
9	Combustion gases	-	Over 600 °C	1	-
10	Charcoal	-	80	1	
11	Pyrolysis gases	-	500	1	-
12	Combustion air	10 % excess	25	1	-
13	Air	-	25	1	-
14	Hot air	-	120	1	-
15	Combustion gases	-	-	1	-
16	Ash	-	80	1	-

The idea is to use the same facilities employed for the preparation of bulking agents, so that we do not have to purchase a new grinder.

If we need to move an extra 100 ton day⁻¹ of biomass then it is necessary to purchase two new front-end loaders (20 ton hour⁻¹ capacity each) that will process the 100 ton day⁻¹ of biomass in three hours. The processing of woody biomass will be carried out between 3 pm and 6 pm. The product from the grinder is discharged to the conveyer that brings the chips into a chips pile. The conveyor contains a screen that allows the smaller particles to by-pass the grinder while the oversize material continues across the screen into the grinder. This is the biggest energy cost of the process.

Fuel consumption in the tube grinder: This equipment is used to reduce the size of the over passing through the secondary pre-screen. The grinder energy requirement was estimated supposing a consumption of 10.6 kWh ton⁻¹ and fuel consumption of 0.25 L kWh⁻¹ (Levis and Barlaz 2013). In our case we will be processing 100 wet ton day⁻¹, so the amount of diesel needed to run the grinder will be: **265 L day⁻¹**.

Fuel consumption by Front loader: The fuel consumption of this equipment was estimated as 0.33 kWh ton⁻¹ transported (Komilis and Ham 2004, Levis and Barlaz 2013). This equipment consumes 0.26 L kWh⁻¹ (Levis and Barlaz 2013). Every day the front loaders move 100 wet tons

of biomass from: (1) storage pile to the tube grinder, so in total the two new front loaders will be consuming: **8.58 L day⁻¹**. The chips will have 25 x 25 mm and will be stored in a covered storage system.

Drier: The energy requirement was estimated as follows. Mass of biomass in: 50 ton day⁻¹; Mass of water in: 50 ton day⁻¹; Mass of water removed: 50 – 5.55 = 44.45 ton day⁻¹. Energy needed to remove water that is initially at 25°C in a form or a vapor at 80°C, the pile will also be heated till 80°C:

$$\Delta H = \dot{m}_{\text{water}} C_{p\text{water}} (80-25) + \dot{m}_{\text{water evaporated}} \lambda_{80^{\circ}\text{C}} + \dot{m}_{\text{biomass}} C_{p\text{ biomass}} (80-25)$$

$$\Delta H = 50 \times 10^3 \text{ kg day}^{-1} \times 4.18 \text{ kJ kg}^{-1} \text{ }^{\circ}\text{C}^{-1} \times (80-25) + 44.45 \times 10^3 \text{ kg day}^{-1} \times 2,277 \text{ kJ kg}^{-1} + 50 \times 10^3 \text{ kg day}^{-1} \times 1.7 \text{ kJ kg}^{-1} \text{ }^{\circ}\text{C}^{-1} (80-25) = 11,495,000 \text{ kJ day}^{-1} + 101,212,650 \text{ kJ day}^{-1} + 1,925,000 \text{ kJ day}^{-1} = 117,370,000 \text{ kJ day}^{-1} = \mathbf{117.4 \text{ GJ day}^{-1}} \text{ (1 G = } 10^9)$$

We will suppose the heat losses on the walls of the drier to be 15% of the energy required for drying. Consequently the energy that is required for the drying is: 134.9 GJ day⁻¹. This energy needs to be provided by the combustion gases that will get in direct contact with them. In order to obtain enough energy for drying and to make sure that the gases leaving the oven are over 130°C (to avoid condensation of water) we have to use combustion gases at 584°C (which is the result of blending the combustion gases from the pyrolysis reactor and the boiler). The total flow of combustion gases used for drying was 310.5 ton day⁻¹. These gases will leave the drier at approximately 143°C.

Pyrolysis: The pyrolysis unit will be fed 44.5 ton day⁻¹ of biomass and 4.94 ton day⁻¹ of water (10% moisture) at 80°C. The yield of char will be estimated in: 25% of the dry biomass. $\dot{m}_{\text{char}} = 0.25 * 44.5 \text{ ton day}^{-1} = \mathbf{11.13 \text{ ton day}^{-1}}$. The yield of vapors + gases = 75%, $\dot{m}_{\text{vapors}} = 0.75 * 44.5 + 4.94 = \mathbf{38.319 \text{ ton day}^{-1}}$

No carrier gas will be used in the pyrolyzer. The elemental composition of the biomass and the char produced is shown in **Table K-2**.

Table K-2. Elemental composition of biomass and char (dry basis) (Suliman et al., *in prep.*)

	C	H	N	O	Ash
Biomass	51.1	8.2	0.4	40	0.3
Char	80.0	4.5	0.3	14	1.2

The elemental composition of the volatiles derived from the biomass will be: C in volatile = 31.1 kg C per 100 kg dry biomass, H in volatiles = 7.075 kg H per 100 kg dry biomass, N in volatiles = 0.325 kg N per 100 kg dry biomass, O in volatiles = 36.5 kg O per 100 dry biomass. Then the flow of elements in the volatiles will be: $\dot{m}_{\text{C}} = 13.839 \text{ ton day}^{-1}$, $\dot{m}_{\text{H}} = 3.14 \text{ ton day}^{-1}$, $\dot{m}_{\text{N}} = 0.144 \text{ ton day}^{-1}$, $\dot{m}_{\text{O}} = 16.425 \text{ ton day}^{-1}$.

Water from biomass: 4.944 ton day⁻¹
 Total volatiles: 38.32 ton day⁻¹

The mass balance in the combustion chamber coupled with the pyrolysis reactor was conducted supposing that 11% of the biomass need to be combusted to provide the energy needs of the pyrolysis reactor. In this case we considered that a 30% of excess air is needed to completely combust the biomass. The flow of combustion air needed was 49.67 ton day⁻¹. The flow of combustion gases obtained was: CO₂ = 10.3 ton day⁻¹, H₂O = 4.67 ton day⁻¹, O₂ = 2.67 ton day⁻¹, N₂ = 55.8 ton day⁻¹.

Energy balance in the pyrolysis reactor:

High heating value of biomass: 22 MJ kg⁻¹

High heating value of charcoal: 30 MJ kg⁻¹.

Enthalpy of pyrolysis vapors

$$\begin{aligned} \dot{h}_{\text{pyrolysis vapors}} &= \dot{h}_{\text{biomass}} - \dot{h}_{\text{char}} + Q_{\text{through the wall}} \\ \dot{h}_{\text{pyrolysis vapors}} &= m_{\text{biomass}} \text{HHV} + m_{\text{biomass}} C_p (80-25) + m_{\text{H}_2\text{O}} C_p (80-25) - m_{\text{char}} \text{HHV} - m_{\text{char}} C_p \\ &\quad (80-25) + Q_{\text{through the wall}} \\ \dot{h}_{\text{pyrolysis vapors}} &= 716.68 \text{ GJ day}^{-1} \end{aligned}$$

In order to provide the heat needed in the pyrolysis reactor we will combust 11 % of the biomass. Knowing the HHV of this biomass and the amount of heat we need to transfer through the walls (66.75 GJ day⁻¹ or 2,636,116 BTU h⁻¹) it is possible to estimate by an energy balance the enthalpy of the combustion gases. $\dot{h}_{\text{combustion gases}} = 47.575 \text{ GJ day}^{-1}$. This enthalpy is achieved when the temperature of the combustion gases is 600°C. This temperature is higher than the temperature of the pyrolysis reactor consequently it should be achievable. We will suppose that the system requires a motor of 30 hp.

Air Heater: The pyrolysis vapors will be combusted with air. We supposed that 10% excess air to be sufficient. The flow of air needed for the combustion is 216.46 ton day⁻¹. The combustion process will result in the production of 50.744 ton day⁻¹ of CO₂, 33.28 ton day⁻¹ of H₂O, 4.58 ton day⁻¹ of O₂, 166.2 ton day⁻¹ of N₂. Total flow of the combustion air will be 254.8 ton day⁻¹. In order to have enough heat for the drying process it was necessary to keep the combustion gases from the air heater relatively hot at 427°C. This will result in an enthalpy of the gases of 200.66 GJ day⁻¹. Knowing the enthalpy of the pyrolysis vapors it was possible to estimate the energy available to produce hot air. In our case we considered that 10% of the energy available was lost through the walls of the air heater. Consequently, the amount of energy for the production of hot air will be 464.41 GJ day⁻¹. The air will be heated from 25°C to 120°C. The question is how many tons of air we can heat with **461.41 GJ day⁻¹**. The air will be heated between 25°C to 120°C. The specific heat of air at 72.5°C is 1.009 kJ kg⁻¹ °C⁻¹). The mass of hot air that can be produced is 4,888.6 ton day⁻¹.

Capital cost estimation (CAPEX)

To obtain the capital expenditure of new biorefinery concepts two main sources of information were consulted. The first one was the book *Product and Process Design Principles* (Seider et al., 2009) and the second one was the book *Plant Design and Economics for Chemical Engineers* (Peters et al., 2003). From the former one, we obtain a first cost estimation of each of the equipment that makes the biorefinery concept. These values were added and updated to 2015

taking into account the *Marshal-Swift (MS) Process Industry Index* between 2006 and the present year. From the later one, we took the coefficients for obtaining the other direct costs such as delivered cost, installation, instrumentation, buildings, etc., and the total indirect costs such as engineering and supervision, construction expenses, legal expenses, etc. After adding these values the Total Capital Investment was obtained.

Drier: The estimation of the size of the drier was conducted using the information reported online (<http://hngxjx.en.alibaba.com>, refer to Competitive Price Sawdust Rotary Drum Dryer). This Rotary drum drier was designed for Sawdust. In our case drum should be able to process 100 ton day⁻¹ (4 ton hour⁻¹). The drum selected has a diameter of 1.2 m and a length of 12 m, speed of 5.8 rpm, and power of 11 kW. The purchase cost of this oven will be \$45,000 (cost 2015).

Pyrolysis reactor: The heat absorbed (Q, Btu hour⁻¹) was the key parameter for the pyrolysis reactor. According with our calculation, 66.7 GJ day⁻¹ (2,636,116 BTU h⁻¹) is the heat that need to be transferred through the wall. After applying proposed by Seider et al. (2009) a value of \$103,251.09 (cost in 2009) (or \$120,724 in 2015) was obtained.

Fan 1: This fan is feeding the air for biomass burning in order to start running the pyrolysis reactor. The actual cubic feet per min (ACFM) was the key parameter to obtain the cost. Our calculations had shown a value of 49.67 ton day⁻¹ as the required air to be used. With this value, and chosen a centrifugal backward-curved fan in (Seider et al., 2009), a value of \$2,000 was obtained (\$2,338 in 2015 costs).

Fan 2: Following the same procedure as the one mentioned before, and with a capacity of 216.46 ton day⁻¹ of air, a value of \$3,000 was obtained (\$3,508 in 2015 costs).

Combustion Chamber: It was assumed that the Q absorbed for the air is going to be the same as the enthalpy of the gases. Therefore, using a value of 200.66 GJ day⁻¹ (after converting the units to Btu hour⁻¹) (Seider et al., 2009) a value of \$300,000.00 was obtained (\$350,770 in 2015 costs).

The capital recovery will be: $0.081609 * 2,108,686 = \$172,088 \text{ year}^{-1}$

Table K-3. Equipment cost for the pyrolysis model (Seider et al., 2009)

Equipment	Estimated cost (\$)
Drier (direct-heat rotary drum) (2015)	45,000
Pyrolysis reactor (2015)	120,724
Fan 1 (biomass burning) (2015)	2,338
Fan 2 (pyrolysis vapor burning) (2015)	3,508
Combustion chamber (2015)	350,770
Total (2015)	522,340

Table K-4. Calculation for the Total Capital Investment (TCI) for a pyrolysis system to be added to a composting facility (Peters et al., 2003 (page 251) for Solid processing Plant)

Calculation of FCI	Coefficients	Cost updated 2015 (\$)
Purchased equipment cost (PEC)	100%	522,340
Delivering of Equipment cost	10%	52234
Delivered Equipment (DPEC)		574,574
Installation % of DPEC	45%	258,558
Instrumentation and controls (installed) % of DPEC	18%	103,423
Piping (installed) % of DPEC	16%	91,931
Electrical System (installed) % of DPEC	10%	57,457
Buildings (including services) % of DPEC	25%	143,643
Yard improvements % of DPEC	15%	86,186
Total direct plant cost		1,315,774
Engineering and supervision % of DPEC	33%	189,609
Construction expenses % of DPEC	39%	224,083
Legal expenses % of DPEC	4%	22,983
Contractors' fee % of DPEC	17%	97,677
Contingency % of DPEC	35%	201,100
Total indirect plant cost		735,454
Fixed capital investment (FCI)		2,051,229
Start up (SU) % of DPEC	10%	57,457
Total Capital Investment (TCI)		2,108,686

Operational Costs (OPEX)

Cost of diesel: Fuel consumption in the tube grinder: 265 L day⁻¹, Fuel consumption by front loader: 8.58 L day⁻¹, Total fuel consumption: 273.6 L day⁻¹. For our estimates we will consider a retail price of \$3 gallon⁻¹ or (\$0.8 L⁻¹). The annual cost of diesel will then be: 273.6 x 240 x 0.8 = **\$52,531 year⁻¹**

Cost of Electricity: Cost of kWh: **\$0.052**. We will consider that the main electricity costs will be associated to two 30 hp motors working with the pyrolysis unit and the drier. In total the unit will be consumed in these two motors 60 hp or 45 kW (in a day we will consume 24 x 45 kW = 1,080 kWh). The total consumption in a year will be: \$0.052 * 1,080 kWh * 360 = \$20,218. We will consider that the lights of the building and the other electrical equipment will consume 20% more of electricity. Total cost of electricity per year: 1.2 * 20,218=**\$24,262**

Maintenance: The annual maintenance cost calculated as 5% of the capital following the recommendations of (Seider et al., 2009). In this case it will be: 0.05 * 2,108,686 = \$105,434 year⁻¹

Labor: For the estimation of labors we will suppose that the unit hires 12 workers (3 per shifts) (4 shifts) and assumed benefits corresponding to 29% of their base salary.

Table K-5. Estimation of labor costs on a composting facility

Appointment	Number of workers	Number of hours day ⁻¹	Salary (\$ h ⁻¹)	Annual salary (\$ year ⁻¹)	Total salary and benefits (\$ year ⁻¹)
Operators	12	8	20	460,800	594,432

The total labor expenses will be: **\$594,432 per year**

Property Taxes and Insurance: The property taxes will be considered 3% of the Capital Investment (Seider et al., 2009). In our case it will be: $0.03 * 2,108,686 = \mathbf{\$63,261}$

Operating Overhead: The operating overhead will be considered as 22.8% of the maintenance and labor costs: $0.228 * (594,432 + 105,434) = \mathbf{\$159,569}$

Total Operational costs: **\$999,489**

Earnings

The unit will commercialize biochar. The default selling price for the biochar produced will be \$200 per ton, which assumes mostly bulk sales. For concept of tipping feeds the new unit will receive \$60 ton⁻¹ processed. So the revenues for concept of tipping fees will be: $100 \text{ ton day}^{-1} \times 300 \text{ day year}^{-1} \times 60 \text{ \$ ton}^{-1} = \$1,800,000 \text{ year}^{-1}$. The unit will produce 11.1 ton day⁻¹ or (3,330 tons year⁻¹, 300 days per year of operation). The selling of the biochar will be \$200 ton⁻¹. So the revenue for selling the char will be: $\$666,000 \text{ year}^{-1}$. The gross earning (before tax) will be: $\$2,466,000 \text{ year}^{-1}$

Case 1: All the capital obtained from the bank at 5.12% interest per year. In order to pay the capital (\$2.1M) and the interest in 20 years we will need to pay every year: $\$172,088 \text{ year}^{-1}$. When federal taxes ($\$440,496 \text{ year}^{-1}$) are included, the net earning is $\$855,081 \text{ year}^{-1}$.

Case 2: Here we assume that all of the capital cost is provided by the owner of the facility. The gross earnings of the plant (before taxes) are $\$1,468,310 \text{ year}^{-1}$. The federal taxes are $\$499,225 \text{ year}^{-1}$. The net earnings are $\$969,085 \text{ year}^{-1}$. This results in a return on investment (ROI) of **46%** per year which is very high much higher than the composting facility alone which has a ROI of **12%**. Our results are similar with to those reported by Tom Miles (2009). For a similar capacity Mr. Miles estimated a capital cost (2009) of \$500,000-\$1,000,000 (2015 Costs: \$0.57- 1.14 M). Our capital cost was slightly bigger (around \$ 2.1M). Mr. Miles considered that it was possible to obtain revenues for the heat produced equivalent to $\$320,000 \text{ year}^{-1}$. We did not consider it as a source of revenue. Our operation and maintenance cost are also higher than the cost estimated by Mr. Miles ($\$1.0 \text{ M year}^{-1}$ vs. $\$0.4 \text{ M year}^{-1}$). A reduction in the capital cost and operational cost of the unit, obtaining better selling prices for the biochar and obtaining revenue for selling the heat produced can definitively improve the economic viability of producing biochar. The tipping fees are needed to make this approach viable. The revenue for the selling of the biochar does not cover the operational costs.

Case II: Production of biochar and electricity

The scheme for a pyrolysis system with a Rankine cycle for electricity and biochar production is shown in **Figure K-2**. The capacity is 100 ton day^{-1} (4.17 ton h^{-1}). The woody biomass will have 50% moisture.

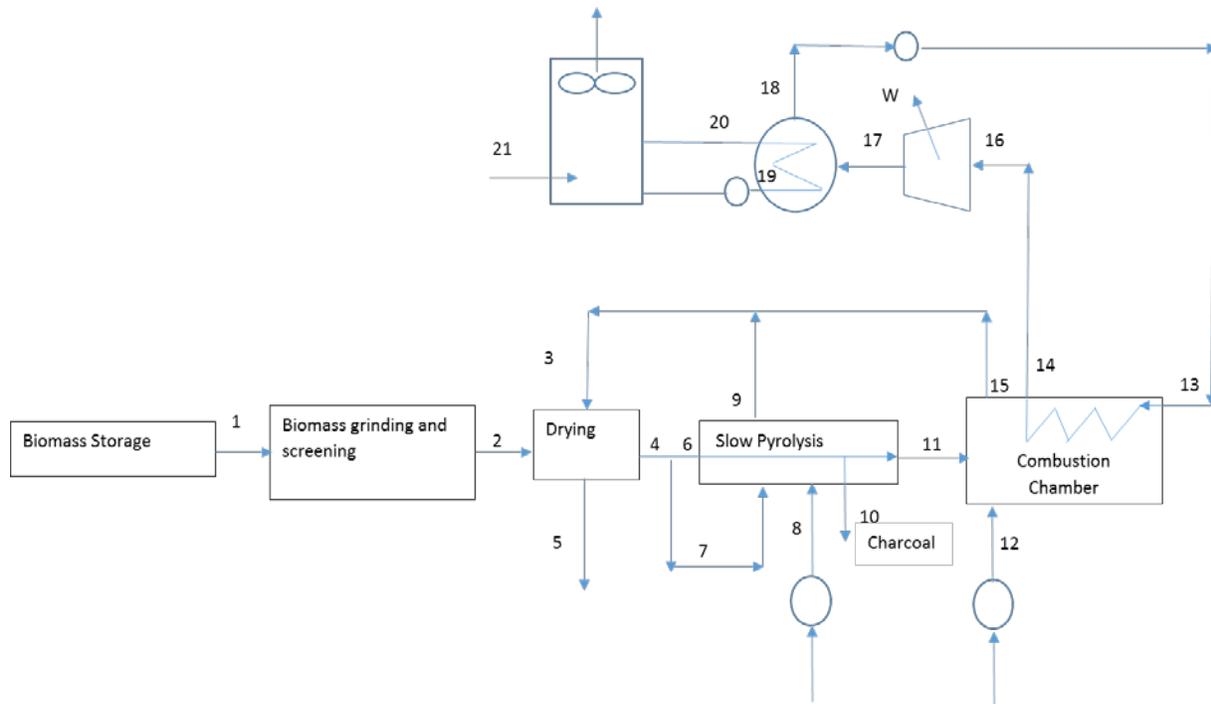


Figure K-2. System for the production of electricity

Mass/Energy and Economic Calculations

The mass and energy balance of the Rankine cycle is very similar to the previous case. We will also suppose that we have $464.4 \text{ GJ day}^{-1}$ available to produce steam. The water will enter the boiler at 40°C and will be used to produce super-heated steam at 320°C and 20 atm.

$$h_{\text{water}} (20 \text{ atm}, 40^\circ\text{C}, \text{liquid}) = 169 \text{ kJ kg}^{-1}, h_{\text{steam}} (20 \text{ atm}, 320^\circ\text{C}, \text{super-heated steam}) = 3,070 \text{ kJ kg}^{-1}$$

The amount of steam that will be produced was equal to **$160.1 \text{ ton day}^{-1}$** . The performance of the steam turbine was calculated using the Turbine Steam-Consumption calculator considering an inlet steam pressure of 20 atm, a temperature of 320°C (593 K), an exhaust pressure of 2 atm and an isentropic efficiency of 70%. The software estimated the temperature at the exit of the turbine as 408.1 K (135.1°C). The specific steam consumption will be: $10.86 \text{ kg kWh}^{-1}$. The power output of the turbine will be $160,096.7/10.86 = \mathbf{14,741 \text{ kWh (per day)}}$. The composting facility consumes everyday **$9,325 \text{ kWh}$** . So the overall production for export will be **$5,417 \text{ kWh}$** . The amount of heat that will be removed in the condenser will be: *Inlet:* Steam 2 atm and 135.1°C on this conditions the enthalpy will be $2728.31 \text{ kJ kg}^{-1}$ (TLV.com, 2015). *Outlet:* Water 2 atm and 80°C on this condition the enthalpy will be $334.949 \text{ kJ kg}^{-1}$. The amount of heat that is

transferred is: $2,728.31 - 334.94 = 2,393.37 \text{ kJ kg}^{-1}$. For a flow of steam condensed of 160.1 ton day⁻¹ the amount of heat lost will be: 383,178,537 kJ day⁻¹ or **383.17 GJ day⁻¹**

Capital cost estimation (CAPEX)

As it was stated before, in this concept instead of producing hot air, electricity is obtained. The two main equipment that are added to the ones mentioned before are the steam boiler and the turbine (**Figure K-2**).

Steam boiler: The key parameter to find the steam boiler cost is the heat absorbed (Q , Btu h⁻¹). Taking into consideration the value of 464.4 GJ day⁻¹ that is the available energy for steam production, as the same amount of energy that is going to be absorbed, and using Eq. 1, a value of \$143,710.44 (\$166,704 when corrected for 2015) is obtained.

$$Cp = 0.367Q^{0.77} \quad \text{Eq. 1}$$

Turbine: The output power (P , Hp) is the parameter used for Turbine cost determination. According with our previous results, a total power output of 14,741 kWh day⁻¹ can be produced in the new alternative. A steam turbine (condensing) was chosen, and after applying Eq. 5, the value of \$392,101.18 (\$454,837 for 2015 costs) was obtained.

$$Cp = 25,000P^{0.41} \quad \text{Eq. 2}$$

Condenser: For condenser cost, it is necessary to find the Area (A) in order to obtain the cost of this equipment. Using Eq. 3 it is possible to obtain the value of A .

$$Q = UA\Delta T_M \quad \text{Eq. 3}$$

Where,

Q = heat transferred (W)

U = overall heat transfer coefficient (W m⁻²K⁻¹)

ΔT_M = mean temperature driving-force.

ΔT_M is expressed in the form as log mean as it can be seen in Eq. 4:

$$\Delta T_M = \frac{\Delta T_1 - \Delta T_2}{\ln \frac{\Delta T_1}{\Delta T_2}} \quad \text{Eq. 4}$$

Where,

ΔT_1 = Temperature difference in the inlet of a concurrent condenser

ΔT_2 = Temperature difference in the outlet of a concurrent condenser

The following data was obtained in our previous calculations:

$$Q = 383.17 \text{ GJ day}^{-1}$$

T1 hot stream (after steam turbine) = 135.1°C

Assuming the following information it is possible to find the Area of heat transfer in the condenser.

T2 hot stream (after condenser) = 80°C

T1 cold stream = 25°C

T2 cold stream = 30°C

$U = 1000 \text{ (W m}^{-2} \text{ K}^{-1}\text{)}$

Using the information stated below on Eq. 3, a value of A is obtained.

$$A = 12.70 \text{ m}^2 \text{ (136.73 ft}^2\text{)}$$

Using the area in ft^2 on the Figure 22.10 (Seider et al., 2009) for a fixed head condenser, a FOB purchase cost of \$10,000 (\$11,600) is found.

Adding the new equipment to the ones selected for the previous concept, a total value of equipment cost of \$1,155,481 was obtained. This is the total capital investment cost.

The capital recovery will be: $0.081609 * 4,664,677 = \$378,123$

Table K-6. Equipment cost

Item	Cost (\$)
Steam boiler (2015)	166,704
Turbine (2015)	454,837
Condenser (2015)	11,600
Other equipment (see previous section) (2015)	522,340
Total (2015)	1,155,481

Operational Costs (OPEX)

Cost of diesel: Fuel consumption in the tube grinder: 265 L day⁻¹. Fuel consumption by front loader: 8.58 L day⁻¹. Total fuel consumption: 273.6 L day⁻¹. For our estimates we will consider a retail price of \$3 gallon⁻¹ or (\$0.8 L⁻¹). The annual cost of diesel will then be: $273.6 \times 240 \times 0.8 =$ **\$52,531 per year**

Cost of Electricity: Cost of kWh: **\$0.052**. We will consider that the main electricity costs will be associated to two 30 hp motors working with the pyrolysis unit and the drier. In total the unit will be consumed in these two motors 60 hp or 45 kW (in a day we will consume $24 \times 45 \text{ kW} = 1,080 \text{ kWh}$). The total consumption in a year will be: $0.052 * 1,080 \text{ kWh} * 360 = \$20,218$
We will consider that the lights of the building and the other electrical equipment will consume 20% more of electricity. Total cost of electricity per year: $1.2 * 20,218 =$ **\$24,262**

Maintenance: The itemized annual maintenance cost calculated is close to 5% of the capital cost following the recommendations of (Seider et al., 2009). In this case it will be: $0.05 * \$4,664,677 =$ **\$233,233 per year**

Table K-7. Calculation for the Total Capital Investment (Peters et al., 2003)

Calculation of FCI	Coefficients	Cost updated 2015 (\$)
Purchased Equipment cost (PEC)	100%	1,155,481
Delivering of Equipment cost	10%	115,548
Delivered Equipment (DPEC)		1,271,029
Installation % of DPEC	45%	571,963
Instrumentation and controls (installed) % of DPEC	18%	228,785
Piping (installed) % of DPEC	16%	203,364
Electrical System (installed) % of DPEC	10%	127,102
Buildings (including services) % of DPEC	25%	317,757
Yard improvements % of DPEC	15%	190,654
Total direct plant cost		2,910,656
Engineering and supervision % of DPEC	33%	419,439
Construction expenses % of DPEC	39%	495,701
Legal expenses % of DPEC	4%	50,841
Contractors' fee % of DPEC	17%	216,074
Contingency % of DPEC	35%	444,860
Total indirect plant cost		1,626,917
Fixed capital investment (FCI)		4,537,574
Start up (SU) % of DPEC	10%	127,103
Total Capital Investment (TCI)		4,664,677

Labor: For the estimation of labors we will suppose that the unit hires 12 workers (3 per shifts) (4 shifts) and assumed benefits corresponding to 29% of their base salary. The total labor expenses will be: **\$594,432 per year**

Table K-8. Estimation of labor costs on a composting facility

Appointment	Number of workers	Number of hours day ⁻¹	Salary (\$ h ⁻¹)	Annual salary (\$ year ⁻¹)	Total salary and benefits (\$ year ⁻¹)
Operators	12	8	20	460,800	594,432

Property Taxes and Insurance: The property taxes will be considered 3% of the Capital Investment (Seider et al., 2009). In our case it will be: $0.03 * 4,664,677 = \$139,940$

Operating Overhead: The operating overhead will be considered as 22.8% of the maintenance and labor costs: $0.228 * (594,432 + 139,940) = \mathbf{\$188,708}$. Total Operational costs: **\$1,233,107**

Earnings

For concept of tipping feeds the new unit will receive $\$60 \text{ ton}^{-1}$ processed. So the revenues for concept of tipping fees will be: $100 \text{ ton day}^{-1} \times 300 \text{ day year}^{-1} \times 60 \$ \text{ ton}^{-1} = \mathbf{\$1,800,000 \text{ per year}}$. The unit will produce $11.1 \text{ ton day}^{-1}$ or $(3,330 \text{ tons year}^{-1}, 300 \text{ days per year of operation})$.

The selling of the biochar will be \$200 ton⁻¹. So the revenue for selling the char will be: **\$667,800 per year**. The unit will sell electricity: 14,741 kWh per day or 4,422,300 kWh per year at a price of \$0.052 per kWh, the actual revenue from the electricity will be: **\$229,960 per year**. Annual Revenues: **\$2,697,760**

Case 1: All the capital obtained from the bank at 5.12% interest per year. In order to pay the capital and the interest in 20 years we will need to pay every year: **\$378,123 per year**

Net earnings

Gross earnings are \$1,086,529 year⁻¹. Because the gross earning is between \$300,000 and \$10M, we will consider the federal taxes as 113,900 + 34 % (Over 335,000) (Seider et al., 2009). The Federal taxes will be: \$369,420 year⁻¹. The Net earnings of the unit will be: \$717,109 year⁻¹

Case 2: Capital provided by the owner of the facility. The gross earnings of the plant (before taxes) will be: \$1,464,653 year⁻¹. The federal taxes will be \$497,982 year⁻¹. The net earnings in this case will be: \$966,671 year⁻¹. This results in a return on investment (ROI) of 20.7 % per year. This ROI is considered acceptable and competitive with current commercial interest rates.

Case III: Production of pellets

The description of the pellets plant including pretreatment is as follow. The woody biomass is placed in the rotary cutter to reduce the size of the original woody biomass, and then it is transported by a belt conveyor to a hot air stove to reduce the moisture content up to 10%. Then another belt conveyor delivers the dry biomass into the hammer mill where the final size, less than 3 mm, is reached. Then the dried pieces of woody biomass are carried up into a material bin in which it is stored. From the material bin, there is a feeder that feed the biomass into two parallel units of pellet mill. Using a belt conveyor and a bucket elevator the pellets are transported to a counter flow cooler. From here another belt conveyor and bucket elevator carries the cold pellets to a vibrating screener before going to a finished product silo which ended with a packing machine.

Figure K-3 shows the unit operations and the flow of biomass in a typical biomass pelleting operation (Mani et al., 2006) that consist of three major unit operations, drying, size reduction (grinding) and densification (pelleting). The biomass is dried to about 10 % in the rotary drum drier. Superheated steam dryers, flash dryers, spouted bed dryers, and belt dryers are also common in European countries but they are not used in North America. The drying medium is the flue gas from the direct combustion of natural gas. Solid fuels, especially biomass fuels are gradually replacing natural gas because of recent price increases in fossil fuels. After drying a hammer mill equipped with a screen size of 3.2 to 6.4 mm reduces the dried biomass to a particle size suitable for pelleting. The ground biomass is compacted in the press mill to form pellets. The individual pellet density ranges from 1,000 to 1,200 kg m⁻³ and can be handled by systems typically used to handle grains. In some operations, binders or stabilizing agents are used to reduce the pellet springiness and to increase the pellet density and durability. The temperature of the pellets coming out of the pellet mill ranges from 70 to 90°C. The elevated temperature is due the frictional heat generated during extrusion and material pre-heating. Pellets are cooled to within 5°C of the ambient temperature in a cooler (Mani et al., 2006).

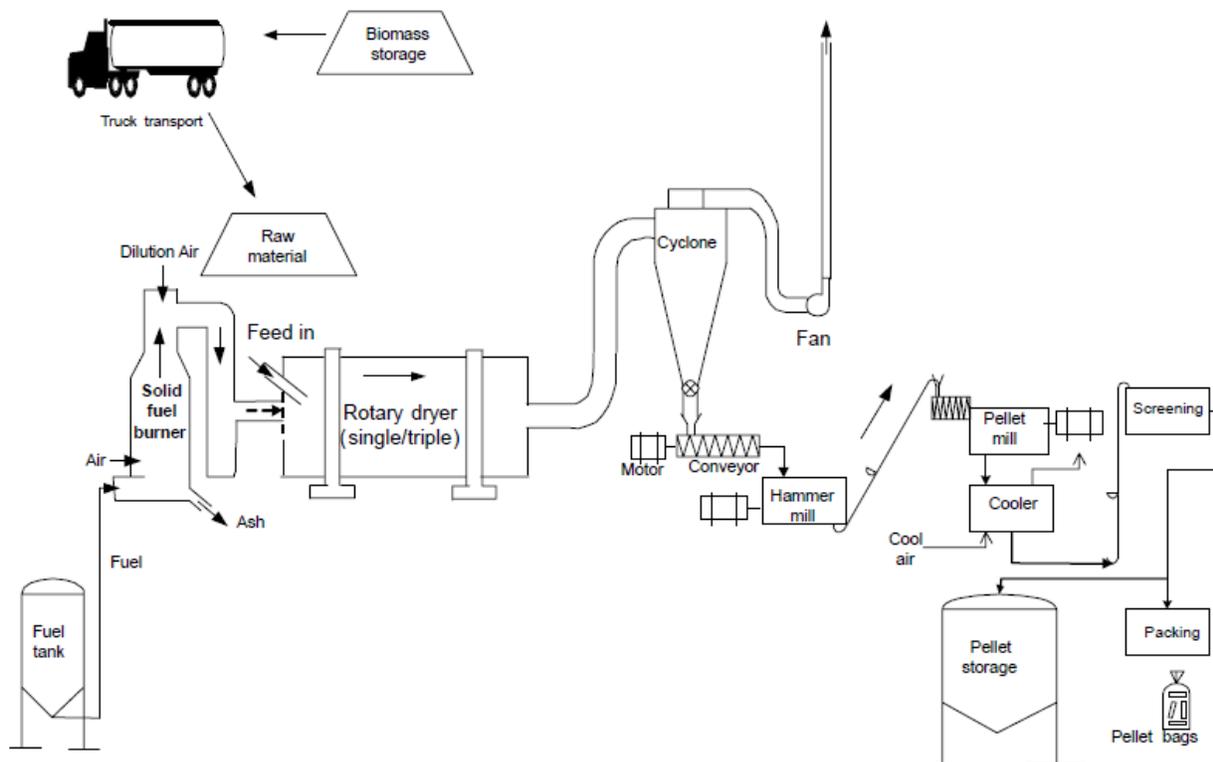


Figure K-3. Schematic layout of typical biomass pelleting plant (Mani et al 2006).

General considerations about to integrating a pellets plant in a MSW facility are shown in **Table 9**. Land cost was not be considered for any the new plant due to we are assuming that the new biorefinery will be built adjacent to the existing MSW composting facility, and no new acquisition of land is required.

Table K-9. General assumptions for the MSW facilities baseline scenario

	Value
Woody biomass flow rate (ton day ⁻¹)	100
New plant operational hours (h)	24
Lifespan project (y)	25
Woody biomass moisture	50% (w/w)

Before going to the pellets plant, it is necessary to reduce the size and the moisture content (up to 10% w/w) of the woody biomass. Therefore a pre-treatment technology that includes the following equipment was included: biomass press, rotary cutter, belt conveyor, rotary drum dryer, fan blowers, cyclones, air locks, belt conveyor, and hammer mill among others.

Capital cost estimation (CAPEX)

A list of the equipment, their use, cost and the factors used for CAPEX analysis can be seen in **Tables K-10 and K-11**. The purchasing information for each of the equipment was obtained

from a quotation generated by Jinan Biomass Machinery Equipment Co., Ltd (<http://www.bio-machinery.com/>, retrieved 4/14/2015). The estimated effect of the scale on the equipment cost was calculated using the relationship known as the six-tenths factor rule shown in Equation 1, below (Peters et al., 2003). Here, by knowing the cost of a unit b , the cost of a similar unit a with X times the capacity of the first unit is $X^{0.6}$ (Peters et al., 2003). The installation cost was calculated as 25% of the delivered purchased-equipment cost (Peters et al., 2003).

$$\text{Cost of equipment } a = (\text{cost of equipment } b)X^{0.6} \quad \text{Eq. 1}$$

Table K-10. Equipment needed for woody biomass pretreatment

Equipment	Function	Power (kW)	Useful-life (years)	Total price (\$)	Total price with scaling factor (\$)	Total Cost (\$)
Rotary Cutter	Reducing-biomass size	132	10	59,016	79,780	199,450
Belt Conveyor	Biomass transportation	5.5	25	4,590	6,205	6,205
Rotatory Drum	Reducing MC	18.5	15	69,672	85,181	141,968
Fan blower	Drying system	37	25	4,836	6,538	6,538
Cyclone	Drying system		25	4,344	5,873	5,873
Air lock	Drying system	1.5	25	1,230	1,662	1,662
Belt Conveyor	Dry biomass transportation	5.5	25	4,590	6,205	6,205
Hammer Mill	Cutting the biomass	220	15	28,689	38,782	64,637
Fan blower	Hammer Mill system	30	25	4,098	5,540	5,540
Cyclone	Hammer Mill system		25	4,016	5,430	5,430
Air lock	Hammer Mill system	11	25	3,689	4,986	4,986
						448,494

In addition to the equipment mentioned for the pretreatment step, the pelletization unit includes the purchasing cost of the pellets mill, bucket elevators, silos, packing machine, bag dust collector etc. The installation cost was calculated as 25% of the delivered purchased-equipment cost (Peters et al., 2003).

Parameters from CAPEX with a lifespan equal or greater of the project selected time (25 years) were discounted in year zero (0) in the cash flow. Other parameters with a lifespan lesser than 25 years were discounted as an annual equivalent cost. The discount rate chosen for assessing all projects was 10%.

The capacity of the pellets plant on fresh biomass basis, as it was stated before, was 100 ton day⁻¹. This capacity applies for the pretreatment process. However, after taking into consideration the reduction on moisture content from 50 to 10%, the specific equipment for pelletization will have a capacity of 2.31 ton hour⁻¹. **Table 12** shows the calculation of the total capital investment (TCI) for both the pretreatment process and the pelletization.

Table K-11. Equipment needed for woody biomass pelletization

Equipment	Function	Power (kW)	Useful -life (years)	Total price (\$)	Total price with scaling factor (\$)	Cost 2015
Biomass level meter	Indicate biomass level	0.2	25	689	433	433
Biomass bin	Hydraulic storing the biomass level	7.5	25	10,164	6,395	6,395
Feeder	Feed the biomass	4	25	6,066	3,816	3,816
Conditioner	adjust the biomass conditions	3	25	5,738	3,610	3,610
Pellet Mill	Pressing pellets	227.55	15	131,148	82,517	137,528
Belt conveyor	Transport finished pellets	4	25	1,885	1,186	1,186
Bucket elevator	Elevate the hot pellets	4	25	3,033	1,908	1,908
Air lock	Working with cooler	3	25	2,049	1,289	1,289
Counter flower cooler	Cooling the hot pellets	0.37	25	7,869	4,951	4,951
Fan blower	Working with cooler	22	25	2,541	1,599	1,599
Cyclone	Working with cooler		25	1,443	908	908
Air lock	Working with cooler	1.1	25	902	567	567
Belt conveyor	Transport pellets into buckets	3	25	2,377	1,496	1,496
Bucket elevator	Elevate the hot pellets	3	25	3,443	2,166	2,166
Vibrating Screener	Quality test	0.74	25	4,672	2,940	2,940
Air lock	Working with Screener	5.5	25	1,230	774	774
Transporting pipes	Bad pellets resent pipe		25	2,131	1,341	1,341
Cyclone	Working with pipes		25	820	516	516
Silo	Store the good pellets		25	4,508	2,837	2,837
Biomass level meter	Indicate the pellets level	0.2	25	689	433	433
Packing machine	Packing pellets-bags (20kg - 50kg)	0.75	25	7,969	5,014	5,014
Bag dust collector	Collect dust producing in the line	15	25	15,738	9,902	9,902
Electronic Control Cabinet	Control motor of pellets line		25	18,852	11,862	11,862
Control cabinet	Control		25	23,770	14,956	14,956

Operational Costs (OPEX)

Cost of diesel: Fuel consumption in the tube grinder: 265 L day⁻¹. Fuel consumption by front loader: 8.58 L day⁻¹. Total fuel consumption: 273.6 L day⁻¹. For our estimates we will consider a retail price of \$3 gallon⁻¹ or (\$0.8 L⁻¹). The annual cost of diesel will then be: 273.6 x 240 x 0.8 = **\$52,531 per year**.

Cost of Electricity: Cost of kWh: **\$0.052**. The pelletization line includes, beside the pellet mill, a fan blower, bag dust collector and other component that have a total electricity consumption of 111 kWh t⁻¹ biomass. The daily consumption of the unit will be 11,100 kWh. The total consumption in a year will be: \$0.052 * 11,100 kWh * 300= \$173,160 year⁻¹.

Maintenance: The itemized annual maintenance cost calculated is close to 5 % of the capital cost following the recommendations of (Seinder et al., 2009). In this case it will be: 0.05 * \$ 2,692,360 = **134,618 \$ per year**

Table K-12. Fixed capital investment (FCI) calculations for pretreatment and pelletization system for a 5 ton hour⁻¹ capacity and with and scaling factor of 1.65. The coefficients for the calculations were taken from (Peters et al., 2003).

Calculation of FCI	Coefficients	Cost updated 2015 (\$)
Purchased Equipment cost (PEC)	100%	666,921
Delivering of Equipment cost (of PEC)	10%	66,692
Delivered Equipment (DPEC)		733,613
Installation % of DPEC	45%	330,126
Instrumentation and controls (installed) % of DPEC	18%	132,050
Piping (installed) % of DPEC	16%	117,378
Electrical System (installed) % of DPEC	10%	73,361
Buildings (including services) % of DPEC	25%	183,403
Yard improvements % of DPEC	15%	110,042
Total direct plant cost		1,679,974
Engineering and supervision % of DPEC	33%	242,092
Construction expenses % of DPEC	39%	286,109
Legal expenses % of DPEC	4%	29,344
Contractors' fee % of DPEC	17%	124,714
Contingency % of DPEC	35%	256,765
Total indirect plant cost		939,025
Fixed capital investment (FCI)		2,618,999
Start up (SU) % of DPEC	10%	73,361
Total Capital Investment (TCI)		2,692,360

Labor: For the estimation of labors we will suppose that the unit hires 12 workers (3 per shifts) (4 shifts) and assumed benefits corresponding to 29% of their base salary. The total labor expenses will be: **\$594,432 per year.**

Table K-13. Estimation of labor costs on a composting facility

Appointment	Number of workers	Number of hours day ⁻¹	Salary (\$ h ⁻¹)	Annual salary (\$ year ⁻¹)	Total salary and benefits (\$ year ⁻¹)
Operators	12	8	20	460,800	594,432

Property Taxes and Insurance: The property taxes will be considered 3% of the Capital Investment (Seider et al., 2009). In our case it will be: $0.03 * 2,692,360 = \$80,771$

Operating Overhead: The operating overhead will be considered as 22.8% of the maintenance and labor costs: $0.228 * (594,432 + 134,618) = \$166,223$

Total Operational costs: **\$1,201,735 per year**

Earnings

The unit will commercialize pellets. The default selling price for the pellet produced will be \$230 ton⁻¹, which assumes mostly bulk sales. For concept of tipping feeds the new unit will receive \$60 ton⁻¹ processed. So the revenues for concept of tipping fees will be: $100 \text{ ton day}^{-1} \times 300 \text{ day year}^{-1} \times 60 \text{ $ ton}^{-1} = \$1,800,000 \text{ year}^{-1}$. The unit will produce 50 ton day⁻¹ or (15,000 tons year⁻¹, 300 days per year of operation). The selling of the pellets will be \$200 ton⁻¹. So the revenue for

selling the pellet will be: $\$3,000,000 \text{ year}^{-1}$. Total Earnings: $1,800,000 + 3,000,000 \text{ \$ year}^{-1} = \$4,800,000 \text{ year}^{-1}$

Case 1: All the capital obtained from the bank at 5.12% interest per year. In order to pay the capital ($\$2,692,360$) and the interest in 20 years we will need to pay every year: $\$193,334$. The total cost will be: **$\$1,395,069 \text{ per year}$** . Gross earnings: $4,800,000 - 1,395,069 = \mathbf{\$3,404,931 \text{ per year}}$

Because the gross earning is between $\$300,000$ and $\$10\text{M}$, we will consider the federal taxes as $113,900 + 34\%$ (Over $335,000$) (Seider et al., 2009). The Federal taxes will be: $\$1,157,677 \text{ year}^{-1}$. The net earnings of the unit will be: $\$2,247,255 \text{ year}^{-1}$.

Case 2: Capital provided by the owner of the facility. In this case the gross earnings will be $\$3,598,265 \text{ year}^{-1}$ but the production cost will be lower only. The federal taxes will be $\$1,223,410 \text{ year}^{-1}$. The net earnings will be $\$2,374,855 \text{ year}^{-1}$. This results in a return on investment (ROI) of 88.2% per year.

References

- Komilis, D.P., and Ham, R.K. 2004. Life-Cycle Inventory of Municipal Solid Waste and Yard Waste Composting in the United States. *J. Env. Eng.*, 130 (11), 1390–1400.
- Levis, J.W., and Barlaz, M.A. 2013. Composting Process Model Documentation. North Carolina State University. NC 27695-7908.
- Mani, S., Sokhansanj, S., Bi, X., and Turhollow, A. 2006. Economics of the Producing Fuel Pellets from Biomass. *Appl. Eng. Ag.*, 22(3), 421–426.
- Miles, T.R. 2009. The Economics of Biochar Production. PNW Biochar Group Meeting, Richland, WA.
- Peters, M.S., Timmerhaus, K.D., and West, R.E. 2003. *Plant Design and Economics for Chemical Engineers*, Fifth Edition, McGraw-Hill. 1008 pp.
- Seider, W.D., Seader, J.D., Lewin, D.R., and Widagdo, S. 2009. *Product and Process Design Principles. Synthesis, Analysis, and Evaluation*. Third Edition. John Wiley & Sons, Inc.
- Suliman, W., Harsh, J., Abu-Lail, N., Fortuna, A., Dallmeyer, I. and Garcia-Perez, M. *In preparation*. Understanding the Effect of Pyrolysis Conditions and Feedstock Composition on the Bulk and Surface Properties of Bio-chars. For submission to Biomass and Bioenergy.
- TLV.com. 2015. Superheated Steam Table. TLV® A Steam Specialist Company. Retrieved from <http://www.tlv.com/global/TL/calculator/superheated-steam-table.html>.

Appendix L. Construction of the AD-CNG model

This appendix details the information used to model the hypothetical AD-CNG process.

Building the Model

The development of the anaerobic digestion process model was based on the data on an anaerobic digester (AD) receiving food scraps collected mainly from domestic kitchens (Banks et al., 2011). The industrial plant of the AD technology is assumed to operate 8,000 hour year⁻¹ with a daily production capacity of 220 tons per day. The feedstocks include 120 tons food scraps day⁻¹ and 100 tons compost leachate day⁻¹. The flowsheet of the AD processes were constructed in the Aspen PlusTM process engineering software.

Scheme 1: Anaerobic digestion with food scraps

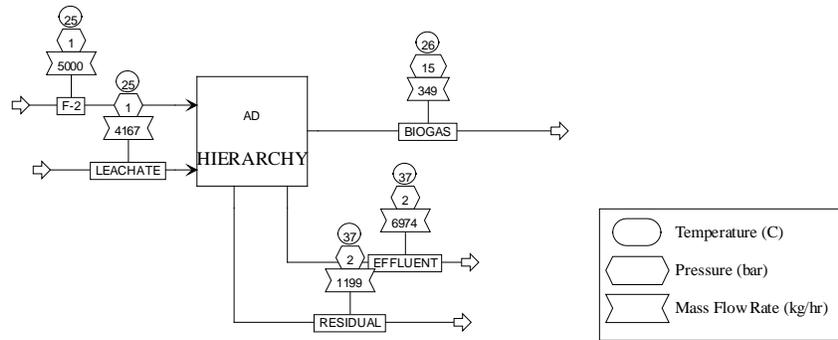


Figure L-1: Block flow diagram of anaerobic digestion with food scraps.

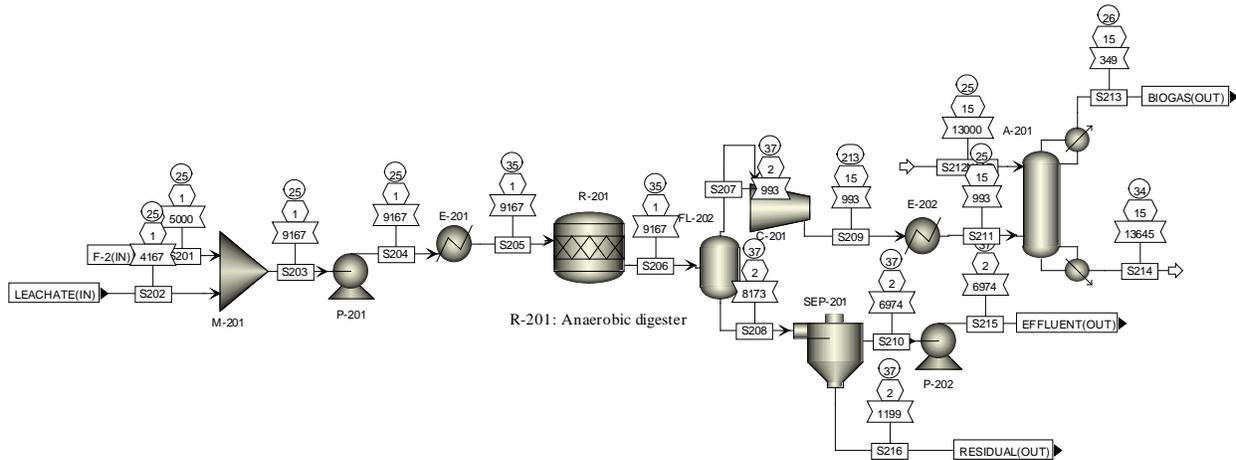


Figure L-2: Process flow diagram of anaerobic digestion with food scraps

Process description: Food scraps (F-2) including most of degradable organic wastes such as carbohydrate, protein and lipid is fed to a mixer (M-201) and diluted by compost leachate. The slurry stream (S203) is pumped to heat exchanger (E-201), and then into anaerobic digester (R-201). After anaerobic digestion, the slurry is sent to a buffer tank (FL-202) to separate biogas. The slurry is continually sent to a solid-liquid separator (SEP-201). After separation, the effluent

is pumped out of the system and the residuals are also removed. The residuals will be used as organic fertilizer. The biogas is sent to gas purification (A-201). N-methyl-2-pyrrolidone (NMP) is one of the popular physical solvent methods to remove acid gas such as CO₂ and H₂S (Burr and Lyddon, 2008). Higher pressure favors the absorption of CO₂. Thus the biogas stream (S208) first uses a compressor (C-201) to increase pressure, and then uses heat exchanger (E-202) to decrease temperature. After purification, CH₄ and partial CO₂ in biogas are sent out the system.

The compounds that are used in the holistic process model are shown in **Table L-1**. Cellulose, hemicellulose and lignin are measured for lignocellulosic materials. Here we use food scraps and equations are provided by Angelidaki et al. (1999) where carbohydrate, lipid and protein are used. Cellulose and hemicellulose are considered as carbohydrate. It is hard to degrade lignin in anaerobic digestion. In this project, ash was assumed as ASH1CA, ASH2K, ASH3Mg. Ash will not react with any substrate and microorganism. NMP is a physical solvent and does not react with CO₂. The solubility of CO₂ increases with decreasing temperature and increasing pressure. Using this property, NMP can remove CO₂ from biogas. In anaerobic digestion, orthophosphate (PO₄²⁻-P) is dissolved in the effluent.

Reactions used to build the model

R-201 (anaerobic digester) Reactions: Angelidaki et al. 1999



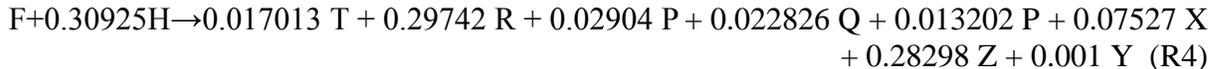
x_{CONV, A}: fractional conversion (Range between 0 and 1: 1)



x_{CONV, D}: fractional conversion (Range between 0 and 1: 1)



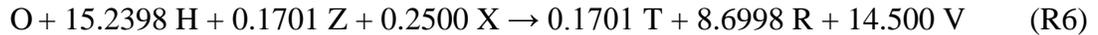
x_{CONV, G}: fractional conversion (Range between 0 and 1: 1)



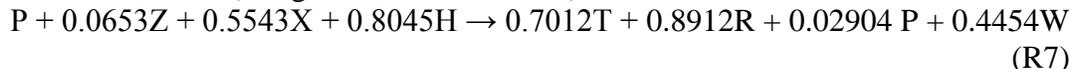
x_{CONV, F}: fractional conversion (Range between 0 and 1: 1)



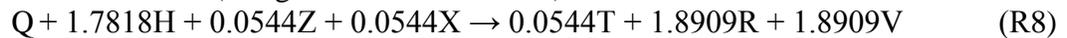
x_{CONV, B}: fractional conversion (Range between 0 and 1: 1)



x_{CONV, O}: fractional conversion (Range between 0 and 1: 1)



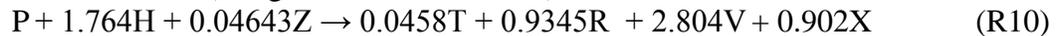
x_{CONV, P}: fractional conversion (Range between 0 and 1: 1)



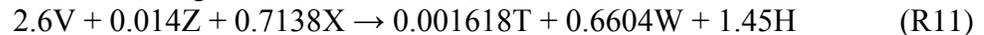
x_{CONV, Q}: fractional conversion (Range between 0 and 1: 1)



x_{CONV, S}: fractional conversion (Range between 0 and 1: 1)



x_{CONV, P}: fractional conversion (Range between 0 and 1: 1)



x_{CONV, V}: fractional conversion (Range between 0 and 1: 1)



x_{CONV, V}: fractional conversion (Range between 0 and 1: 1)

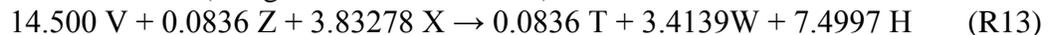


Table L-1. Components for the holistic process

No	Symbol	Compound	Data base availability	Name in Aspen Database	Chemical formula	Reference
1	A	CARBO-IS	Solid		C ₆ H ₁₀ O ₅	Angelidaki et al. 1999
2	B	CARBOH-S	Solid		C ₆ H ₁₀ O ₅	Angelidaki et al. 1999
3	C	CARBOH-I	Solid		C ₆ H ₁₀ O ₅	Angelidaki et al. 1999
4	D	PROTE-IS	Solid		CHONS-U ₁	Angelidaki et al. 1999
5	E	PROTE-I	Solid		CHONS-U ₂	Angelidaki et al. 1999
6	F	PROTE-S	Solid		CHONS-U ₃	Angelidaki et al. 1999
7	G	LIPID	Solid	TRIOLEIN	C ₅₇ H ₁₀₄ O ₆	Angelidaki et al. 1999
8	H	H ₂ O	Conventional	WATER	H ₂ O	
10	J	LIGNIN	Solid		C ₂₀ H ₃₀ O ₆	Sole-Mauri et al. 2007
12	L	ASH1CA	Solid		CaO	
13	M	ASH2K	Solid		K	
14	N	ASH3Mg	Solid		Mg	
15	O	LCFA	Conventional	OLEIC-ACID	C ₁₈ H ₃₄ O ₂	Angelidaki et al. 1999
16	P	VALERATE	Conventional	NEOPENTANOIC-ACID	C ₅ H ₁₀ O ₂	Angelidaki et al. 1999
17	Q	BUTYRATE	Conventional	N-BUTYRIC-ACID	C ₄ H ₈ O ₂ -1	Angelidaki et al. 1999
18	P	PROPIONA	Conventional	PROPIONIC-ACID	C ₃ H ₆ O ₂ -1	Angelidaki et al. 1999
19	R	ACETATE	Conventional	ACETIC-ACID	C ₂ H ₄ O ₂ -1	Angelidaki et al. 1999
20	S	GLYCEROL	Conventional	GLYCEROL	C ₃ H ₈ O ₃	Angelidaki et al. 1999
21	T	BIOMASS (micro-organisms)	Solid		C ₅ H ₇ NO ₂	Angelidaki et al. 1999; Sole-Mauri et al. 2007
23	V	H ₂	Conventional	HYDROGEN	H ₂	
24	W	CH ₄	Conventional	METHANE	CH ₄	
25	X	CO ₂	Conventional	CARBON-DIOXIDE	CO ₂	
26	Y	H ₂ S	Conventional	HYDROGEN-SULFIDE	H ₂ S	
27	Z	NH ₃	Conventional	AMMONIA	H ₃ N	
30	CC	NMP	Conventional	N-METHYL-2-PYRROLIDONE	C ₅ H ₉ NO-D ₂	
33	FF	PO ₄ ⁻³	Conventional	PO4---	PO ₄ ⁻³	

$$x_{\text{CONV}, v}: \text{fractional conversion (Range between 0 and 1: 0.82)}$$

$$R + 0.022Z \rightarrow 0.022T + 0.945W + 0.066H + 0.945X \quad (\text{R14})$$

$$x_{\text{CONV}, R}: \text{fractional conversion (Range between 0 and 1: 1)}$$

T_{R-201} : Temperature ($^{\circ}\text{C}$), Value: 37

P_{R-201} : Pressure (atm), Value: 1

The aforementioned fractional conversions were estimated based on biogas yield of 642 mL g^{-1} VS and methane yield 402 mL g^{-1} VS (Banks et al., 2011).

Input Variables used by ASPEN

Food scraps (27.7% TS, total solids) was used in this case (Banks et al., 2011). The total flow rate of the food scraps was 120 ton day^{-1} .

\dot{m}_{F1} : Mass flow rate (kg h^{-1})

$\dot{m}_{F1 \text{ solid}}$: Mass flow rate (kg h^{-1}) (Range between 0 and 10000: 1385)

$\dot{m}_{F1 \text{ liquid}}$: Mass flow rate (kg h^{-1}) (Range between 0 and 10000: 3615)

T_{F1} : Temperature ($^{\circ}\text{C}$) (same for solid and liquid) (Range between 10 and 40: 25)

P_{F1} : Pressure (atm) (same for solid and liquid) (Range between 1 and 10: 1)

For the solid (in F1)

No	Symbol	Compound	Mass Fraction	Range
1	A	CARBO-IS	$x_{F1 A}$	0.484
4	D	PROTE-IS	$x_{F1 D}$	0.308
7	G	LIPID	$x_{F1 G}$	0.181
10	J	LIGNIN	$x_{F1 J}$	0.019
12	L	ASH1CA	$x_{F1 L}$	0.008
13	M	ASH2K	$x_{F1 M}$	0
14	N	ASH3Mg	$x_{F1 N}$	0
Total			1	

For the liquid (in F1)

No	Symbol	Compound	Mass Fraction	Range
8	H	H_2O (liquid)	$x_{F1 H}$	0.9999954
33	FF	PO_4^{-3}	$x_{F1 FF}$	0.0000046
Total			1	

Compost leachate (2.6% Sugar) was sent to dilute the food scraps in the digester. The total flow rate of the food scraps was 100 ton day^{-1} .

\dot{m}_L : Mass flow rate (kg h^{-1})

$\dot{m}_{L \text{ solid}}$: Mass flow rate (kg h^{-1}) (Range between 0 and 10000: 0)

$\dot{m}_{L \text{ liquid}}$: Mass flow rate (kg h^{-1}) (Range between 0 and 10000: 4166.7)

T_L: Temperature (°C) (same for solid and liquid) (Range between 10 and 40: 25)

P_L: Pressure (atm) (same for solid and liquid) (Range between 1 and 10:1)

For the solid (in Leachate)

No	Symbol	Compound	Mass Fraction	Range
1	A	CARBO-IS	X _{F1 A}	0
4	D	PROTE-IS	X _{F1 D}	0
7	G	LIPID	X _{F1 G}	0
10	J	LIGNIN	X _{F1 J}	0
12	L	ASH1CA	X _{F1 L}	0
13	M	ASH2K	X _{F1 M}	0
14	N	ASH3Mg	X _{F1 N}	0
Total			0	

For the liquid (in Leachate)

No	Symbol	Compound	Mass Fraction	Range
2	B	CARBOH-S	X _{F1 B}	0.026
8	H	H ₂ O (liquid)	X _{F1 H}	0.9999954
Total			1	

Validation of Mass Balances

The aforementioned process model was validated by the study at the biogas plant with food scraps (Banks et al., 2011). The data of the food composition for model validation can be found in **Table L-2**.

Table L-2. Typical composition for food scraps used in anaerobic digestion

Composition	Food scraps (Bufierre et al., 2006)	Input in ASPEN plus
Carbohydrate (mg g ⁻¹ DM)	302 – 735	399
Hemicellulose (mg g ⁻¹ DM)	85 – 295	85
Lignin (mg g ⁻¹ DM)	19 – 96	19
Crude protein (mg g ⁻¹ DM)	90 – 208	308
Lipid (mg g ⁻¹ DM)	35 – 81	181
Ash	0-10	
ASH1Ca		8
ASH2K		0
ASH3Mg		0

ASPEN plus strictly implements both element balance and mass balance. **Figure L-3** shows a comparison of mass balance between experimental data and prediction. Comparison of results between experimental data and prediction show that a good agreement is observed in CO₂ and CH₄ content and CO₂ and CH₄ productivity.

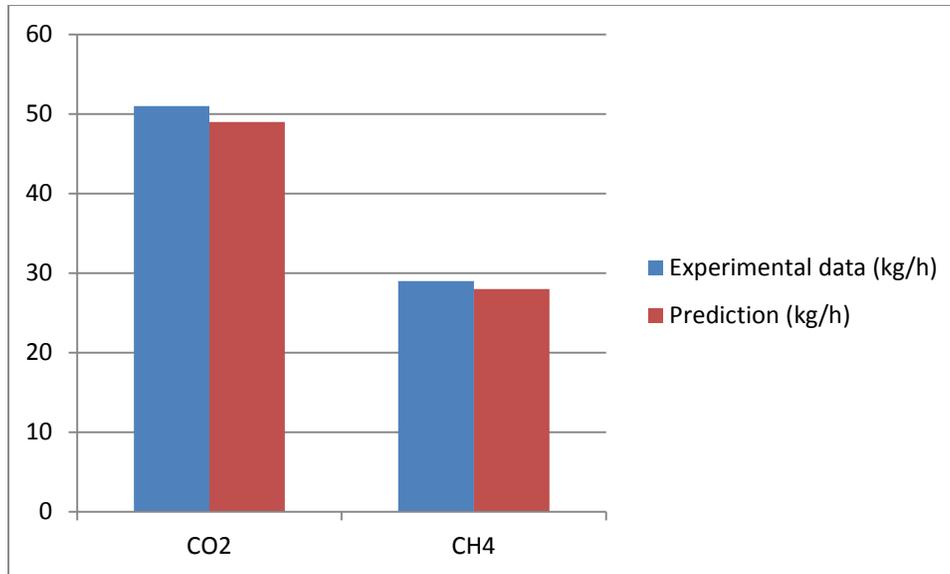


Figure L-3. Comparison of mass balance between experimental data and prediction (Banks et al., 2011)

ASPEN Techno-economic Analysis

The economic analysis for the aforementioned AD process was based on the first quarterly 2012 pricing basis.

Capital costs

Before an industrial plant can be put into operation, a large sum of money must be available to purchase and install the required machinery and equipment. The required manufacturing and plant facilities need capital called the fixed capital investment (FCI) to supply anaerobic digestion facilities for biogas production. The fixed-capital investment is further subdivided into direct cost (manufacturing fixed-capital investment), and indirect cost (nonmanufacturing fixed-capital investment).

Capital investment cost and product value for each scenario was estimated by finding costs for the construction and operation of a plant for 20 years. Total capital investment was evaluated by determining equipment costs and adding installation and indirect costs. Using Dr. Craig Frear source and Aspen Icarus Process Evaluator software, the equipment employed in the scenario was sized and costs estimated. The unit of anaerobic digester is unique and could not be evaluated using cost estimation software. Therefore, the digester cost was estimated by adapting the methodology from Pacific Clean (Elk Heights, Washington 100-Ton Digester 11/13/2012). In this case, the digester was scaled to 220 ton day⁻¹. When a piece of equipment was scaled to a different size Eq. (1) was used which adjusts the initial cost, Cost₀, based on a scaling factor, n, typically ranging between 0.6–0.8 (Humbird et al., 2011). In this case, n was set as 0.6.

$$\text{Cost}_{new} = \text{Cost}_0 \cdot \left[\frac{\text{Size}_{new}}{\text{Size}_0} \right]^n \quad (1)$$

For the food scraps anaerobic digestion, the optimum retention time from an economical point of view is 20 days (Rajendran et al., 2012; Rapport et al., 2008). The flow rate is 220 ton day⁻¹. Thus the digester effective volume is 4400 m³.

Table L-3. Estimation of major equipment cost

Component Name	Purchased Equipment (USD)	Equipment Setting (USD)	Characteristic Size
Biogas purification tower	2,061,500	387,300	V=321 m ³
Compressor	1,252,200	131,400	P=125HP
Heat exchanger E-201	7,700	36,900	Duty=87kW
Heat exchanger E-202	8,700	45,000	Duty=91kW
Liquid-gas separator	16,800	84,900	V=3.3 m ³
Pump P-201	4,500	33,100	Q=8.61m ³ h ⁻¹
Pump P-202	4,500	27,900	Q=7.8 m ³ h ⁻¹
Anaerobic digester	3,468,546	143,054	V=4400 m ³
Total Cost	6,824,446	889,554	
Adjusted equipment cost	7,048,255		

Table L-4. Estimation of Capital Costs

Account	Total Cost (\$)
Equipment	7,048,25
(Above Ground) AG Pipe	382,579
Piling	35,201
Concrete	77,793
Grout	4,719
Steel	57,346
Instrumentation	650,124
(Under Ground) UG Electrical	22,532
(Above Ground) AG Electrical	512,462
Pipe Insulation	26,505
Equip Insulation	4,827
Paint	31,643
Direct Total Cost	8,853,986
Const Equip & Indirects	395,600
Const Mgt, Staff, Supv	301,600
Freight	337,300
Taxes and Permits	527,000
Engineering	1,550,400
Other Project Costs	720,914
Contingency	2,283,624
Indirect Total Cost	6,116,438
Total Project Capital Cost	14,970,424
Adjusted Total Project Cost	14,800,271

Operational cost

The necessary for the operation of AD process is termed as the operational cost. Total Operating Cost includes the total of raw material, utility, operating labor, maintenance, operating charges, plant overhead and G and A expenses (general and administrative costs). In the following schemes of the operating unit costs, labor cost is \$10 hour⁻¹ (Levis and Barlaz, 2013) and electricity is \$0.0775 kWh⁻¹.

The operating labor costs include 3 operators per shift and no supervisory costs. The plant operates 8,000 hour year⁻¹. Thus, the operating cost is \$240,000 year⁻¹.

The maintenance cost is 3.3% of total project cost. Maintenance cost of the equipment including labor and materials.

The Operation charges are 25% of operating labor cost. This includes operating supplies and laboratory charges. It is specified as a percentage of the operating labor costs.

Plant overhead is 50% of operating labor and maintenance costs. This field consists of charges during production for services, facilities, payroll overhead, and so on This number is specified as a percent of operating labor and maintenance costs. This number should not be used for the construction of the facility, only for operation after start-up.

G and A cost 8% Specify this number as a percentage of subtotal operating costs. This represents general and administrative costs incurred during production such as administrative salaries/expenses, R&D, product distribution and sales costs. Specify this number as a percentage of subtotal operating costs. The subtotal operating cost is \$1,282,415.59 that does not includes the cost of raw material.

Total utility cost was calculated based on cooling water (heat sink: 24°C), hot water (heat source: 50°C) and electricity. The electricity price is \$0.078 kWh⁻¹ and the total electricity cost is \$98,695. The water price is \$0.0317 m⁻³ and the total water heat and cooling cost is \$23,562. Therefore, the total utility cost is \$122,257.

Table L-5. Estimation of operational costs.

Account		Total Cost (\$)
Total Raw Materials Cost	Cost/Period	0
Total Utility Cost	Cost/Period	122,257
Operating Labor Cost	Cost/Period	240,000
Maintenance Cost	Cost/Period	498,000
Operating Charges	Cost/Period	60,000
Plant Overhead	Cost/Period	369,000
G and A Cost	Cost/Period	103,141
Total Operating Cost		1,392,397

Gross income

Natural gas is 1.86\$ GGE⁻¹. 70% food scraps is eligible for carbon credits 5\$ ton⁻¹, and 0.5 credit per ton of eligible food scraps. RINS is 0.73\$ GGE⁻¹. AD fertilizer is \$20 ton⁻¹ (Levis and Barlaz, 2013). Tipping fee is \$60 ton⁻¹.

Table L-6. Estimation of Gross Income

Name	Units	Item
Main Product Name		Biogas (96%CH ₄)
Main Product Rate	m ³ H ⁻¹	489.25
Main Product Unit Cost	USD m ⁻³	0.52
Main Product Production Basis		m ³
Main Product Rate per Period	m ³ Year ⁻¹	3,913,978.00
Main Product Sales	USD Year ⁻¹	2,035,268.46
By-product (Fertilizer) Sales	USD Year ⁻¹	70,017.63
Carbon credits	USD Year ⁻¹	140,035.27
RINS	USD Year ⁻¹	348,562.04
Tipping fee	USD Year ⁻¹	2,400,000.00
Products Sales per Hour	Cost Hour ⁻¹	638.76
Total Products Sales	Cost/Period	5,046,355

Return on investment

Economic Life of Project Indicates the length of time in terms of periods over which capital costs will be depreciated.

Tax was set as zero.

Table L-7. Investment parameters.

Name	Units	Item
Period description		Year
Number of weeks per period	Week/period	52
Number of periods for analysis		20
Tax rate	Percent /period	0
Interest rate/desired rate of return	Percent /period	10
Economic life of project	Period	10
Salvage value (Percentage of initial capital cost)	Percent	20
Contingency	Percent	18
Depreciation method		Straight line
Escalation parameters		
Project capital escalation	Percent /period	5
Products escalation	Percent /period	5
Raw material escalation	Percent /period	3.5
Operation and maintenance labor escalation	Percent /period	3
Utility escalation	Percent /period	3
Project capital parameters		

Table L-7 (continued). Investment parameters.

Working capital percentage	Percent /period	5
Operating cost parameters		
Operating charges	Percent /period	25
Plant overhead	Percent /period	50
G and A expenses	Percent /period	8
Facility operation parameters		
Operating mode		Continuous processing
Length of Start-up period	Weeks	2
Operating hours per period	Hours /period	8000
Process fluid		Liquids, gases, and solids

Table L-8. Estimation of Investment.

INVESTMENT:		
Currency Conversion Rate	1	USD/U.S. DOLLAR
Total Project Capital Cost	14,800,271.00	USD
Total Operating Cost	1,392,397.20	USD Year ⁻¹
Total Raw Materials Cost	0	USD Year ⁻¹
Total Utilities Cost	122,256.67	USD Year ⁻¹
Total Product Sales	5,046,354.53	USD Year ⁻¹
Desired Rate of Return	10	Percent Year ⁻¹
P.O. (Payout) Period	5.31	Year

References

- Angelidaki, I., Ellegaard, L., and Ahring, B.K. 1999. A Comprehensive Model of Anaerobic Bioconversion of Complex Substrates to Biogas. *Biotechnol. Bioeng.*, 63(3), 363–372.
- Banks, C.J., Chesshire, M., Heaven, S., and Arnold, R. 2011. Anaerobic Digestion of Source-Segregated Domestic Food Waste: Performance Assessment by Mass and Energy Balance. *Bioresour. Technol.*, 102, 612–620.
- Burr, B., and Lyddon, L. 2008. A Comparison of Physical Solvents for Acid Gas Removal. 87th Annual Gas Processors Association Convention, Grapevine, TX, March. pp. 2–5.
- Buffiere, P., Loisel, D., Bernet, N., and Delgenes, J.P. 2006. Towards New Indicators for the Prediction of Solid Waste Anaerobic Digestion Properties. *Water Sci. Technol.*, 53(8), 233–241
- Humbird, D., Davis, R., Tao, L., Kinchin, C., Hsu, D., Aden, A., Schoen, P., Lukas, J., Olthof, B., Worley, M., Sexton, D., and Dudgeon, D. 2011. Process Design and Economics for Biochemical Conversion of Lignocellulosic Biomass to Ethanol – Dilute-Acid Pretreatment and Enzymatic Hydrolysis of Corn Stover. Technical Report, NREL/TP-5100-47764. National Renewable Energy Laboratory.

- Levis, J.W., and Barlaz, M.A. 2013. Composting Process Model Documentation. North Carolina State University. NC 27695-7908.
- Rajendran, K., Aslanzadeh, S., and Taherzadeh, M.J. 2012. Household Biogas Digesters—A Review. *Energies*, 5(8):2911–2942.
- Rapport, J., Zhang, R., and Jenkins, B.M. 2008. Current Anaerobic Digestion Technologies used for Treatment of Municipal Organic Solid Waste. California Environmental Protection Agency. Sacramento, CA.
- Sole-Mauri, F., Illa, J., Margí, A., Prenafeta-Boldú, F.X., and Flotats, X. 2006. An Integrated Biochemical and Physical Model for the Composting Process. *Bioresour. Technol.*, 98(17)3278–3293.

Appendix M. Additional resources related to the marketing of finished compost

- Baum, T. 2013. Being more sustainable. Potato Grower. Available online at <http://www.potatogrower.com/2013/09/being-more-sustainable>
- Collins, H.P., Streubel, J.D., Frear, C., Chen, S., Granatstein, D., Kruger, C., Alva, A.K., Fransen, S.F. 2010. Application of AD dairy manure effluent to fields and associated impacts. CSANR Research Report 2010-001, Climate Friendly Farming.
- Collins, H.P., Alva, A.K., Streubel, J.D., Fransen, S.F., Frear, C., Chen, S. 2011. Greenhouse gas emission from an irrigated silt loam soil amended with anaerobically digested dairy manure. *Soil Science Society of America Journal*, 75(6), 2206-2216.
- Frear, C., Ma, J., Kennedy, N., Yorgey, G. 2013. Review of emerging nutrient recovery technologies for farm-based anaerobic digesters and other renewable energy systems. Innovation Center for U.S. Dairy.
- Granatstein, D., Stone, A., Williams, C., Miles, C., Bezdicek, D., Perillo, C. 2005. Organic Farming Research in the Pacific Northwest: Challenges, Opportunities, and Outlook. *Organic Farming Compliance Handbook: A Resource Guide for Western Region Agricultural Professionals*.
- Larkin, R. 2014. Complementary Crops: Maine researchers develop crop rotation best practices for potatoes. *Potato Grower*.
- Seyedbagheri, M.-M. 2004. Humic acid can increase potato yields, quality, and value. College of Agriculture and Life Sciences, University of Idaho. Available online at <http://www.cals.uidaho.edu/edComm/magazine/summer04/humic.html>
- Seyedbagheri, M.-M. 2010. Compost: production, quality, and use in commercial agriculture. University of Idaho Extension. CIS 1175.
- Seyedbagheri, Mir-M. 2010. Influence of Humic Products on Soil Health and Potato Production. *Potato Research* 53,341–349.
- Seyedbagheri, M.-M., He, Z., Olk, D.C. 2012. Yields of potato and alternative crops impacted by humic product applications. *Sustainable potato production: global case studies*. Springer, New York.
- Seyedbadheri, M., Arp, A.L. 2013. Fishy Soil: Productive Soils Resulting in High Yields and Quality. *Potato Grower*, February, 2013.
- Seyedbagheri, M.-M. 2014. Influence of humic substances on soil health, crop production, and environmental quality. College of Agriculture and Life Sciences, University of Idaho. Available online at <http://www.deq.idaho.gov/media/760229-seyedbagheri-monitoring-workshop-2011.pdf>
- Washington State Potato Commission. 2015. “Spud Syllabus” and other content from the Commission, available online at <http://www.potatoes.com>
- Washington State University Extension. 2003. Using Green Manures in Potato Cropping Systems. EB1951E.
- Waste & Resources Action Programme. Using quality compost to benefit potato crops. <http://www.wrap.org.uk/composting>.
- Westennann, D.T. 2005. Nutritional Requirements of Potatoes. *American Journal of Potato Research* 82, 301-307.