Ecology Solid Waste Management Program
And WSU Partnership

Organic Waste Research
Biological and Thermal Processing

Literature Reviews and Biennial Reports

FY 2005 through 2018

A. Biomass Inventory Documents:

Biomass Inventory and Bioenergy Assessment: An Evaluation of Organic Material Resources for Bioenergy Production in Washington State
https://fortress.wa.gov/ecy/publications/SummaryPages/0507047.html
ECY Publication -- 05-07-047 -- Solid Waste Management -- 2011, completed 2005, and revised by Craig Frear. 126 pages. See database update by Jim Jensen: Pacific Regional Bioenergy Partnership: http://68.179.221.48/biomassinv.aspx.

A biomass inventory and bioenergy assessment for Washington State was completed, producing this final report as well as a web accessible computer database complete with GIS maps on a Visual Basic platform (http://www.pacificbiomass.org). The goal of the study was to inventory Washington's bioresources as a first essential step for all related planning efforts to implement the state Beyond Waste strategy for reduction of organic residuals in solid waste. This inventory also represents a first step toward a sustainable energy policy and vision within the state since information on type and geographic distribution of biomass was perceived as critical for feasibility analysis and project prioritization.

Biomass Inventory Technology and Economics Assessment -- Report 1. Characteristics of Biomass
https://fortress.wa.gov/ecy/publications/SummaryPages/0707025.html
ECY Publication -- 07-07-025 -- Solid Waste Management -- 2007, Wei Liao, Craig Frear and Shulin Chen. 50 pages.

The purpose of this project is to study potential energy production technologies for biomass feedstocks available in Washington State. The project includes four parts: 1). characterizing 42 feedstocks according to their chemical properties such as carbon content, protein content, fiber content, etc.; 2). identifying and grouping the feedstocks; 3). simulating the potential conversion processes such as thermal-chemical conversion, anaerobic digestion, and ethanol production on individual feedstock or their combinations; and 4). economic analysis of the processes from feedstock collection and distribution to energy production.

It is important both for the ensuing research and end-users of the research to know the characteristics of the feedstocks in order to select the proper conversion process to produce bioenergy products. Thus, the characterization of these 42 feedstocks has been conducted as the first effort to fulfill this project. A wide literature search for the available characterization data as well as fill-in gaps with laboratory analysis generated a detailed

feedstock database that is configured by five categories (fiber/starch/sugar, ultimate analysis, elemental analysis, other parameters), and includes 33 parameters such as moisture, carbon, starch, cellulose, minerals, etc. The database could be used not only by the researchers to conduct the next steps of the project to identify and group the feedstocks and further simulate the conversion processes, but also by farmers and producers to know more about the agricultural and municipal residues they are producing or plan to utilize.

B. Solid Waste Management Background Documents:

Waste Composition Analysis for the State of Washington
https://fortress.wa.gov/ecy/publications/SummaryPages/1507037.html
ECY Publication -- 15-07-037 -- Solid Waste Management -- 2015, Green Solutions, Inc. 57 pages.

This document was published in 2003 and posted online in 2015. The document uses data from several counties to provide an estimate of the composition of solid waste throughout the State of Washington. This report focuses on municipal solid waste (MSW), or the garbage that typically is brought to landfills for disposal.

Soil Organic Carbon Storage (Sequestration) Principles and Management
https://fortress.wa.gov/ecy/publications/SummaryPages/1507005.html
ECY Publication -- 15-07-005 -- Solid Waste Management -- 2015 , Canming Xiao, 103 pages.

Soils, especially managed agricultural soils, have the potential to store (sequester) carbon (C) and contribute to mitigation of GHGs emissions. Increasing the amount of organic C in soils may not only mitigate GHG emissions, but also benefit agricultural productivity through improvements in soil health and environmental quality by reducing soil erosion. This report reviews soil carbon forms and potential carbon storage using conservative estimates.

C. Digestion and fermentation of food and green waste, and manure for fuels:

Producing Energy and Fertilizer From Organic Municipal Solid Waste -- Project Deliverable #1
https://fortress.wa.gov/ecy/publications/SummaryPages/0707024.html
ECY Publication -- 07-07-024 -- Solid Waste Management -- 2007, Usama Zaher, Dae-Yeol Cheong, Binxin Wu, and Shulin Chen. 97 pages.

The earlier collaborative effort between Washington State University (WSU) and the Washington Department of Ecology (Ecology) (www.ecy.wa.gov/pubs/0507047.pdf) has identified municipal solid waste as a major biomass in the state. With directed funding from the State, WSU and Ecology established a new partnership under Inter Agency Agreement C-0700136 to explore the beneficial uses of the waste material. This project was proposed to produce fuel and fertilizer from the organic fraction of municipal solid waste (OFMSW) through the application/development of anaerobic digestion technology. The purpose of this project is to develop a design of an effective high solids anaerobic digestion (HSAD) system that is ready for pilot test. The design will be tested on a bench scale to demonstrate the potential of biogas and nutrients recovery from various types of organic municipal wastes. This project includes five objectives: (1) evaluation and review of existing HSAD designs, (2) bench scale trials and validation, (3) development of modeling tools for evaluation and development of high solids digestion systems, (4) developing a technology for enhancing

the anaerobic bacterial population in the high solids digestion, and (5) design of a pilot digester. This report is the first deliverable of the project.

Organic Waste to Resources Research and Pilot Project Report: Evaluation of Pretreatment Technologies for Converting Washington Biomass to Bioethanol
https://fortress.wa.gov/ecy/publications/SummaryPages/0907063.html
ECY Publication -- 09-07-063 -- Solid Waste Management -- 2009, Xiaochen Yu and Shulin Chen. 34 pages.

Organic Waste to Resources Research and Pilot Project Report. In this project we optimized parameters of pretreatment for four different lignocellulosic feedstocks that are prevalent in Washington State. Barley and wheat straw were two feedstocks studied as they account for 80% of the 1.9 million dry tons/year of crop residue biomass produced in the state. Since forestry residue accounts for 48% of the 16.4 million dry tons/year of total biomass available in Washington State, hard and soft wood were also tested as feedstocks. The results of this project can be used as reference in the development of a commercially available cellulosic ethanol industry in the state.

Organic Waste to Resources Research and Pilot Project Report: Producing Energy and Fertilizer from Organic Municipal Solid Waste
https://fortress.wa.gov/ecy/publications/SummaryPages/0907064.html
ECY Publication -- 09-07-064 -- Solid Waste Management -- 2010, Usama Zaher, Shulin Chen, Chenlin Li, Liang Yu and Timothy Ewing. 135 pages.

Organic Waste to Resources Research and Pilot Project Report. This report was prepared as a result of work sponsored by the California Energy Commission (Commission) and Washington State Department of Ecology (Interagency Agreement C0700136). It does not necessarily represent the views of the Commission, Ecology, or their employees, the State of California, or the State of Washington. This report describes an innovative technology that is subject to patent application by the Authors (see contact information on the cover page). Inquiries related to this deliverable should be directed to the Authors. Publishing this report in full or in part is subject to the prior approval (in writing) from the Authors.

Organic Waste to Resources Research and Pilot Project Report: Biodiesel and Biohydrogen Co-Production with Treatment of High Solid Food Waste
https://fortress.wa.gov/ecy/publications/SummaryPages/0907065.html
ECY Publication -- 09-07-065 -- Solid Waste Management -- 2009, Yubin Zheng, Jingwei Ma, Zhanyou Chi and Shulin Chen. 30 pages.

Organic Waste to Resources Research and Pilot Project Report. Great public and development interest exists in potential use of biofuel for transportation. The goal of this project was to evaluate possibilities converting food waste to biohydrogen and yeast as biodiesel feedstock through biological processing. The project results contribute to technology development and technical data for policy making in developing Washington's bioeconomy using the available low-cost organic resources. A two-step process was developed in this project as a potential technology to produce hydrogen and biodiesel feedstock using the food waste. The first step of this process is dark fermentative hydrogen production, in which the fermentative bacteria use glucose derived from waste carbon to produce hydrogen and volatile fatty acids (VFA; e.g. acetate or butyrate). One third of the carbon is converted to carbon dioxide in the first-step while two thirds of the carbon is converted to VFA. In the second step, carbon in the form of VFA is used to feed yeast for

simultaneous carbon sequestration and production of biodiesel feedstock from the oil-enriched microbial biomass. The work conducted in this project proved the concept with laboratory scale experiments. Further study needs to be conducted to scale up this process and assess its economic viability.

Organic Waste to Resources Research and Pilot Project Report: Waste to Fuels Technology: Evaluating Three Technology Options and the Economics for Converting Biomass to Fuels
https://fortress.wa.gov/ecy/publications/SummaryPages/0907058.html
ECY Publication -- 09-07-058 -- Solid Waste Management -- 2010, Hayk Khachatryan et al. 216 pages.

Organic Waste to Resources Research and Pilot Project Report. This study expands upon previous biomass work by: spatially investigating specific types of the inventoried biomass, comparing three conversion technologies (dilute acid pretreatment with simultaneous saccharification and co-fermentation (SSCF) for producing bioethanol, biomass gasification for synthesizing mix-alcohols, and anaerobic digestion (AD) for producing biogas), and determining feedstock transportation, processing and total delivered costs for the produced biofuels. To assess the final delivered costs of biofuel, the study integrated all the major cost factors including, biomass availability, feedstock prices, transportation costs, processing costs, and geographic distribution into a comprehensive model framework using geographical information system (GIS) and MATLAB-SIMULINK platforms.

D. Organics use to improve soil health:

Organic Waste to Resources Research and Pilot Project Report: Land Application-a true path to zero waste?
https://fortress.wa.gov/ecy/publications/SummaryPages/0907059.html
ECY Publication -- 09-07-059 -- Solid Waste Management -- 2010, Katie Kurtz, Sally Brown and Craig Cogger. 41 pages.

Organic Waste to Resources Research and Pilot Project Report. Soils where compost and/or biosolids have been land applied as single or repeated applications were retested. Rates of carbon storage per dry Mg of amendment ranged from 0.012 in a long term study of turf grass to 0.54 in an organic pear orchard with a long history of compost use. Carbon content in soils also increased with time, meaning that the organic matter added with the residuals application resulted in long term carbon increases in soils. Increases in soil carbon content were much greater when composts and biosolids were incorporated into the soils rather than surface applied. Total N (%) in soils that received organic amendment addition was higher than conventionally fertilized or control soils. Bulk density decreased after amendment addition in a number of the soils. Finally, soil water holding capacity was increased in 5 of the 9 sites sampled. Increases ranged from 10% to 50%. For both soil moisture tension levels tested, soil amendment or soil carbon were significantly positively correlated with water storage.

Organic Waste to Resources Research and Pilot Project Report: Creating High Value Potting Media from Composts Made with Biosolids and Carbon-Rich Organic Wastes
https://fortress.wa.gov/ecy/publications/SummaryPages/0907069.html
ECY Publication -- 09-07-069 -- Solid Waste Management -- 2009, Rita Hummel, Craig Cogger, Andy Bary, and Bob Riley. 25 pages.

Organic Waste to Resources Research and Pilot Project Report.

E. Thermochemical processing of wood and straw waste for fuels and biochar:

The Formation of Polyaromatic Hydrocarbons and Dixons During Pyrolysis: A Review of the Literature with Descriptions of Biomass Composition, Fast Pyrolysis Technologies and Thermochemical Reactions
Pacific Regional Bioenergy Partnership Library. June 2008. 63 pages. http://pacificbiomass.org/documents/TheFormationOfPolyaromaticHydrocarbonsAndDioxinsDuringPyrolysis.pdf. Manuel Garcia-Perez, references contributions from Judy Metcalf, WSU Extension Energy Program Library.

This report provides guidance on how to avoid environmental concerns (avoid heavy metals and chlorine) and have processes operated below 700 degrees C. In addition, it provides the results of a worldwide literature review of what is known and what are areas needing further research.

Organic Waste to Resources Research and Pilot Project Report: New Bio-refinery Concept to Convert Softwood Bark to Transportation Fuels Final Report to the Washington State Department of Ecology
https://fortress.wa.gov/ecy/publications/SummaryPages/0907061.html
ECY Publication -- 09-07-061 -- Solid Waste Management -- 2009, Manuel Garcia-Perez et al. 116 pages.

Organic Waste to Resources Research and Pilot Project Report. This project has identified a new pretreatment concept to enhance the production of sugars from the fast pyrolysis of wood and straw. It also proves, for the first time, that sugars recovered from pyrolysis can be easily converted into ethanol. These two results are important because they show that fast pyrolysis of wood or straw followed by bio-oil hydrotreatment can create green gasoline and green diesel (from the lignin fraction), as well as ethanol (from the cellulose fraction). These three common transportation fuels are of greater value than bunker fuel, which is the only fuel that can be currently replaced with pyrolytic oils. More investigations at the bench scale are needed to generate enough data for scale up of this technology and to evaluate its economic viability.

Organic Waste to Resources Research and Pilot Project Report: Use of Biochar from the Pyrolysis of Waste Organic Material as a Soil Amendment
https://fortress.wa.gov/ecy/publications/SummaryPages/0907062.html
ECY Publication -- 09-07-062 -- Solid Waste Management -- 2009, David Granatstein et.al. 181 pages.

Organic Waste to Resources Research and Pilot Project Report. Biochar is a charcoal-like material produced by the thermochemical pyrolysis of biomass materials. It is being considered as a potentially significant means of storing carbon for long periods to mitigate greenhouse gases. Much of the interest comes from studies of Amazonian soils that appear to have been amended with biochar which led to significant improvements in soil quality and large increases in crop yields. These changes have persisted for hundreds, if not thousands, of years. What is not known is how long it takes for biochar to integrate with the soil and thus express its benefits.

However, biochar does represent a stable form of carbon in soils and thus provides an intriguing potential carbon storage strategy. In this study, biochars from several different feedstocks were evaluated for their characteristics and their fate in five different Washington State soils. Herbaceous feedstock sources such as switchgrass and digester

fiber (from anaerobically digested dairy manure) had C contents of 60 and 67% respectively, as well as significantly higher N contents then the other biochars. Woody feedstock biochars had C contents above 75% with C:N ratios ranging from 176-588. Activated charcoal had a C and N content of 87% and 0.47%, respectively. Biochars tested in this project raised soil pH, but did not lead to consistent plant growth improvements. Soil nitrate levels were reduced with increasing biochar rate, perhaps due to ammonium adsorption by the biochar. All biochars on all soil types did increase soil C; the largest carbon impact was on the Quincy sand, the soil with the lowest organic matter content. Biochar C was stable in soil, and mean residence times are estimated to be in the hundreds of years. Also, the biochar did not accelerate loss of indigenous organic matter through the 'priming effect.'

Methods for Producing Biochar and Advanced Biofuels in Washington State Part 1: Literature Review of Pyrolysis Reactors
https://fortress.wa.gov/ecy/publications/SummaryPages/1107017.html
ECY Publication -- 11-07-017 -- Solid Waste Management -- 2011, Manuel Garcia-Perez, Trevor Lewis, Chad Kruger. 150 pages.

The following series of 4 literature reviews were conducted under Interagency Agreement C100172 with the Center for Sustaining Agriculture and Natural Resources, Washington State University. This first report reviews the historic technologies that have been developed for kilns, retorts and pyrolysers.

Methods for Producing Biochar and Advanced Bio-fuels in Washington State Part 2: Literature Review of the Biomass Supply Chain and Preprocessing Technologies From Field to Pyrolysis Reactor
https://fortress.wa.gov/ecy/publications/SummaryPages/1207033.html
ECY Publication -- 12-07-033 -- Solid Waste Management -- 2012, Manuel Garcia-Perez et al. 75 pages.

Turning organic waste into resources like bio-fuels and other valuable products, in addition to recovering stable carbon and nutrients, promotes economic vitality and aides in the protection of the environment. This creates robust markets and sustainable jobs in multiple sectors of the economy and facilitates closed-loop material management where a by-product from one process becomes feedstock for another with no or minimal waste generated. The objective of this review is to describe existing technologies to create clean, non-polluting pyrolysis units for the production of energy, fuels and valuable by-products.

Methods for Producing Biochar and Advanced Bio-fuels in Washington State Part 3: Literature Review Technologies for Product Collection and Refining
https://fortress.wa.gov/ecy/publications/SummaryPages/1207034.html
ECY Publication -- 12-07-034 -- Solid Waste Management -- 2012, Manuel Garcia-Perez et al. 125 pages.
This is the third of a series of reports exploring the use of biomass pyrolysis to sequester carbon and to produce fuels and chemicals.

Methods for Producing Biochar and Advanced Biofuels in Washington State - Part 4: Literature Review of Sustainability Issues, Business Models, and Financial Analyses
https://fortress.wa.gov/ecy/publications/SummaryPages/1207035.html
ECY Publication -- 12-07-035 -- Solid Waste Management -- 2013, Manuel Garcia-Perez et al. 85 pages.

This is the fourth and final in a series of reports on the application and benefits of thermochemical pyrolysis for fuels, heat and biochar from organic resources. This report focuses on the criteria that need to be followed to integrate these technologies into sustainable business models. This last report presents sustainability criteria and several business models that could be used to build sustainable enterprises based on biomass pyrolysis technologies.

Biochar: Background & Early Steps to Market Development
https://fortress.wa.gov/ecy/publications/SummaryPages/1207067.html
ECY Publication -- 12-07-067 -- Solid Waste Management -- 2012, Mark Fuchs, Manuel Garcia-Perez, David Sjoding. 21 pages. Biochar Industry Opportunities in the Pacific Northwest.

Biochar from Biomass and its Potential Agronomic and Environmental Use in Washington - A Promising Alternative to Drawdown Carbon from the Atmosphere and Develop a New Industry.
https://www.pnnl.gov/main/publications/external/technical_reports/PNNL-25239.pdf.
PNNL-25239. March 2016. James Amonette, Manuel Garcia Perez, David Sjoding and Mark Fuchs. 19 pages.

It has been estimated that the impact from this warming could cost the state $10 billion per year by 2020, and $16 billion per year by 2040. Long-term solutions to the climate problem likely will require that large quantities of CO2 be removed from the atmosphere. One of these potential actions is the large-scale production of biochar from abundant woody biomass waste and its storage in soils, where it remains stable for hundreds to thousands of years. Moreover, for the carbon emission intensity of Washington's fuel mix, biochar production from biomass is twice as effective in offsetting GHG emissions as complete biomass combustion of the same biomass.

F. Recent Biennial reports from combined CSANR Principal Investigators. Includes assessment of biological and thermal processing and multiple use scenarios to support the WSU bio-refinery design concept including co-composting, green house studies, literature reviews, and county assessments of biomass resources for soil carbon:

Odor in Commercial Scale Compost: Literature Review and Critical Analysis
https://fortress.wa.gov/ecy/publications/SummaryPages/1307066.html
Publication -- 13-07-066 -- Solid Waste Management -- 2013, Jingwei Ma, Kelpie Wilson, Quanbao Zhao, Georgine Yorgey and Craig Frear. 74 pages.

Managing residual organics in cities has been a major sustainability challenge of every historical civilization, with negative impacts ranging from nuisance odors and inefficient resource use to serious human health and environmental consequences. In spite of the technological progress achieved in recent decades, managing organic residuals remains a significant challenge, particularly as more programs have been established to recycle highly biodegradable food scraps.

Applied Research and Extension for Second-Generation Organic Waste Processing: High Solids Anaerobic Digestion, Nutrient Recovery, and Pyrolysis
https://fortress.wa.gov/ecy/publications/SummaryPages/1407010.html
ECY Publication -- 14-07-010 -- Solid Waste Management -- 2013, Craig Frear, et al. 246 pages.

The applied research and extension projects described in this report were carefully selected to address specific barriers to commercial viability that exist with these emerging technologies, as well as to provide ongoing extension and technological support to the next generation organics industry in Washington State. As a body, this work increases the likelihood that the local organics recycling industry will be able to utilize second generation waste treatment technologies, and that the public will benefit from further improvements in environmental impact and reductions in nuisance and public health concerns associated with municipal food and green waste recycling programs.

Advancing Organics Management in Washington State: The Waste to Fuels Technology Partnership
https://fortress.wa.gov/ecy/publications/SummaryPages/1607008.html
ECY Publication -- 16-07-008 -- Solid Waste Management -- 2016, Shulin Chen, Craig Frear, Manuel Garcia-Perez and others. 321 pages.

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 report presents work from 2013-2015 on WSU's Waste to Fuels Technology project.

Advancing Organics Management in Washington State: The Waste to Fuels Technology Partnership, 2015-2017 biennium
https://fortress.wa.gov/ecy/publications/SummaryPages/1807010.html
ECY Publication -- 18-07-010 -- Solid Waste Management -- 2018, Shulin Chen, Manuel Garcia-Perez, Chad Kruger and many others. 424 pages.

Washington State University's (WSU) Center for Sustaining Agriculture and Natural Resources has conducted targeted applied research and extension on emerging technologies for managing residual organic matter. This report presents work from 2015-2017 on the Ecology and WSU partnership - Waste to Fuels Technology project.

G. Other Biomass Energy Resources:

http://www.pacificbiomass.org/Library.aspx. This very good regional resource bio-energy projects library is supported by the Pacific Regional Bioenergy Partnership, within the Washington State University Energy Program office.

http://csanr.wsu.edu/publications/. The Center for Sustaining Agriculture and Natural Resources (CSANR) has supported research on dozens of sustainable agriculture and food systems topics for two decades. This publications database serves as a catalog of available resources. You can either browse Program Areas and Topics or search for relevant publications by key words.

This includes references from the Organic Waste to Resources project (07-09 biennium) and the continuing partnership (since 2006) with the Washington Department of Ecology on Waste to Fuels Technology and project.