Advancing Organics Management in Washington State

The Waste to Fuels Technology Partnership 2021-2023 Biennium

DEPARTMENT OF
ECOLOGY
State of Washington

Publication Information

This document is available on the Department of Ecology's website at:
https://apps.ecology.wa.gov/publications/summarypages/2307057.html

Cover photo credit

- Veronica Crow, 2023

Contact Information

Solid Waste Management Program

Headquarters
P.O. Box 47600
Olympia, WA 98504-7600
Phone: 360-407-6900
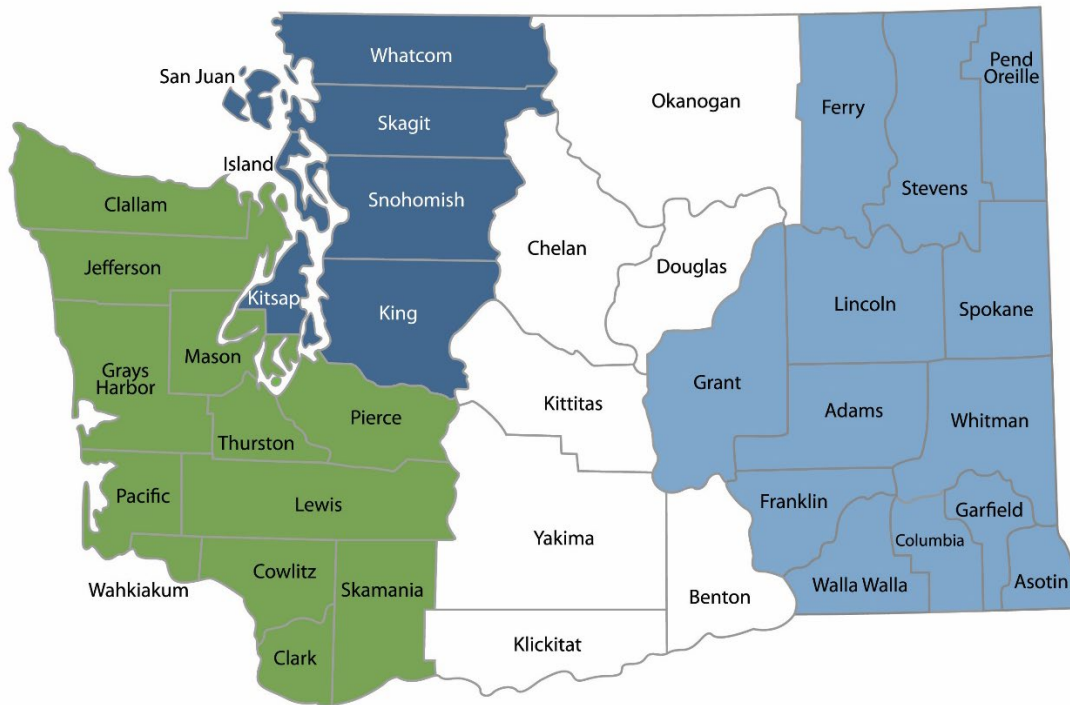**Website[1]:** Washington State Department of Ecology

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Headquarters	Across Washington	PO Box 46700 Olympia, WA 98504	360-407-6000

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By
Karie Boone[1], Manuel Garcia-Perez[2], Tom Jobson[3], Embrey Bronstad[1], Veronica Crow[2], Karen Hills[1], Aaron Whittemore[1] and Georgine Yorgey[1],

[1]WSU Center for Sustaining Agriculture and Natural Resources; [2]WSU Department of Biological Systems Engineering; [3]Laboratory for Atmospheric Research, WSU Department of Civil and Environmental Engineering

Solid Waste Management Program
Washington State Department of Ecology

Olympia, WA

October 2023 | Publication 23-07-057

DEPARTMENT OF
ECOLOGY
State of Washington

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Acknowledgements

The authors of specific chapters would like to thank the following people for their contribution to this study:

- Chapter 1 (Jobson): Tim O'Neil, Patrick O'Keeffe, Rhonda Skaggs, Dheapika Vijakumar, Ron Redman, Rick Finch, Brett Rodes, and Jake Reeves
- Chapter 2 (Crow and Garcia-Perez): Bikram Borkotoki, The Cobos family and their seven hens for providing wonderful chicken litter feedstock on a consistent basis to help us produce all our compost!
- Chapter 3 (Yorgey et al.): WTFT team members from past years who contributed to extension efforts during the current biennium.

Executive Summary

Wastes – including materials such as lumber scraps, yard clippings, food waste, and even some plastic wastes – represent an untapped resource hiding in plain sight. If recovered and used, these resources have exciting potential to help Washingtonians feed people, mitigate climate change, generate renewable energy and sustainable products, and improve soil health, all while adding to our economy. Washingtonians generated more than 18.5 million tons of solid waste in 2021 and less than half of this was recovered for beneficial uses (Figure 1).
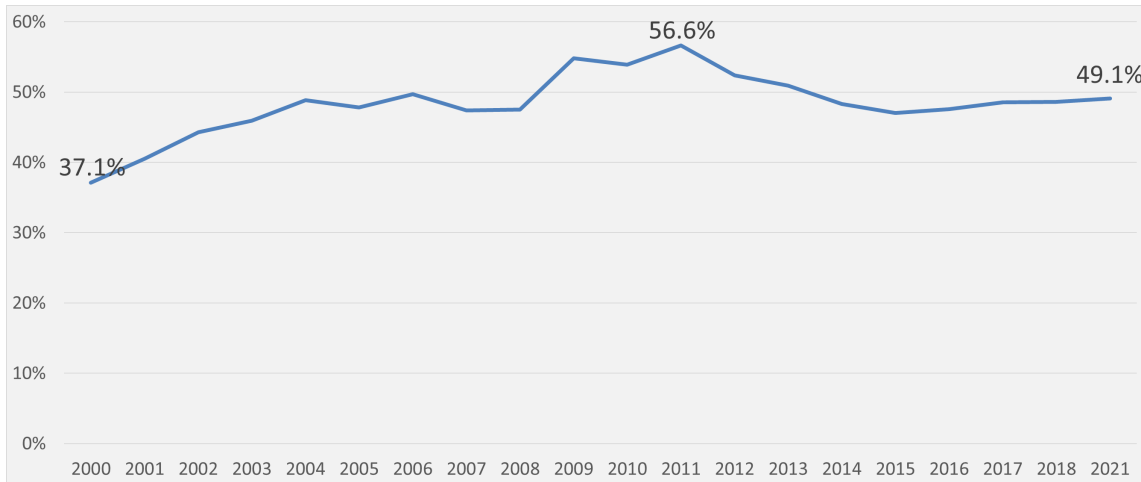
Figure 1: The recovery rate for Washington solid waste, indicating the percentage of materials collected for recycling, composting, and other beneficial uses such as burning for energy. From Washington Department of Ecology, 2023a.

Not all wastes are appropriate for diversion and resource recovery. Some wastes are hazardous. Others are contaminated – such as when composted organic materials contain bits of glass or plastics, or other contaminants. However, there is certainly room to improve the diversion of organic and other wastes to generate clean products that can benefit individual citizens and the public more broadly.

Washington's organic waste management hierarchy captures graphically the goal of managing food scraps and yard trimmings in the most beneficial way possible (Figure 2, left). A similar hierarchy has been proposed for plastics reuse (Figure 2, right). In both hierarchies, reducing sources of waste is the most preferable strategy. With wastes minimized as much as possible, uses that recover as much of the value as possible are preferred.

SOURCE REDUCTION: Reduce creation of organic waste by implementing SOURCE REDUCTION educational outreach programs

FEED PEOPLE: Reduce amount of good food going to disposal options by supporting/creating programs that get edible food to people

FEED ANIMALS: Reduce the amount of food scraps going to disposal by supporting/creating programs the send food scraps to animals

ON-SITE Organics Management: Food scraps, yard debris, landclearing debris, food processing, animal manure/bedding, forest biomass,

OFF-SITE Organics Management Food scraps, yard debris, food processing, animal manure bedding, forest biomass

Landfill Disposal
Incineration
With Energy Recovery

Landfill Disposal
Incineration
Without Energy
Recovery

Open
Burn

October 2016

Prevention

Reduction or Minimization

Regeneration

Reuse

Recycle

"4 R" principle of green design

Energy Recovery

Disposal

Figure 2: The Washington organics waste hierarchy (top) and the plastics use hierarchy (bottom) both emphasize preventing waste as a first priority; then for wastes that cannot be prevented, uses that retain more of the materials, energy, and nutrient value are preferred. Top figure: Adapted from Washington Department of Ecology (2016). Bottom Figure: Adapted from Roy et al. 2021.

Over the last several years, several important evolutions have happened in the waste management landscape. Public awareness of the negative environmental impacts associated with plastic wastes has risen, as has awareness of contamination within composting. Meanwhile, the passage of the 2022 Organics Management Law (HB1799) in Washington has increased attention on waste prevention, source reduction and the need to divert and process more of the state's organic wastes to minimize methane generation as well as other negative impacts that occur with landfilled organic wastes. The goal of this law is to promote sustainable waste management and increase the use of compost and food rescue programs. The law aims to reduce landfill disposal of organic waste by 75% by 2030 and rescue 78,000 tons of edible food by 2025. It mandates organics management by governments and businesses, establishes a Food Center, develops model ordinances, and enforces compost procurement and labeling requirements.

Actions taken within other agencies recognize the important connections between waste and other important aspects of Washington's environment and economy. Building on longstanding efforts to generate value from materials often considered "waste", the state also established an industrial symbiosis grant program within the Washington Department of Commerce. These funds have been used to support a variety of entrepreneurs seeking to create marketable goods from organic wastes. And the state has begun to implement the Climate Commitment Act, taking strong action to address climate change and reduce greenhouse gas emissions.

Throughout these changes, the Waste to Fuels Technology Partnership between Washington Department of Ecology, Solid Waste Management Program, and Washington State University has been supporting research and extension on the technologies and economics that could guide the next generation of organic waste processing. This report summarizes the work carried out through the partnership over the last two years. Within the partnership, technologies including composting, anaerobic digestion, and pyrolysis are being further developed to maximize the environmental benefits provided, minimize unintended negative impacts, understand and improve economics and address other barriers to broader implementation.

During the 2021-2023 biennium, one large research effort focused on ensuring that compost facilities in the state can better understand, air emissions. Another focused on developing new strategies for controlling air emissions during the composting process. Research and extension efforts improved understanding of solid waste-to-energy and materials recovery technologies and educated a diversity of individuals on the beneficial impact of using soil amendments derived from organic materials. These efforts additionally created new pathways for converting food and woody biomass into valuable products. Together, these projects support the implementation of the State's Solid and Hazardous Waste Plan (Washington State Department of Ecology, 2021), with particular attention to the following goals:

- GOAL SWM 12: State and local governments have increased understanding of solid waste-to-energy and material recovery technologies.
- GOAL SWM 14: Understanding and use of recycled organic products to amend soil, filter storm and surface water, and sequester carbon, which helps diversify end-use markets.

- GOAL SWM 16: Compost facilities operate well and produce clean, quality end products.

A diverse set of projects was carried out via the partnership in the 2021-2023 biennium. The work described in *Chapter 1, Implementing Method 25.3 to Measure VOC Emissions from Composting in Washington State,* was motivated by the need to better understand volatile organic compound (VOC) emission factors to inform questions relating to Title V air emissions permitting for commercial composting facilities in Washington. This has become a more pressing issue as policies encouraging diversion of urban food and green waste from landfills to composting facilities are pursued, with the simultaneous risk that these same facilities may be subject to more costly and complicated Title V air permitting applications as they expand their facilities to meet demand.

This project measured VOC emissions from green waste / food waste composting using a small scale continuously aerated static pile (CASP) system built at WSU Pullman. The capability of measuring compost emissions using a test method required in California for this purpose, SCAQMD Method 25.3, was developed and implemented in this project. Samples collected from the CASP system were sent to an accredited lab in California and our test results compared well with that lab. In general, the results between the accredited lab and WSU agreed within ±20%, an acceptable level of agreement for emission testing work. It was found the test method does not work well in colder weather (<40 °F) encountered in the fall and a winter in Pullman. Method 25.3 measures carbon mass and does not identify and quantify the types of VOC emitted which is needed for developing emission factors for air permitting requirements.

Continuous VOC testing methods were also developed in the study to determine compound emission rates for negatively aerated piles (45 cubic yards in size). The CASP system allowed for variation in air flow rates through the pile to control oxygen levels and pile temperature. We developed a method for continuously measuring VOC mass flux through the negative aeration duct and measured specific compound emission rates with 1-minute time resolution, 24 hours a day, for the entire ~2-week active phase composting period. For well aerated green waste / food waste piles, 90% of the total VOC mass emitted occurred in the first 3 to 5 days. VOC mass flux through the duct was typically 10-100 x greater than mass flux from the pile surface. We determined a total VOC emissions factor of 0.54 ± 0.50 lbs VOC / wet ton based on 4 negatively aerated pile tests. Most of the VOC mass emitted was in the form of oxygenated compounds such as methanol and acetic acid and from terpene compounds inherent as essential oil compounds in the pile material. The data suggests that modern CASP systems may have much lower VOC emission rates than those determined 15 years ago in California on windrow composting (5.71 lbs VOC as methane / wet ton) and currently utilized in the air permitting community (Jobson 2021).

Chapter 2, Reduction of odors and greenhouse gases from composting processes using biochar from locally available bio-resources, investigated the potential for biochar application to reduce greenhouse gas emissions from the composting process using locally available biochar resources. Characterization of 12 biochar samples based on their physical and chemical properties determined suitability for adsorption of certain greenhouse gases, harmful and

odorous air pollutants associated with composting: ammonia, methane, and hydrogen sulfide. Given that a diversity of biochars is expected to perform differently, the biochars were fully characterized (with results presented in Chapter 2) measuring pH, surface area, surface chemistry, ash content, volatile content, moisture and fixed carbon content, and their elemental carbon, nitrogen, hydrogen, and oxygen content. In addition to lab characterizations and adsorption studies, the study engineered acidic biochar and combined it with a commercial biochar sample to create a biochar cocktail, which was used as a filter in bench scale composting reactors designed and constructed for this study to investigate the application of biochar to the composting process.

The lab characterizations suggested that a majority of the locally available biochar samples examined in this study had a neutral to basic pH, however the surface areas of the biochar samples varied across a wide range (151-533 m^2/g). The results of the adsorption tests showed that higher pH and ash content is ideal for hydrogen sulfide adsorption, acidic biochars adsorb ammonia effectively, and that biochar with a high surface area will be most successful in methane adsorption. For both ammonia and methane, some locally available biochars tested in this study outperformed adsorption capacities of engineered biochars reported in the literature. For ammonia, the highest adsorption capacity of biochar tested was 242 mg/g char (sample "ACIDIC"), compared to 24-53 mg/g char reported in the literature (Ro et al. 2015). For methane, the highest adsorption capacity of biochar tested was 30 mg/g char (sample "OLYM, 7"), compared to 6.5 mg/g char reported in the literature (Song et al., 2021). In contrast, for hydrogen sulfide the highest adsorption capacity of biochar tested was 97 mg/g char (sample "KFESA, 2"), compared to 272 mg/g char reported in the literature (Abid et al., 2000). When compared to literature values for emission factors for these compounds from compost, these translate to relatively low application rates of 0.58% for hydrogen sulfide, 0.01- 0.5% for ammonia, and 0.17-1.6% for methane.

The bench scale composting portion of this study, designed to mimic an aerated static pile with positive aeration, showed that a biochar filter of 5% by weight, containing a 10:1 mixture of commercial sample 7 (OLYM) and the acidic biochar we had engineered, could effectively adsorb ammonia emissions and continue to reduce them significantly throughout the active stage of composting. The biochar filter reduced ammonia emissions below the recognition threshold (RT) such that no odor was detectable at the exhaust outlet and measured ammonia was not detectable at the beginning of the active phase. Biochar saturated with ammonia from the composting gases was altered dramatically in terms of its surface chemistry and functional groups but continued to reduce ammonia emissions throughout the course of the experiment.

Based on this work, further studies will be conducted to investigate different methods of biochar application in the composting process (co-composting, other methods of biofiltration), directly measure the effects of composting gases on the physical and chemical composition of biochar, significantly expand sampling of locally available biochar resources (including information about pyrolysis conditions and feedstock), understand mechanisms of interaction between biochar and composting gases, and compare experimentally determined adsorption

capacities with the quantity of a pollutant adsorbed measured during the actual composting process.

The research work carried out during the 2021-23 biennium was supported by an extension effort, described in *Chapter 3, Extension, Engagement, and Technology Transfer*. Through this work, the team sought to educate stakeholders about issues relating to sustainable organics management, next generation organics processing, and share the results of prior and ongoing partnership work with a diversity of stakeholders throughout the region. This includes those who work in the organics management industry, purchasers and users of organic residuals, others working on sustainable organics management at non-profits, county and local governments, and private companies, students, and Washington's residents. Live, in-person and virtual presentations opportunities were provided to 774 individuals via WTFT. Resources including publications, webpages, and recordings, were viewed at least 24,801 times. There has also been substantial ongoing interest in "projects on the ground" in the state and region. Projects are clearly influenced by several actors and factors, but the WTFT team members are frequently told that our advice, coming from a land grant university that isn't selling a product or service, is valued. Our relationships with individuals across the region who reach out to us for advice and information (and often, return to us periodically over time) indicates that they find these conversations helpful. Often, it's these more consultative discussions that facilitate movement toward (or deter when appropriate) capital-intensive investments in waste recovery projects.

This biennium was notable for the WTFT team's work on two Legislative provisos (with complementary funding). The first proviso directed WSU to explore and evaluate existing models to estimate carbon sequestration from the application of organic soil amendments to croplands, and identify technologies, methods, and potential funding for carbon sequestration from Washington's organic wastes. A second component of this proviso assessed local and state government compost usage in projects and buy-back programs. In a second separate proviso effort, Washington State University was asked to work with a number of partners to develop recommendations for increasing the economic value and sustainability of Washington's agricultural sector through the use of industrial symbiosis principles, connect agriculture producers and processors with partners to achieve synergies through systems-based resource sharing resulting in economic benefits and value creation for all participants, through sustainable resource recovery and optimization of energy, water, and organic waste streams. The reports produced through these proviso efforts are now available and will provide guidance to the Legislature and others seeking to make progress in these areas.

In conclusion, the efforts undertaken by the WSU-Ecology partnership are focused on contributing to the achievement of Washington State's long-term waste management goals. This includes goals to divert organics (including food wastes) from landfills as appropriate and facilitating "highest and best use" of materials that are often considered wastes. It also includes supporting ongoing development and application of waste conversion technologies, such as anaerobic digesters, pyrolizers and gasifiers, and other technologies as appropriate. These varied and innovative efforts are contributing to keeping Washington at the forefront of organics and waste management.

Meanwhile, amid signs of progress, new challenges emerge. This includes, for example, the emerging need to better understand emissions from commercial composting facilities in the state. Throughout these many developments, WSU researchers have been available as a resource when needed, and the partnership has continued to explore new production methods and uses for organics that could drive marketability, and to address emerging issues in organics management. Ongoing exchanges of ideas between researchers and practitioners will continue to support a range of efforts across the region, and progress from research concepts towards more widespread adoption.

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Chapter 1: Implementing Method 25.3 to Measure VOC Emissions from Composting in Washington State

Tom Jobson

1.1 Introduction

Measurement of volatile organic compound (VOC) emissions from composting is of interest to the State of Washington air permitting authorities. The Washington public policy goal of diverting more organic waste from landfills to composting facilities with the aim of reducing waste of valuable resources and decreasing emissions has increased composting volumes in some locations. This may cause some large facilities to be classified as major air pollution sources if they process enough material annually. Facilities that rise to the threshold of major air pollution sources would be required to carry a Title V air emissions permit as required by the Clean Air Act. This classification threshold occurs when a facility has a "potential to emit" (PTE) more than 100 tons of VOCs annually. For hazardous air pollutants (HAPs), the threshold is 10 tons per year, or 25 tons per year if more than one HAP is emitted. Emissions of VOCs are regulated under the Clean Air Act because they act as ozone precursors and some pose health concerns as HAPs. A Title V permit is a significant extra expense to the facility and could present a barrier to continued compost industry expansion to meet the state's policy goals.

There is currently limited information on VOC emission rates from the composting process on which to base an estimate of PTE. To determine annual emissions from a facility, an emissions factor is often used. Under this approach, a certain rate of emissions is estimated to occur for each wet ton of feedstock processed by the facility. This emissions factor is calculated by measuring mass emissions rate of VOCs from a composting pile as it composts over the active and curing phases. Studies conducted in California in the 2000's on windrow composting measured VOC emission rates from the pile surface as the pile aged. These studies are the most relevant data available for emission factor determination (SJV 2010). WA Department of Ecology has reviewed these studies and has adopted an emission factor of 5.71 lbs VOC as methane / wet ton as an active phase composting emission factor (Jobson, 2020).

However, our past work (Jobson et al. 2021) has shown that these emission factors developed in CA on windrows may not be relevant to WA state's most common material feedstocks and facilities that use forced aeration instead of windrow composting. Forced aeration systems allow for better temperature control and improved oxygen levels, and thus would likely impact VOC emissions rates. A survey conducted by WSU in 2020 on nine of the twelve largest compost facilities in the state, representing 60% of total annual material composted in the state, found that eight of the nine facilities surveyed used forced aeration systems. For large facilities where the question of Title V air permitting is more pressing, emission factor data from forced aeration systems is needed.

Given this finding, the purpose of this project was to develop compost emissions analysis capability at the Washington State University (WSU) pilot plant. Specifically, the goal was to

develop the capability to measure VOC emission rates from composting utilizing the SCAQMD Method 25.3, a method utilized for regulatory purposes within California's composting industry. Results from method 25.3 analysis capability developed through the project at WSU were compared against a Method 25.3 service provider from California.

A second important goal of this work was to use analytical methods that measure specific compounds to understand emission variation over time. This is fundamental to establishing PTE emission factors. This was accomplished by continuously measuring from the duct of a negatively aerated pile, a novel sampling approach for composting emissions research. These observations will be useful in the design of a statewide study of emissions from commercial compost facilities in Washington.

Background on sampling methods

A basic issue for emission factor development is selection of testing methods used to determine total VOC mass emitted. California's State Implementation Plan requires[2] the utilization of specific collection and analytical methods to determine total VOC emissions from composting facilities. The method to measure surface fluxes from compost piles uses a surface flux isolation chamber – meaning a chamber that sits on top of the pile and collects emissions. This method was developed in the 1980's for diffuse soil flux emission sampling from landfills. Air samples are collected from the small, stationary flux chamber to compute a generalized total VOC flux density from the surface. The analytical method for sampling and measuring VOC from the flux chamber is a modification of EPA Method 25 for determining total hydrocarbons. This method is referred to as the South Coast Air Quality Management District (SCAQMD) Method 25.3 "Determination of Low Concentration Non-Methane Non-Ethane Organic Compound Emissions from Clean Fueled Combustion Sources".[3]

To develop Method 25.3 analysis capacity at WSU, surface flux chambers were constructed and used to measure pile surface fluxes. Samples were collected from a two-zone aerated static pile composting pilot plant that was constructed at WSU in Pullman in 2021 with complementary funding under an Environmental and Education Research Foundation (EREF) grant with Tim O'Neil of Engineered Compost Systems (Seattle, WA).

In addition to analysis by Method 25.3, canister samples were analyzed by EPA method TO-15 (gas chromatography mass spectrometry) for speciated VOC analysis. Continuous speciated VOC sampling was done from the negative aeration duct by proton transfer reaction mass spectrometry (PTR-MS). The PTR-MS instrument can measure water soluble VOCs, such as acetic acid, that are not measurable by canister sampling. It has been demonstrated that water soluble acids and alcohols are important emissions from green waste composting (Kumar et al., 2020). In conversations on emissions measurement methods with the EPA Office of Research

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[2] by Rule 1133.3 (Emission Reductions from Greenwaste Composting)

[3] As the method title indicates, this analytical method has been adopted from a method that is used for measuring hydrocarbons in stack gas emissions. For compost emissions purposes, this Method 25.3 was listed as a federal EPA Conditional Test Method (EMC Conditional Test Methods | US EPA) in March 2000.

and Development (ORD) the importance of speciated measurements was emphasized to determine mass emission rates of HAPs and to determine total VOC mass. It is the total VOC mass that determines PTE. Method 25.3 does not measure total VOC mass but rather mass of carbon in the VOCs. The GC-MS and PTR-MS data determined what specific compounds were emitted and how their mass emission rates varied as the pile aged to compare with Method 25.3.

This report summarizes the major findings of this project. Additional detail is available in the technical report *Implementing SCAQMD method 25.3 to Measure VOC emission from Composting* on the WTFT 2021-2023 webpage of Washington State University's Center for Sustaining Agriculture & Natural Resources.

1.2 Sampling and analysis methods

WSU pilot plant

The WSU pilot plant is a two zone mechanically aerated static pile system (CASP) located within a large 3-sided storage building to help shield it from the weather. The system was designed to measure the influence of composting conditions (i.e., O_2 levels, temperature, moisture) on VOC emission rates. Flow rates from the zones to the piles are controlled by dampers and a programmable computer system.

Each pile was approximately 45 cubic yards and built into bunkers 12 feet wide by 18 feet long as shown in Figure 3. Pile depth was 6.5 to 7 feet. Piles were built upon two aeration ducts (4" diameter perforated plastic tubes) and can be negatively aerated (air pulled through the pile) or positively aerated (air pushed through the pile) by fans to simulate commercial systems used in WA state. Pile temperature was controlled by a computer system that measures pile temperatures in 4 places and automatically adjusts air flow rates to bring the average pile temperature to the desired set-point. By having two piles operating simultaneously, the experiment can compare the impact of compost conditions such as aeration mode and rate, pile temperature, oxygen levels, or moisture levels on VOC emissions. Piles were covered with ~8 inches of finished compost from the WSU compost facility.

Figure 3: Photos of aeration plenum with compost overs covering aeration tubes (right photo) and a picture as pile is being built into the bunker.

Sampling from active composting piles began in the summer of 2022 and seven runs were conducted shown in Table 1. Green waste material was supplied by Barr-Tech (Sprague, WA) for the first run, and subsequent runs from the Whitman County Transfer station or from the WSU compost yard. For runs R3-R7 the green waste material was combined with pre-consumer food waste, which was received monthly from Denali Water Solutions, collected from grocery stores (Walmart, Sams Club, Fred Myers) in eastern WA. The food waste was crushed into the green waste material with the loader and the material was then processed through the compost mixer to blend it and add water to bring to desired moisture level if required. One issue with the green waste material used from Whitman County was that it aged as it was stored on-site for runs R2-R6. Volatiles, such as monoterpenes, could be lost from the feedstock as it stores. The green waste used for R7 was recently ground material collected from the WSU campus. It consisted of both fresh material and older material that had accumulated and stored at the compost yard over the summer.

Negative duct sampling

Ejector Diluter and PTR-MS Measurements

With the ejector diluter, an air sample is continuously pulled from the duct and diluted with clean dry air to reduce water vapor concentrations. VOC and GHG gas concentrations also had to be diluted to be compatible with measurement ranges of the analyzers. A portion of this air flow was pulled to the instruments located in a van parked beside the aeration ducts.

Measurements of VOCs were made using a quadrupole type PTR-MS which continuously measures VOCs by chemical ionization using a proton transfer reaction. The PTR-MS method is described in detail in the literature (Lindinger et al., 1998; de Gouw et al., 2007). Many

compounds reported from compost emissions can potentially be measured using the PTR-MS (i.e., alcohols, ketones, aldehydes). The *in-situ* continuous sampling and high time resolution measurements are a distinct advantage for the study of compost emissions that can change by orders of magnitude in response to rapid changes in air flow rates and pile temperature. The attribution of measured ions to particular compounds was facilitated by comparison to GC-MS analysis of duct samples.

Flux chamber sampling and GC-MS analysis of canister samples

To determine VOC emission fluxes from the pile surface flux, isolation chambers were constructed at WSU according to dimensions outlined in the surface flux chamber method (EPA 1986) and with input from consultant Chuck Schmidt (PE) who routinely provides this sampling service in California. Mr. Schmidt's modifications to the original EPA chamber design included using a stack to vent the flow rather than a simple hole in the flux chamber dome. We also placed a cap on the stack to reduce the impact of wind diluting the chamber.

Canisters samples obtained from flux chamber sampling were analyzed by gas chromatography mass spectrometry (GC-MS) at WSU's Laboratory for Atmospheric Research (LAR) following EPA Method TO-15. The analysis allowed for quantification of most of the major compounds emitted from composting including methanol, acetaldehyde, acetone, 2-butanone, and monoterpenes and qualitative assessment of dozen or more other compounds identified in the chromatogram including alcohols, aldehydes, furans, and sesquiterpenes. Canister replicates were done every 4th or 5th sample as a QA/QC measure.

1.3 Key results

Table 1 lists the seven runs that were conducted in the study with zone aeration modes where zone 2 was always in negative aeration mode and zone 1 was run in positive, reversing, and negative modes. Table 2 lists chemical analysis of the feed stock materials. Each run had a slightly different mix composition. The R6 run was wet and had lower food waste due to cold wet weather, while run R7 was dry compared to the other runs, with a moisture level of 47%, as noted in Table 2.

Table 1: Compost runs conducted with aeration mode and feedstock descriptions

Run #	Date	Zone 1	Zone 2	Feed Stock	Bulk Density (lbs/CY)
R1	5/21/2022	neg	neg	fresh yard waste (Bar-Tech)	938
R2	7/13/2022	neg	neg	old yard waste (Whitman County)	916
R3	8/26/2022	neg	neg	WC green waste + 26,000 lbs Organix food waste + 20 CY dry wood waste (Ironsides)	938
R4	9/20/2022	pos	neg	WC green waste + 18,000 lbs Organix food waste	978
R5	10/17/2022	reversing	neg	WC green waste + 27,000 lbs Organix food waste + 5% manure	1033
R6	2/23/2023	pos	neg	WC green waste + 13,000 lbs Organix food waste + 5% manure	1129
R7	4/7/2023	pos	neg	WSU green waste + 25,000 lbs Organix food waste	767

Table 2: Selected results for feedstock chemical analysis

Run #	pH	C:N	Moisture (%)	Total N (%)	Ammonium – N (mg/Kg)	Organic Matter (%)
R1	7.5	23	59.1	0.60	0.3	23.5
R2	6.7	30	51.6	0.61	128	32.1
R3	4.7	24	49.1	0.71	433	35.7
R4	5.1	28	53.1	0.62	451	30.9
R5	5.1	24	61.6	0.61	416	29.0
R6	7.0	20	61.1	0.70	161	26.8
R7	7.3	22	47.3	0.44	16	41.6

Method 25.3 analysis

The intercomparison exercise, designed to compare our ability to perform the Method 25.3 analysis, compared analysis of canisters and impingers between WSU and the contract lab Atmospheric Analysis and Consulting (Ventura, CA). In this exercise samples were collected from surface flux chambers on compost piles and from the negative aeration duct (R6, R7 runs) and from prepared test gas mixtures in a laboratory setting.

The level of agreement between WSU and AAC was good for the prepared test gas mixtures. The mixture contained 14 components, including water soluble oxygenated species and insoluble hydrocarbons. Figure 4 shows the percent difference for the total VOC measured (sum of canister and impinger analysis) versus the test gas mixture concentration. Most of the

samples agreed within 20%. The test mixture exercise demonstrated that the two labs can get consistent results (±20%). However, there were unknown analytical or sampling issues that sometimes caused reasonably large differences (> ±20%) to occur for 6 out of the 16 samples. The basic level of agreement suggests the two labs have similar calibrations for the TOC and TVOC analyzers and there is no bias between the labs.

The field sampling exercise comparing WSU and AAC analyses for R6 and R7 produced mixed results. Samples were collected from surface flux chambers and from the negative aeration duct. The data for R7 sampling generally showed a good level of agreement for the total VOC with most samples falling in the ±20% difference range compared to the AAC result. However, there were again a few outliers, with WSU results being both lower and higher than the AAC result. There was no consistency in the differences in the results that could be readily attributed to some sampling or analysis issues. The results for R6 were poor and there was no correlation between the WSU and AAC data. AAC reported much lower values for both the canister and impinger, with largest differences for the canister analysis. WSU measured total VOC up to 325 ppmC while AAC data were < 60 ppmC. We attributed this poor result to sampling problems in cold weather where ambient temperatures during sampling ranged from -0.6 °C to 6 °C. Sample loss to cold tubing used in the Method 25.3 sample kits was likely the problem. The WSU canisters were also analyzed by GC-MS. The GC-MS analysis of the canister revealed that monoterpenes accounted for 97% of the total VOC mass in the canister.
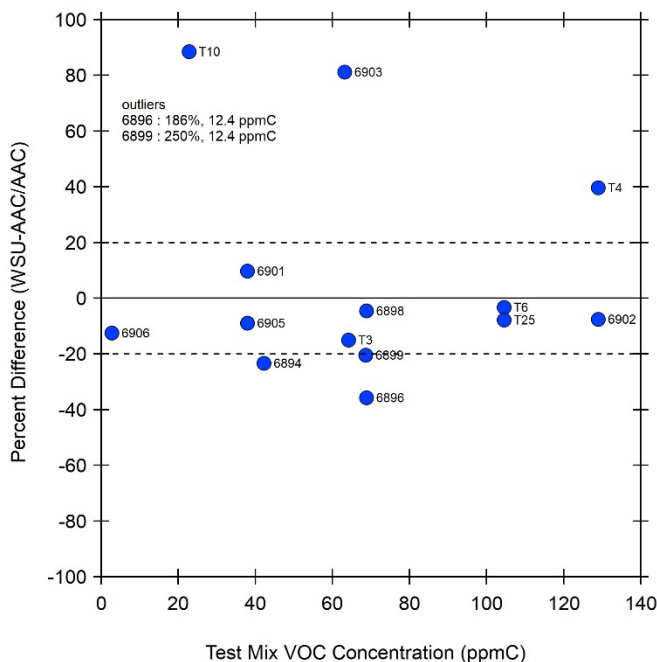

Figure 4: Percent difference of total measured VOC between WSU and AAC labs relative to the AAC lab result versus the test mixture concentration. Symbol identification is the WSU canister ID for reference.

We concluded that WSU can perform the Method 25.3 sampling and analysis and get similar results to a contract lab. However, such testing appears to have its limitations, notably

weather-related sampling issues. We note here that compost VOC emissions are comprised of water-soluble VOCs such as acids, alcohols, and ketones, that would be efficiently collected by the impinger, and monoterpenes which are not very soluble and would be collected in the canister. Determining impinger collection efficiencies of these water-soluble components and canister storage stability of monoterpenes and oxygenated VOCs that pass through the impinger is a critical need to prove the reliability of this method. There is no information in Method 25.3 on the collection efficiency of the impinger. In fact, the contract labs do not follow the SCAQMD Method 25.3 impinger design of using 2 mL of liquid in a 4 mL vial. This small volume seems inadequate for efficient collection at high VOC concentrations and is incompatible with liquid volume requirements for the impinger analysis by commercial TOC analyzers.

Since contract labs are using their own homemade impingers and liquid volumes, collection efficiencies would be expected to vary. AAC uses instead 10 mL in a 30 mL vial. WSU used 15 mL impingers and was more efficient than the AAC impinger. If oxygenated compounds are passing through the impinger to the canister, then there is the potential problem of recovery of polar compounds from the canister and underreporting emissions by this method since polar compounds adsorb to the canister wall. Canisters are principally used for sample collection and analysis of non-polar VOCs such as hydrocarbons found in gasoline; these compounds stay in the gas phase and do not adsorb as strongly to canister walls. Some companies sell canisters with amorphous glass coatings to increase storage stability of polar VOCs such as mercaptans and oxygenated compounds. Variations in canister storage stability would be expected amongst contract labs using different equipment.

Compost pile emission rates

The runs performed allowed us to examine emissions, including temporal variability of emissions, through the negative aeration duct. In some runs both piles were in negative aeration mode and sampling between zones allowed us to effectively measure impact of different pile conditions on emission rates as a function of pile age using the PTR-MS instrument. The "principle VOCs" summed the ion signal for m/z 33 (methanol), m/z 47 (ethanol + formic acid), m/z 59 (acetone), m/z 61 (acetic acid), m/z 73 (2-butanone), m/z 75 (propanoic acid), m/z 87 (pentanones and 2,3-butadione) m/z 89 (butanoic acid and ethyl acetate), m/z 137 (monoterpenes), m/z 153 (camphor and related $C_{10}H_{16}O$ compounds), m/z 205 (sesquiterpenes). The "total VOC" mass observed by the PTR-MS included "other" ion signals attributed to acetaldehyde, H_2S, dimethyl sulfide, furans, methyl furans, isoprene, and a few other unknown compounds and typically accounted for less than <10% of total mass. We report emission factors based on the "principle VOC" mass for simplicity. Table 3 lists emission factors from the negatively aerated piles for these principle VOCs, along with average air flow rates, pile temperature and O_2 levels. The emission factors for runs R1 and R3 are underestimated because the zones were not being measured 100% of the time. For fresh green waste composting done in R1 the emissions were dominated by methanol, monoterpenes, sesquiterpenes, and $C_{10}H_{16}O$ terpenoids. Adding a little bit of food waste (~ 15% by volume) dramatically changed the nature of what was emitted. While methanol and monoterpenes were still major emissions, the mixed food waste / green waste piles also produced large

emissions of organic acids (acetic acid in particular), alcohols, and ketones. This is illustrated in emission pie charts of Figure 5, contrasting the make-up of R1 zone 2 emissions with that of R7 zone 2.

Table 3: VOC mass emitted and corresponding emission factor for negatively aerated piles measured by the PTR-MS instrument.

	Mass emitted (lbs)		Emission Factor (lbs VOC / wet ton)		Air flow first 2 days (SCFM/CY)		Average air flow remaining days (SCFM / CY)		Average pile temperature (°F)		Average pile O$_2$ level (%)	
Run #	Z 1	Z2	Z 1	Z 2	Z1	Z 2	Z 1	Z 2	Z 1	Z 2	Z1	Z2
R1*	3.91	6.22	0.25	0.39	19	1.8	3.8	0.9	126	151	19.5	16.6
R3*	25.7	0.99	1.35	0.05	13	0.3	2.4	0.3	113	143	19.2	14.2
R4		14.2		0.66		3.8		1.2		141		18.9
R5		4.65		0.26		4.1		0.8		142		15.7
R6		2.38		0.10		1.1		1.2		158		14.4
R7		22.2		1.20		3.7		1.5		139		19.0

* R1 and R3 mass emitted underestimated because zones were not measured 100% of the time.
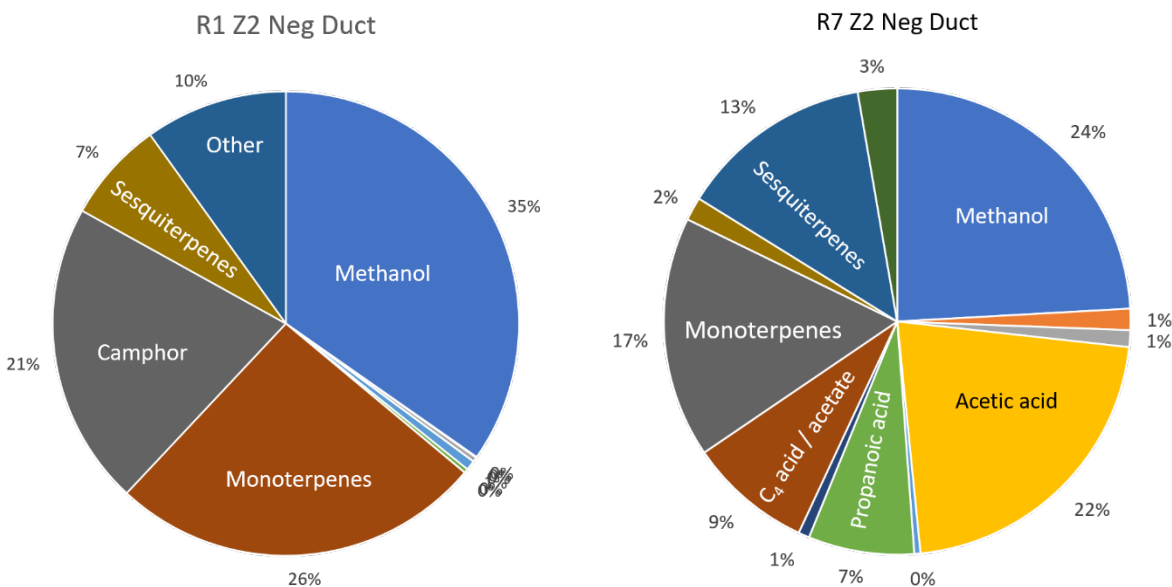
Figure 5: VOC emission pie charts showing fractional mass emitted by compound for R1 zone 2 (green waste only) and R7 zone 2 (green waste / food waste). Food waste mixes displayed organic acid emissions.

The average emission factor for R4, R5, R6, and R7 runs, which had very complete data over the pile age, was 0.54 ± 0.50 lbs / wet ton. These piles had good levels of air flow and reasonably similar pile temperatures. The surface flux emission rates for negative aerated piles, were

typically lower by an order of magnitude or more than the flux through the duct, but exceptions were occasionally observed.

In terms of Method 25.3 reporting that counts carbon mass, this average emission rate is equivalent to 0.39 ± 0.38 lbs VOC as CH_4 / wet ton, given the compounds emitted. These differences in reported mass are due to high emission rates of oxygenated compounds such as methanol and acetic acid which are ~50% by mass oxygen and not counted by Method 25.3 analysis methods. This emission factor is significantly lower than average value of 5.71 lbs VOC as CH_4 / wet ton from California windrow studies used by the San Joaquin Valley Air Pollution Control District to establish their emission factors (SJV 2010) and adopted elsewhere (CDPHE, 2012).

The principle difference between the highest and lowest emission factor runs was the air flow rate through the pile. The lowest emission rates runs were for zones with lower air flows, a rate of 1 SCFM / CY (R6 zone 2) and 0.3 CFFM / CY (R3 zone2). The highest emission rates (R3 zone 1 and R7 zone 2) were for runs with high initial air flow rates as shown in Table 4. Most of the mass emitted occurred in the first few days when the piles were heating up, and for R3 zone 1 most of this mass was acetic acid. Acetic acid was a dominant emission in R3, R4, and R7. This work highlights the need to measure methanol and acetic acid as these were dominant VOCs with high fractional contributions to the total mass emitted from these piles. For piles with low air flow rates (R3 zone 2 and R6 zone 2), the emissions were spread out over a longer period of time, more similar to that observed for windrow composting.

Table 4: Percent of total VOC mass emitted over time period for negatively aerated piles

Pile	First day	First 3 days	First 5 days	First 7 days	First 10 days
R3 Zone 1	38	90	94	97	98
R3 Zone 2	8	15	33	47	80
R4 Zone 2	39	74	89	97	99
R5 Zone 2	84	93	94	94	99
R6 Zone 2	9	77	90	95	99
R7 Zone 2	56	94	97	99	100

For emission determination by grab sampling methods, like Method 25.3, it will be important to collect samples during the first few days, perhaps a morning and afternoon sample, to provide adequate temporal resolution of large emission rate changes (factor of 10 or more) that can occur over the course of a day. These differences are best illustrated with R3 piles that displayed the highest and lowest emission factors in the study. The R3 run, where two identical feedstocks were compared under different flow rates, was the most dramatic example of how emissions may vary as function of air flow rate and pile temperature. We note that surface flux samples obtained from R3 showed that the surfaces emission rates (mg / hour) from the ~100 ft^2 pile surface were typically 10 to 100 times less than mass emission rates of methanol, acetone, 2-butanone, and monoterpenes measured in through the duct for both zones. Figure 6 shows duct emission rates for R3 zone 1 and Figure 7 for R3 zone 2, illustrating the capacity

developed in this project to continuously measure VOC mass flow rates through negative aeration ducts over a very wide dynamic range. Zone 2 emissions of ethanol / formic acid were initially greater than 10^6 mg/hr (1 kg / hr) for the first few hours then rapidly dropped. Acetic acid emissions rose this this level in the first day and stayed at this level for the next 2 days while the air flow rate was high. Note the orders of magnitude change in the acetic acid emission rate when air flow dropped from 550 SCFM to 200 SCFM at end of day 3. For future site testing it seems critical to understand what is happening with air flow rates and temperatures in CASP systems. This knowledge would assist in conducting an appropriate emissions testing as almost all the mass was emitted in the first few days.
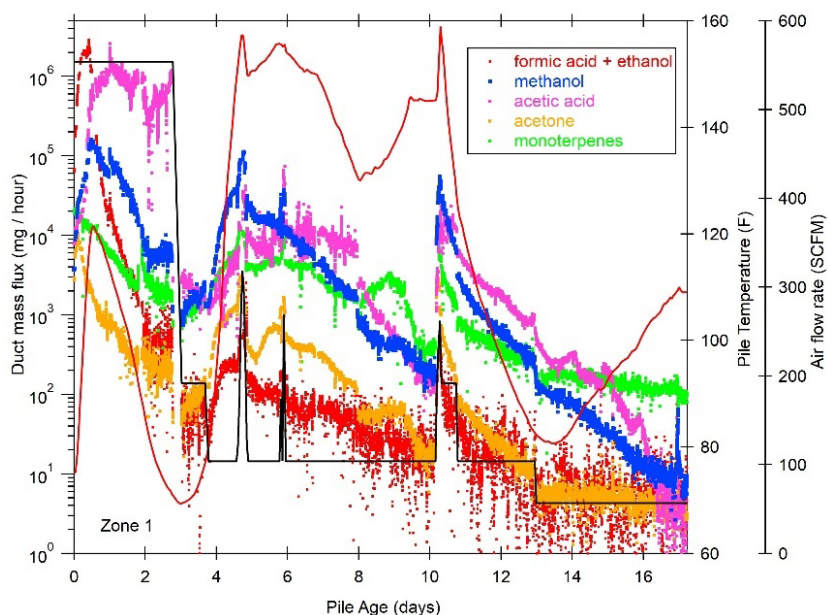
Figure 6: R3 zone 1 mass emission rates (mg / hr) versus pile age of various compounds through the duct (colored symbols), air flow rate (black trace), and average pile temperature (red trace)
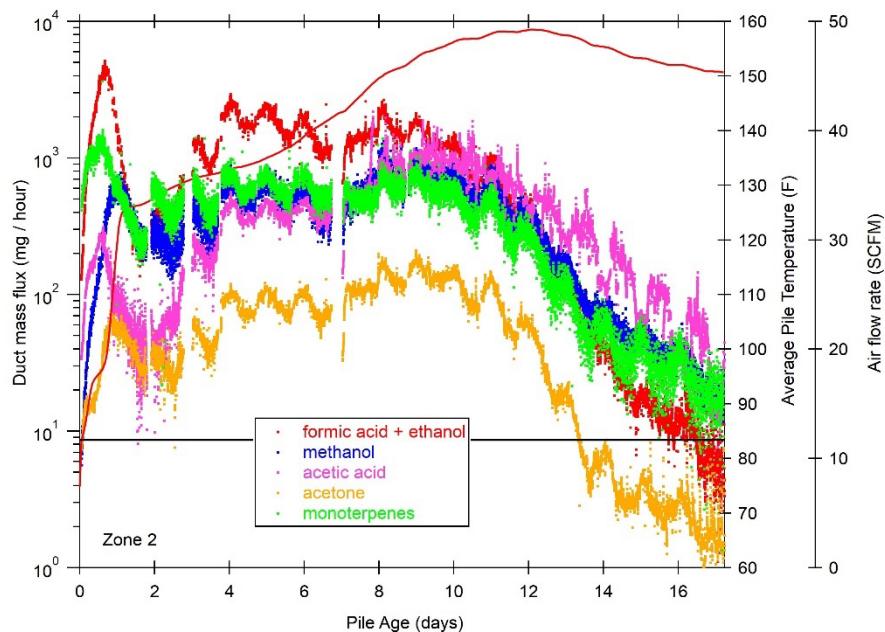
Figure 7: R3 zone two mass emission rates (mg / hr) versus pile age of various compounds through the duct (colored symbols), the constant air flow rate (black trace), and average pile temperature (red trace).

1.4 Discussion and conclusion

Method 25.3 was successfully implemented at WSU and compared with the contract service lab Atmospheric Analysis and Consulting (Ventura, CA). Comparison of test gas mixtures prepared in the lab and R7 pile surface and duct sampling showed that most samples agreed within 20% but there were outliers that could not be explained. The comparison did not work well for the cold weather sampling done for R6 and suggests there are sampling issues for this approach in the cold (~3 °C).

Method 25.3 is a carbon accounting method that does not measure actual VOC mass as was done in this study to determine VOC emission factors. Results from Method 25.3 sampling cannot be used for determining emission factors for Title V applicability since speciated VOC measurements are required (US EPA 2000). Once emission factors have been established with alternative methods, this method for documenting emissions compliance seems reasonable. It is fairly easy to implement and conduct the relevant analysis. Since impinger designs are not standardized amongst the contract labs supplying the sampling kits, the method needs to be further tested to establish sample recovery from the canister and impinger, something unanticipated when this study began.

Negative aeration of our green waste / food waste feedstock materials yielded an average emissions factor of 0.54 ± 0.50 lbs VOC / wet ton based on the results from R4, R5, R6, and R7 runs. The emissions were often dominated by oxygenated compounds such as methanol and acetic acid. The surface flux emission rates were typically orders of magnitude lower. Given the compounds emitted, the Method 25.3 equivalent average emission factor was 0.39 ± 0.38 lbs

VOC as CH_4 / wet ton, significantly lower than the 5.71 lbs VOC as CH_4 / wet ton from California windrow studies used by the San Joaquin Valley Air Pollution Control District to establish their emission factors (SJV 2010). The CASP system and these green waste / food waste feedstocks yielded an emission factor 10 times lower than windrow composting emission factors from California. This is a significant difference which should be further explored with measurements on other green waste / food waste feedstocks composted in WA. This study suggests that emission factors for WA green waste composting facilities using CASP systems with well aerated piles and moderate temperatures similar to those used here could have significantly lower VOC emission factors than those determined in California.

From discussions with the EPA Office of Research and Development during this project, it was suggested that alternative approved analytical methods be used that are designed for VOC emissions testing. Some of these analytical methods have been developed for the wood products industry (National Association for Air and Stream Improvement, NCASI methods) and are recognized by the US EPA. These methods have been developed to measure alcohols and aldehydes and are relevant to compost emissions, such as the NCASI A105 method. Methods that can speciate acids will necessarily involve collection into an impinger and separation and analysis by a technique that can measure formic acid, such as ion chromatography (IC) or high performance liquid chromatography (HPLC). Such methods are established and can be supplied by contract labs. Methods for monoterpenes involve trapping them on a carbon absorbent and solvent extraction of the monoterpenes for analysis by GC-FID, following EPA Method 18. This amounts to 3 separate sample collection kits and 4 different chemical analyses. Given the time spent in the field and lab conducting Method 25.3 sampling, the burden presented with the need for 3 different sample collection kits to get one data point needs be carefully thought through for future work in the upcoming compost emissions study sponsored by the Department of Ecology.

It was found that the CASP systems can display rapid and large (orders of magnitude) variation in emissions rates through the duct in response to changes in air flow rates and pile temperature. The grab sampling nature of measuring emissions with Method 25.3 will make it difficult to capture fast changes in emission rates that can occur over the first 2-3 days of sampling. These changes occur in response to pile temperature or air flow rate changes controlled by aeration system programming.

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Chapter 2: Reduction of Odors and Greenhouse Gases from Composting Processes Using Biochar from Locally Available Bio-resources

Veronica Crow and Manuel Garcia-Perez

2.1 Introduction

Washington is working towards the goal set by HB-1799 to reduce organic waste in landfills by 70% before 2023. To meet this goal, existing composting facilities will likely need to increase the amount of organic waste they process while still complying with emissions and air quality regulations. Composting facilities are also always at risk for an off-site odor episode that can damage their reputation with the community they serve and upset residents (Eitzer, 1995). Beyond odors, industrial composting facilities can produce greenhouse gases, volatiles, and other air pollutants (Jobson and Khosravi, 2019).

There are a number of operational and technological strategies that composting operations can use to limit odors and other air emissions from composting (reviewed in Ma et al. 2013) and developing additional low-cost methods will add to their toolbox. Reduction of some emissions, including ammonia (NH_3), methane (CH_4) and hydrogen sulfide (H_2S) may be supported with the use of specially formulated biochar cocktails. Because the biochar that most effectively adsorbs each gas differs significantly, designing application methods in the composting processes that maximize emission reduction requires the development of a formulation for a biochar cocktail to be determined experimentally. Once designed, these cocktails could be deployed in exhaust filters, as toppers, as biofilters, or via co-composting.

Current literature and related work in the previous biennium with engineered biochar demonstrates that biochar can adsorb a number of these problematic gases. The potential exists for the application of functionalized locally available biochar resources to produce biochar cocktails for the reduction of greenhouse gas emissions during the composting process, as well as provide methods to reduce odorous compounds below the recognition threshold (Jefferson-Milan, 2021; Font, 2011).

Meanwhile, utilities and lumber companies are producing biochar from forest residuals to manage wastes, create value-added end products and sequester carbon. Some of this material is processed and sold as biochar and developing additional high value uses could help stimulate markets and build the biochar economy. This study serves to assess the locally available biochar resources and experiment with their functionalization in the composting process to reduce ammonia, methane, and hydrogen sulfide emissions.

This study consists of three parts:
1. Characterization of local biochar resources (industrial and commercial) and production of acidic biochar;

2. Measurement of biochar adsorption capacity for ammonia, methane, and hydrogen sulfide; and

3. Measurement of top-layered biochar's ability to reduce ammonia, methane, and hydrogen sulfide emissions during bench-scale, positively aerated composting

Additional details on this study, including full methods and results, are available in a technical report *Reduction of Odors and Greenhouse Gases from Composting Processes using Biochar from Locally Available Bio-resources.* This report can be accessed on the Waste to Fuels Technology 2021-2023 webpage of Washington State University's Center for Sustaining Agriculture & Natural Resources.

2.2 Characterization of Local Biochar Resources and Production of Acidic Biochar for Composting

The study collected 12 biochar samples from commercial and large industrial sources, including utilities and lumber companies. We then performed seven different analyses to identify existing biochar(s) with attributes that would help with adsorption of the target gases, ammonia, methane, and hydrogen sulfide. Analyses included quantifying elemental composition (C, H, N, O), functional surface groups, surface area, micropore and mesopore volume and size distribution, pH, ash content, volatile matter (VM), fixed carbon content, and chemisorption capacity. Elemental analysis quantifies the total composition of principal elements C, H, N, and O in biochar samples, while thermogravimetric tests (measuring the change in a sample's mass over a particular temperature regime) provides information on ash content, volatile matter, and fixed carbon, which is the solid carbon that remains incorporated in the structure of the biochar after volatilization of compounds during pyrolysis, including some carbon-containing compounds (Speight, 2015). These characteristics provide information on the composition of the biochar, while understanding the surface functional groups, surface area, and pore size volume and distribution help predict its behavior and reactions with certain compounds. Test results are presented in Table 5 below.

Biochar characterization indicated that several characteristics of the existing biochar were likely to support adsorption of ammonia, methane, and hydrogen sulfide. Basic pH and high ash biochar is generally good for hydrogen sulfide adsorption, acidic pH biochar is good for ammonia adsorption, and high surface area (SA) and microporosity is most important for methane adsorption (Jefferson-Milan, 2021). Therefore, we categorized the studied biochars based on the results for pH and SA (acidic, neutral, basic, and exceptionally high or low SA). Since none of the 12 biochar samples were highly acidic, study-specific acidic biochars were used in a biochar cocktail to test ammonia adsorption, as biochar with a lower pH has been shown in literature to reduce ammonia volatilization and increase nitrogen retention in composting and environmental applications, and acidic functional groups on the surface of a biochar lend themselves to increased ammonia adsorption, since it is a basic gas (Hestrin et al., 2020; Esfandbod et al., 2016; Jefferson-Milan, 2021).

Table 5: Locally available biochar samples characterization. The basic pH category denotes anything over 9, while neutral to basic samples ranged from 7.5 to 8.7. Average surface area of all the samples was appx. 280 m²/g of char. High SA samples denote anything above 400 m²/g, sample 8 had an extremely low SA of 7 m²/g. Excluding sample 8, SA ranged from appx. 160 to 490 m²/g.

Sample Ref. and Number	Proximate Analysis (wt. %)				Elemental Analysis (C+H+N+O+ash = 100 wt. %) (in dry basis)				Surface Area (SA)	Pore Vol.	pH and SA
	Fixed Carbon	Ash	VM	Moist	C	H	N	O	(m²/g)	(cm³/g)	
KFCA (1)	21.7	64.1	14.2	1.8	30.8	1.0	0.2	6.2	218	0.073	Basic
KFESA (2)	19.4	64.2	16.4	1.6	20.3	3.9	0.1	11.5	158	0.054	Basic
SSUN (3)	79.4	9.7	10.9	2.0	47.9	4.4	0.1	38.0	409	0.11	Basic
WAKE (4)	41.1	49.5	9.4	1.9	38.1	1.4	0.1	10.9	263	0.086	Neutral to basic, high SA
PLANT X (5)	82.2	6.8	11.0	2.2	72.3	1.9	0.3	18.6	500	0.16	Basic
GEN (6)	26.2	56.6	17.2	2.7	27.6	1.1	0.1	14.6	239	0.22	Basic
OLYM (7)	84.8	3.1	12.1	2.0	60.8	3.4	0.2	32.5	513	0.16	Neutral to basic, high SA
CARBO C (8)	87.3	1.4	11.3	1.4	81.0	2.4	0.8	14.3	374	0.0016	Neutral, very low SA
OR60 (9)	65.2	17.8	17.0	4.0	49.6	2.4	0.1	30.2	365	0.18	Basic
OR80 (10)	85.1	5.6	9.3	2.3	75.2	1.9	0.3	16.9	533	0.25	Basic, high SA
Kfcarb (11)	37.3	44.8	17.8	3.1	22.0	5.8	-	27.3	314	0.21	-
Kfash (12)	13.7	72.2	14.0	2.2	9.3	3.8	-	14.7	151	-	-

The 12 biochars analyzed had pHs ranging from neutral to very basic, but none were acidic (Table 5). An acidic biochar was therefore produced by treating biochar from Douglas Fir with phosphoric acid (H_3PO_4), following Ro et al. (2015) and Jefferson-Milan (2021). This produced biochar had an average pH of 1.62.

2.3 Measurement of biochar adsorption capacity for ammonia, methane, and hydrogen sulfide

Using gas chromatography, each biochar was tested for its ability to adsorb methane and hydrogen sulfide. This method injected samples of biogas through vertically oriented columns

of biochar, taking measurements of the resulting breakthrough time (time of the first non-zero concentration reading), and the concentration of gas until the biochar is fully saturated (the point at which the concentration of gas matches the starting concentration of gas). Concentrations were then used to calculate the adsorption capacity for each gas per gram of biochar. Detection and direct measurement of biochar adsorption of these gases required different experimental setups for each emission using model compounds in the lab.

Measuring ammonia adsorption is slightly different; experimental methods used by Jefferson-Milan (2021) were adapted to measure the ammonia adsorption capacity of each biochar characterized in this study.

Ammonia (NH$_3$)

The engineered acidic biochar performed exceptionally well and, surprisingly, the KFCA, which is very basic performed better than the other more neutral biochar (Figure 9). This result suggests that without additional treatment, this byproduct can adsorb some ammonia.
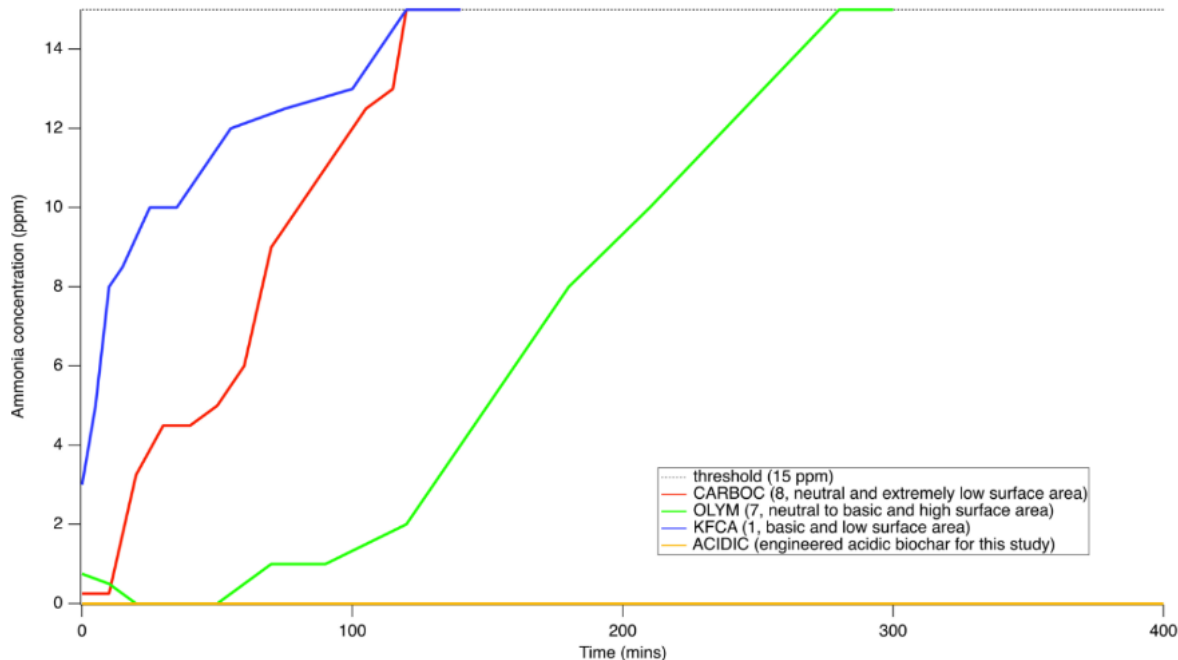
Figure 8: Ammonia breakthrough curves for biochar samples. The 0 ppm ammonia concentration maintained by the adsorption capacity of the biochar engineered with phosphoric acid treatment for this study is depicted along the x-axis.

Hydrogen sulfide (H₂S)

KFESA has the highest ash content and pH, therefore it was no surprise that it outperformed the other biochar materials (Figures 10 and 11). However, its adsorption capacity (97 mg H$_2$S/g biochar) is still lower than what is documented in the literature (272 mg H$_2$S/g biochar).
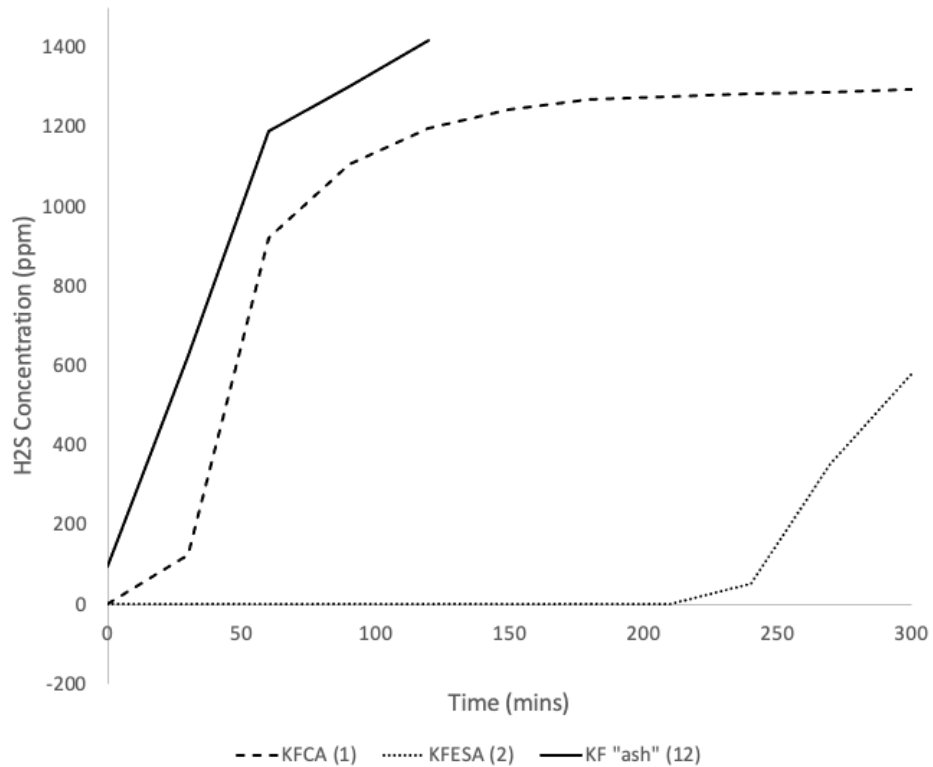
Figure 9: H$_2$S adsorption results for three KFBGS biochar fractions
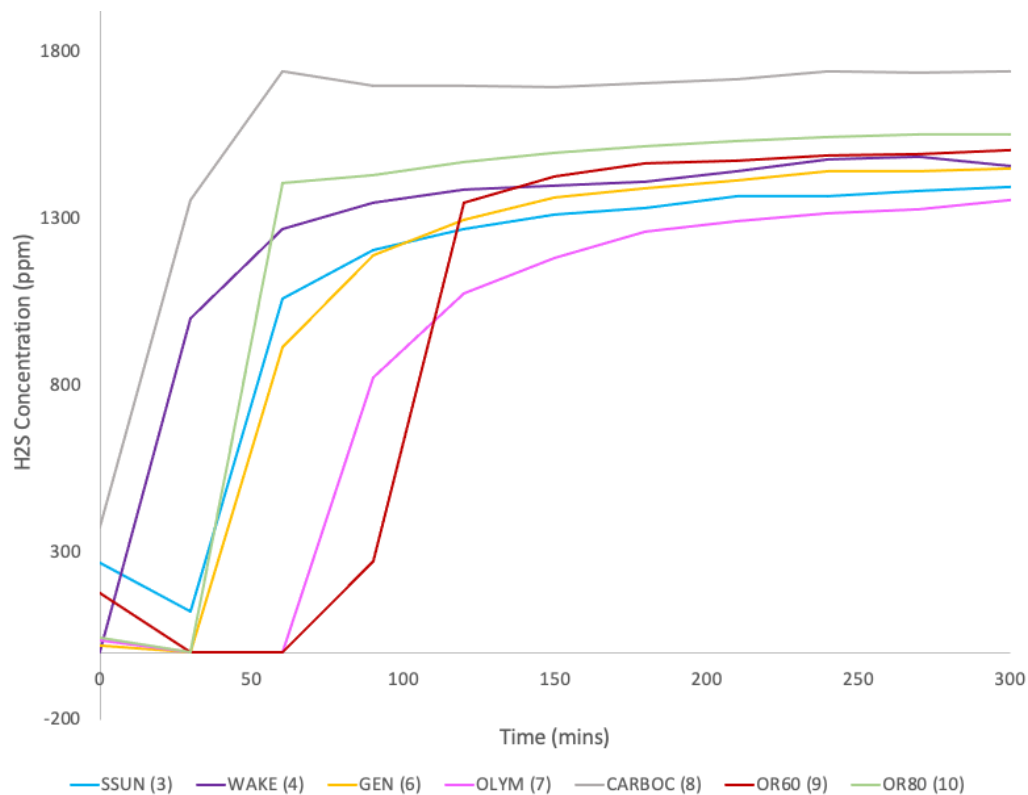
Figure 10: H_2S adsorption curves for seven commercial biochars

Methane (CH₄)

As predicted, biochars with the highest surface area had the best methane-adsorption performance (Figure 12). However, sample 7 (second highest surface area) dramatically outperformed the other tested samples, and further research is needed to understand the roles other characteristics play in this particular sample's ability to adsorb methane.
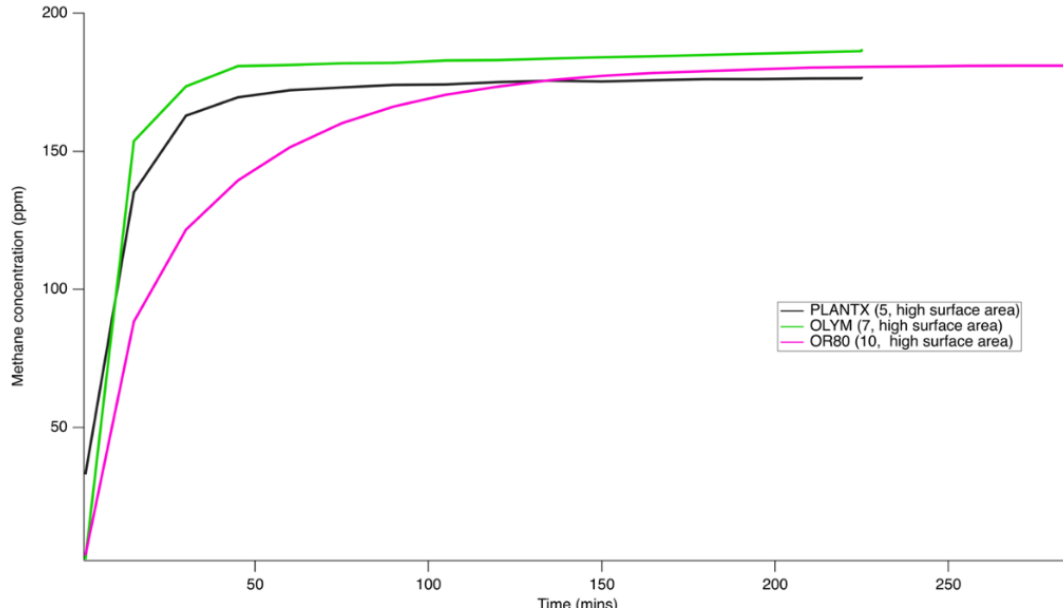
Figure 11: Methane adsorption breakthrough curves for high surface area biochars

Discussion of results from adsorption and characterization studies

Biochars tested and the engineered acidic biochar surpassed literature values for methane and ammonia (Table 6). While KFESA (2) had better hydrogen sulfide adsorption than biochars engineered in the previous biennium, these results are not comparable to literature values. Despite this, KFESA (2) is an end-stage ash product that is readily available in excess (presenting a waste management problem for KFBGS) and could effectively reduce H_2S emissions if properly applied to the composting process.

Table 6: Literature values for biochar adsorption capacity of target compounds vs. biochars studied and produced acidic biochar

Compound	Adsorption capacity (mg/g char)	References	Highest adsorption capacity of Biochar tested or engineered in this study(mg/g char)
H_2S	272	Abid et al., 2000	97 (KFESA, 2)
NH_3	24-53	Ro et al., 2015	242 (ACIDIC)
CH_4	6.5	Song et al., 2021	30 (OLYM, 7)

Utilizing the adsorption capacities determined above and compost emissions factors derived from the literature, calculations of how much biochar would be required to adsorb emissions by weight are listed in Table 7.

Table 7: Biochar needed to reduce emissions. Weight % = g biochar / g waste * 100%

Target Compound	Emission Factor* (mg/g waste)	Adsorption capacity of biochar tested/engineered in this study (mg/g biochar)	Biochar required to adsorb emissions by weight
H_2S	0.561	97 (KFESA, 2)	0.58 %
NH_3	0.018–1.150	242 (ACIDIC)	0.01 % to 0.5 %
CH_4	0.05–0.49	30 (OLYM, 7)	0.17 % to 1.6 %

* References: Han et al., 2019, Clemens & Cuhls 2003; Cadena et al., 2009, Amlinger et al., 2008

2.4 Measurement of top-layered biochar's ability to reduce ammonia emissions during bench-scale, positively aerated composting

Fifteen bench-scale composting reactors, each containing air flow and temperature systems, were constructed to test biochar's ability to reduce emissions when applied as a filtering top layer to aerated static pile composting. The units were built to mimic an aerated static pile (ASP) system with positive aeration, where air flowed into the units from the bottom through a perforated PVC aeration system. Flow into the units was controlled via flowmeters and insulated with black neoprene and mineral wool, surrounded by a layer of plastic sheeting for safety.

Once the composting unit was prepared, biochar was placed a wire-mesh lined filter in the headspace of the composting unit containing 5% biochar by weight (see Figure 13). This proportion was determined by considering literature values, results of our adsorption studies, and economic feasibility and scalability (Steiner et al., 2011; Hestrin et al., 2020). The biochar in the filter was a 10:1 mixture of commercial biochar sample 7 (OLYM) and the acidic biochar that

we had produced for this study. Sample 7 biochar was used because this biochar performed significantly better than both literature values and other biochars tested in this study for methane adsorption and was also the second best performing commercial biochar for ammonia adsorption. Mixing two biochar samples also moderated the overall biochar pH somewhat. The acidic biochar we produced had an average pH of 1.62, lower than literature values for biochar used in co-composting studies (Hestrin et al., 2020), therefore we formulated a biochar cocktail with a measured pH of 4.28.

Figure 12: Biochar biofilter. Small wells are visible at the surface where air has flowed through preferentially after day 3

Reduction in gaseous emissions and odors were measured from compost feedstock mixes that combined grass hay, pine shavings, and chicken manure following standard methods from the USDA's Test Methods for the Examination for Composting and Compost (TMECC) (USDA and US Composting Council, 2001). Consistency between the biochar amended and control units without the biochar ensured that bulk density (765 lbs/cy), moisture content (63% wt.), pH (8.2), C:N ratio (22), and other parameters were all sufficient for composting. Aqueous ammonia samples were collected daily for analysis to measure the potency of ammonia gas from each composting unit, in addition to gas samples that were collected for injection into the gas chromatograph to measure methane concentrations in the composting units. Oxygen content, temperature, compost mass, and moisture were also monitored for compost health and to ensure following the composting process as accurately as possible in the composting units.

that bulk density, moisture content, pH, C:N ratio, and other parameters were all sufficient for composting. Measurements of aqueous ammonia, methane, and hydrogen sulfide were collected each hour by injection into a gas chromatograph. Oxygen concentration, temperature, change in compost mass, and moisture were also tracked hourly.

Ammonia Reductions

Reductions in ammonia were measurable (Figure 14) and were also noticeable in terms of smell. Gaseous samples from the control unit had an incredibly strong ammonia odor, as did the

impinger water, while the exhaust and impinger water from the biochar filtered unit did not smell at all. When the biochar filter was removed for mixing to expose unsaturated biochar surfaces, the smell of the air emitted and the material inside both composting units were indistinguishable. Not only do these results demonstrate a quantifiable reduction in ammonia emissions from composting, but a reduction in odorous compounds below the Recognition Threshold (RT), which is an important aspect of industrial composting (Font 2011).

Also, results (shown in the technical report) indicate that fairly dramatic changes occurred across biochar functional groups during composting. However, further analyses would be necessary to understand the chemical changes to the biochar that occurred when reacting with the compost gases.
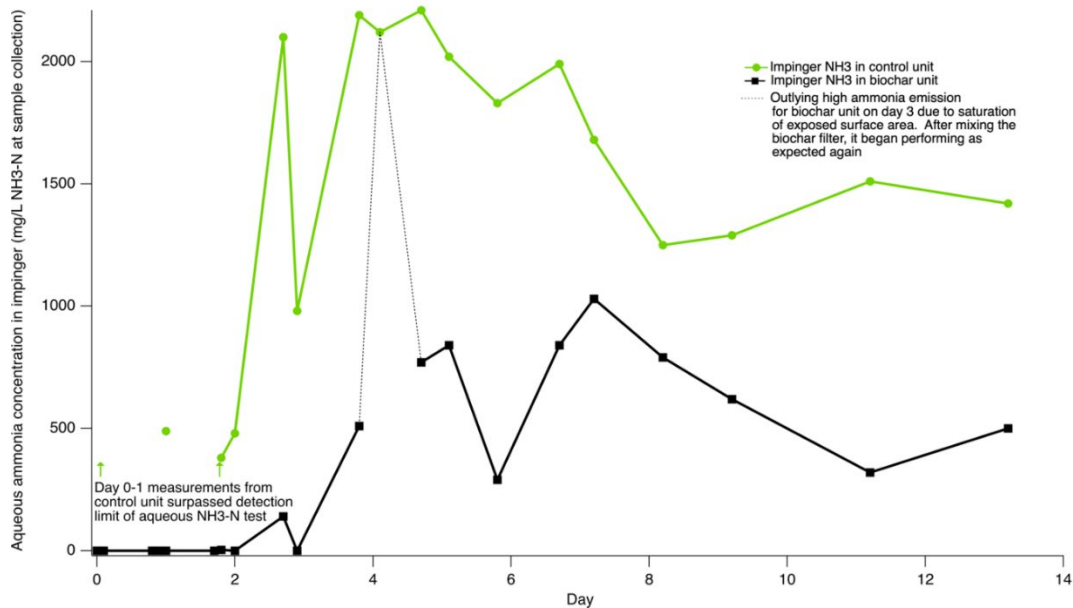
Figure 13: Aqueous ammonia measured in impingers for composting units. The unit containing the biochar filter released significantly less ammonia in the thermophilic period and over the first 15 days than the control. Points represent the ammonia concentration measured at a particular sample interval on a given day.

Hydrogen sulfide, methane, and oxygen concentrations

Across all treatments and runs of the composting reactors, hydrogen sulfide was below 10 ppm for all samples. Likewise, no consistent differences in methane were seen across treatments. Due to the small size of our units and ASP reactor design, it is likely there was not much hydrogen sulfide or methane production due to good aeration. Consistent with this explanation, oxygen content was relativey high, ranging between 17-19%.

2.5 Conclusions and Discussion of Future Work

Characterizations and adsorption studies

While many biochars performed as expected during the adsorption studies, some chars out-performed relative to expectations indicating that there may be other factors, not yet identified, that are important for adsorption of some compounds. Our hypothesis that an acidic biochar would adsorb ammonia most efficiently was supported by the results of the adsorption tests, but surprisingly, the KFCA which is very basic performed better than the other more neutral biochars. The hydrogen sulfide adsorption studies had expected results, with KFESA, the highest ash content and pH biochar, performing the best. As predicted, biochars with the highest surface area had the best methane-adsorption For methane, high surface area biochars performed well, following expectations. However, OLYM (second highest surface area) dramatically outperformed the other tested samples, and further research is needed to understand the roles other characteristics play in this particular sample's ability to adsorb methane.

Many of the commercially available biochars have a relatively low surface area and a high pH. Future studies could assess a larger number of locally available biochar resources with these test methods, and gather information on the pyrolysis conditions, production methods, and feedstock used. This could help determine whether locally available biochar resources could be used in an engineered biochar cocktail for reduction of compost emissions, or whether additional biochars would need to be produced with specific needed properties, similar to the acidic biochars produced for this study.

Estimated Weight of Biochar Needed to Adsorb Emissions

Based on our adsorption studies and organic waste emission factors from the literature, the amount of biochar required to adsorb emissions from organic waste is shown in Table 7. These low weights are encouraging in terms of the ultimate feasibility of using biochar to reduce emissions from commercial-scale composting. Future bench-scale composting studies should be conducted to quantify the emissions from each composting unit with and without biochar as a method to field test the validity of these weight % application recommendations. This represents a next step in scaling up towards applying biochar to the industrial composting process.

One important limitation of this study is that the method of application will likely affect the weight % of biochar required to optimally adsorb or reduce emissions. These adsorption tests measure the biochar's functionality as a filter but biochar could be added to the composting process through co-composting, bio-filtration, and potentially other methods. Future studies are needed to test the effect of biochar application method on emissions reductions, pinpointing the most effective use of biochar in the composting process at larger scale. These studies should explore the effects of acidic biochar on compost quality during co-composting processes, as studies suggest that the addition of biochar can improve compost quality by reducing nitrogen loss (Hestrin et al., 2020). The effect of engineered acidic biochars on

compost quality during co-composting will be explored in future co-composting experiments with phosphoric acid pre-treated biochar.

Top-layered biochar's ability to reduce ammonia emissions during composting

When a biochar filter was used in laboratory-scale composting design mimicking a positively aerated static pile, the biochar filter effectively eliminated ammonia emissions at the beginning of the composting process, and continued to adsorb significant amounts of ammonia even as it became saturated, reducing ammonia emissions by approximately 35% at end of the thermophilic phase. While the biochar reduced ammonia emissions significantly, performance was not consistent across sampling intervals. This could be due to the method of biochar application, as the material did need to be redistributed on the 4th day and wells from air flow did form. This finding further supports the need for future study into the effects of different physical biochar applications (filters, top layers, co-composting, wattles) on its adsorption capabilities and its interaction with compost and compost gases.

The shape of the biofilter that we used did not allow a large amount of exposed biochar surface area, therefore future repetitions of this experiment will explore the impact of different shapes of biofilters, as well as alternative placement (biochar wattle surrounding exhaust pipe or a thin biochar blanket to rest on top of the compost pile that could be easily swapped out once it was saturated, for example). In addition to external biochar application, biochar co-composting will be included in future repetitions with the benchtop composting units to observe its effects on the temperature profile and heat distribution, moisture, compost quality, emissions, and microbial activity.

For the bench-scale composting studies, we used 5% biochar by weight in the filter, which adsorbed ammonia emissions successfully but did begin to saturate. Saturation results (not shown here, see Figure 30 in the technical report) indicate that the surface chemistry and functional groups changed dramatically. Therefore, further tests should be conducted to study biochar chemical and physical characteristics before and after composting and adsorption studies performed with single gas compounds to better understand the interactions between biochar and compost gases, especially saturation over time. Studies such as these would also provide insight about the behavior and the potential uses of "saturated" or "used" biochar (if not co-composted) that has been used as a bio-filter or top layer in the composting process.

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Chapter 3: Extension, Engagement, and Technology Transfer

Georgine Yorgey, Karen Hills, Aaron Whittemore, Embrey Bronstad,
and the Waste to Fuels Technology Team

3.1 Extension, engagement, and technology transfer with regional organics management stakeholders and the organics value chain

The goal of the Waste to Fuels Technology partnership is to promote the efficient recovery of energy, nutrients, and other saleable products from organics and other materials that are normally considered wastes. The approach taken is normally one of supporting "higher and better uses" – including preventing or reducing wastes at the point of generation, promoting reuse when possible, and then supporting conversion that captures as much of the value as possible.

The application of these next-generation technologies and processes depends on adoption by industry and municipal partners, and upon the purchase and use of the generated products (compost, biochar, etc.). Outreach efforts, therefore, targeted stakeholders related to both organics management and product use. Extension efforts incorporate both team members who focus on extension (including Yorgey, Hills, Whittemore, and Bronstad) and the broader Waste to Fuels Technology team, including Drs. Amonette, Brady, Chen, Collins, Garcia-Perez, and Jobson.

Building relationships across the organics management and value chain

The team made a number of presentations during the biennium related to the Waste to Fuels Technology (WTFT) partnership – with in-person opportunities rebounding after covid-related disruptions in the last biennium, and virtual opportunities continuing. Presentations included discussions of anaerobic digestion and renewable natural gas, compost emissions, and the role of organic amendments in supporting soil carbon sequestration, as well as other topics. Some presentations included discussion of work directly supported by WTFT. In a few cases, the underlying work was completed with complementary funding, but the opportunity to share this work with regional and national stakeholders was supported by WTFT.

These targeted presentations and interactions offered more than 774 opportunities for live interactions with stakeholders, including individuals who work in the organics management industry, purchasers and users of organic residuals, others working on sustainable organics management at non-profits, county and local governments, students, and other Washington residents. Work under a complimentary project (not funded by WTFT) provided education on renewable natural gas to an additional 200 individuals.

WTFT presenters are in **bold** here and in other listings throughout the chapter:

- **Haghighi-Mood, S., M. Garcia-Perez, and G. Yorgey.** Evaluation of Emerging Plastics Recycling Technologies and Management Strategies. Pullman, WA (in-person and virtual). June 1, 2023. Estimated attendees: 15

- **Amonette, JE.** 2023. Why Agricultural Bioenergy Needs Biochar and Vice Versa. Virtual presentation at the 2023 American Chemical Society Spring Meeting, Indianapolis, IN, 28 March 2023. Estimated attendees: 40

- **Ball, K.** The role of soil organic matter in soil health: build it, store it, and keep it there! SoilCon 2023. Mount Vernon, WA (virtual). February 14-15, 2023. Estimated attendees:100

- **Yorgey, G.G.** 2023. Carbon Accounting and Carbon Markets, Relevance to Washington Food Systems. Guest Lecture, Agriculture & Food Systems Capstone Class and external partners (food processing sector). Washington State University. February 16, 2023. Estimated attendees: 14

- Ball, K., Burke, I., Collins, D., **Hills, K.**, Kruger, C. and **Yorgey, G.** 2023. Understanding the Short- and Long-Term Soil Carbon Storage Benefits of Compost Application to Agricultural Systems. Presentation at COMPOST 2023. Ontario, CA. January 25, 2023. Estimated attendees: 150

- **Hills, K., Brady, M., Yorgey, G.** and **Collins, D.** 2023. Differentiating the Value and Cost of Compost Across Likely Farm Use Scenarios in Western Washington. Presentation at COMPOST 2023. Ontario, CA. January 25, 2023. Estimated attendees: 80

- **Jobson, T.** WORC / Tilth Annual Meeting, Kennewick WA, Nov 7-11, Measuring VOC Emission Rates from Green Waste Composting. Estimated attendees: 60

- Ball, K.R., **Yorgey, G.G., and Hills, K.** 2022 Tilth-WORC Annual Meeting. Capitalizing on compost: the potential for organic amendments to increase soil carbon and reduce greenhouse gas emissions in WA drylands. Estimated attendees: 50

- **Brady, M**., B Stone, and E.L. Taylor. 2022 Tilth-WORC Annual Meeting. Connecting the Dots on Compost Procurement. November 2022. Estimated attendees: 50

- **Amonette, J.E.** 2022. Biochar: An Overview. Virtual presentation to the Washington Department of Ecology, Clean Fuel Standard: Agriculture and Forestland Carbon Capture & Sequestration Advisory Panel (AF-CCSAP). 27 October 2022. Estimated attendees: 25

- **Jobson, T.** Pacific Northwest International Section Air & Waste Management Association (PNWIS), Annual Conference, Coeur d'Alene Idaho, Oct 10-14, 2022. Measuring VOC Emission Rates from Green Waste Composting. Estimated attendees: 30

- **Amonette J.E.** 2022. Integrated Biochar Research: A Roadmap. Virtual presentation at the Foundation for Food & Agricultural Research Biochar Convening held on 29 March 2022. Estimated attendees: 70

- **Amonette, JE.** 2021. Biochar: Overview of Climate Change Impacts and Use in Agriculture. Virtual presentation to the US Department of Energy, Bioenergy Technologies Office, Feedstock Technologies Team on 15 December 2021. Estimated attendees: 10

- **Amonette, JE.** 2021. Biochar: Potential Impact on Soil Carbon & Water. Virtual presentation to the Bioproducts Seminar Series held at the Bioproducts, Sciences, & Engineering Laboratory, Washington State University Tri-Cities, Richland, WA on 27 October 2021. Estimated attendees: 30

- **Amonette, JE.** 2021. Biochar: Concept, Applications & Barriers to Adoption. Virtual presentation as part of a Biochar Briefing to the Congressional Soils Caucus organized by the Soil Science Society of America on 10 September 2021. Estimated attendees: 50

Providing technical support

The team also answered numerous individual inquiries relating to anaerobic digestion, biochar, nutrient recovery, and carbon sequestration from recycled organic matter. Technical support included both formal participation in advisory panels and stakeholder groups, as well as many ad hoc responses to individuals who reached out to Washington State University (WSU) and the Center for Sustaining Agriculture and Natural Resources (CSANR):

Advisory panels and Legislative provisos

Based on the expertise developed through the Waste to Fuels Technology partnership and related projects, Ms. Yorgey was asked to serve on the Washington Department of Commerce Rural Clean Energy Workgroup which produced recommendations that informed the state's investment of $4.6 million in clean energy funding in 2023 (see https://www.commerce.wa.gov/growing-the-economy/energy/clean-energy-fund/rural-clean-energy/).

In complementary efforts, Ms. Yorgey, Dr. Brady and a number of other colleagues successfully completed work on an "organics proviso" which supports recovery of value from organics waste. Under the proviso, Ms. Yorgey worked with postdoctoral scholar Kirsten Ball and a number of other WSU colleagues to explore and evaluate existing models to estimate carbon sequestration from application of organic soil amendments to croplands, and identify technologies, methods, and potential funding for carbon sequestration from Washington's organic wastes. Another component of the proviso, led by Dr. Brady and supported by several students, assessed local and state government compost usage in projects and buy-back programs.

In a separate proviso effort, Washington State University was asked to work with a number of partners to develop recommendations for increasing the economic value and sustainability of Washington's agricultural sector through the use of industrial symbiosis principles, connect agriculture producers and processors with partners to achieve synergies through systems-based resource sharing resulting in economic benefits and value creation for all participants, through

sustainable resource recovery and optimization of energy, water, and organic waste streams. Though the focus of this work is on the agricultural sector, a holistic vision including both farms and food processing to consumer (from farm through "fork") was addressed. The partners explored opportunities to recover waste heat, water, and organic materials. Given a focus on anaerobic digestion as a technology with good potential to generate value from the types of wet organic wastes produced within agricultural supply chains, there is high potential for synergy with Waste to Fuels Technology objectives around waste management.

Technical support, guidance and resource sharing

Every biennium, experts at Washington State University who are part of the WTFT team respond to numerous requests from stakeholders in the state who are working on projects to recover value from waste materials. This biennium was no exception. Two relevant examples provide a flavor of the types of individuals who reach out. First, team members held a call with individuals from the City of Pasco and other project partners relating to their Pasco Water Reuse Facility (PWRF) upgrades, specifically exploring potential outlets for an algae-based fertilizer product that will be produced. When complete, the upgraded PWRF facility will treat an estimated 2 billion gallons per year of industrial wastewater from seven major food processors. Wastewater will be treated via both anaerobic digestion (generating renewable natural gas) and with algae to reduce nutrient levels, generating a nitrogen-rich fertilizer product. Remaining water with reduced nitrogen levels will be applied to croplands. This project has garnered a number of partners, including a $50,000 investment from the Washington Department of Commerce and collaboration with the non-profit Center for Sustainable Infrastructure. WTFT personnel Bronstad and Yorgey had participated as technical experts in a consultation and visioning project in the 2019-2021 biennium that recommended that the City further explore algae as a potential treatment option.

Similarly, a number of WTFT team members have had discussions with Myno Carbon over the course of the biennium on a range of topics. Myno Carbon is developing a large-scale biochar carbon removal facility that will utilize forestry and mill waste residuals to produce 40,000 tons of biochar and 18 megawatts of carbon negative electricity per year, integrated with Avista's Kettle Falls Generating Station. In a collaborative project with Dr. Amonette, they are also exploring combining waste CO_2 with crushed basalt to create a liming soil amendment.

Technical support has not been limited to industry. WTFT members have also met with a number of non-profit and community groups relating to anaerobic digestion, pyrolysis, and vermi-composting, and other waste management topics. And utilizing complementary funding from the EPA, Ms. Yorgey, Ms. Bronstad, and Mr. Whittemore have had a series of conversations and workshops relating to food waste anaerobic digestion with individuals in the Spokane, Yakima and Olympic Peninsula areas, including individuals working at non-profits, and in municipal or county waste management roles.

Extension resources

Written extension resources on organics management processes are available online and provide on-demand information to a wide variety of stakeholders interested in improved organics management. These resources are an important complement to in-person

presentations and individual consultations. These products utilize a range of formats, including blog posts, extension documents and talk recordings. Products completed via the Waste to Fuels Technology partnership and a wealth of other information related to organic resource recovery is being maintained on the [waste management topic pages](#) of the Center for Sustaining Agriculture and Natural Resources website, which includes subtopic pages for compost, pyrolysis (biochar), anaerobic digestion, biofuels, and nutrient recovery. In total, on-demand products that were directly relevant to Waste to Fuels Technology (those produced this biennium, and those produced in previous biennia) were viewed a total of 24,801 times during the 2021-2023 biennium.

Two publications and one blog post were completed during this biennium. Two of these publications (the Biochar roadmap and the carbon sequestration potential in agricultural lands) are work that was initiated in previous biennia, but for which work continued in this biennium.

- **Bronstad, E.** Building Better Biochar Breakthroughs: A Roadmap for Biochar Research. Blog post on agclimate.net. November 29, 2021.

- **Yorgey, G.G.**, S.A. Hall, **K.M. Hills**, C.E. Kruger, and C.O. Stockle. In press. Carbon Sequestration Potential in Cropland Soils in the Pacific Northwest: Knowledge and Gaps. Pacific Northwest Extension Publication, Pullman, WA.

- **Amonette, JE**, Archuleta, JG, **Fuchs, MR, Hills, KM, Yorgey, GG**, Flora, G, Hunt, J, Han, H-S, **Jobson, T**, Miles, TR, Page-Dumroese, D, Thompson, S, Trippe, K, Wilson, K, Baltar, R, Carloni, K, Christoforou, C, **Collins, DG**, Dooley, J, Drinkard, D, **Garcia-Perez, M**, Glass, G, Hoffman Krull, K, Kauffman, M, Laird, DA, Lei, W, Miedema, J, O'Donnell, J, Kiser, A, Pecha, B, Rodriguez-Franco, C, Scheve, GE, Sprenger, C, Springsteen, B, and Wheeler, E. 2021. Biomass to Biochar: Maximizing the Carbon Value. Report from virtual workshop held April-September 2021. Center for Sustaining Agriculture & Natural Resources, Washington State University, Pullman, WA. https://csanr.wsu.edu/biomass2biochar/

3.2 Leveraging Waste to Fuels Technology funds to increase impact

The Waste to Fuels Technology partnership plays an important role in engaging researchers at WSU and beyond in next-generation waste processing issues. Many partners use their work within the partnership to leverage additional funding that enhances their work and impact in the region. Partnership researchers and extension professionals were able to leverage the Waste to Fuels Technology work to successfully obtain $1,066,505 in non-state funds during the 2019-2021 biennium – and the WTFT partnership also laid the groundwork for an investment by Washington State of $2.5 million for an emissions study of commercial composting facilities (Table 8). Since 2017, the partnership has obtained a cumulative total of more than $6.6 million.

Table 8: External funds obtained during the 2021-2023 biennium by partnership members to work on issues relating to the issues explored under the Waste to Fuels Technology partnership

Award Details	Dollars Awarded
Current Biennium (2019-2021)	
Chen, S., et al.: Producing Biopolymers from Organic Wastes to Achieve Economical and Environmental Wins. USDA National Institute of Food and Agriculture. 2022-2025	$999,505
Jobson, T., D. Collins, et al. Air Emissions from Washington State Compost Facilities. Washington Department of Ecology. 2023-2025.	$2,500,000
Amonette, JE and Yorgey, GG. Explore the commercialization and climate-offset potentials of biochar technologies implemented at the family-farm and food-hub scale. Steward Holdings, LLC. Funded December 2021.	$28,000
Amonette, JE. Biochar life cycle assessment of urban forestry for City of Boulder in support of Carbon Neutral Cities Alliance Project funded by the Urban Sustainability Directors Network. City of Boulder, Colorado. Funded June 2022.	$3000
Amonette, JE. Development of hard-coded climate-focused LCA template and application to a UCOP biochar project. University of California Office of the President. Funded November 2022.	$13,000
Amonette, JE. Quantify life cycle GHG & criteria-pollutant reduction and carbon-sequestration potential from low-emission agricultural burn techniques relative to traditional open burning. Life cycle assessment task. Cal-Fire through San Luis Obispo County Air Pollution Control District, California. Funded January 2023.	$23,000
Current Biennium (2019-2021) Total	**$3,566,505**

3.3 National and international reach

Though not the primary goal of the Waste to Fuels Technology partnership, sharing the results of partnership research with researchers across the U.S. and the world, via presentations and journal publications is an important avenue for generating interest and momentum relating to next-generation organics processing.

Relevant peer-reviewed journal publications from this biennium that resulted from work carried out either in part or in whole as the results of the partnership include:

- **Stacey, N**., T. Tea, **S. Seefeldt, A. Bary,** and **D.P. Collins**. In review. Biochar-poultry manure compost alters temperature and nitrogen dynamics during composting and improves crop growth following field application. Compost Science and Utilization.
- Lehmann, J., A. Cowie, C.A. Masiello, C. Kammann, D. Woolf, **J.E. Amonette,** M.L Cayuela, M. Camps-Arbestain, and T. Whitman. 2021. Biochar in climate change mitigation. Nature Geoscience, 14, 883–892.

- **Haghighi-Mood, S., M. Ayiania**, H. Cao, O. Marin-Flores, **Y. Jefferson Milan, M. Garcia-Perez. 2021.** Nitrogen and Magnesium Co-doped Biochar for Phosphate Adsorption. Biomass Conversion and Biorefinery, https://doi.org/10.1007/s13399-021-01404-1.

Academic/national and international presentations that occurred during the current biennium included:

- Ball., K.R., **Hills, K., Yorgey, G.**, Tautges, N., Zuger, R., McFarland, C., & Burke, I. 2022. American Geophysical Union Meeting (Oral) "Could agricultural drylands be promising candidates for carbon farming? Long-term SOC storage potential demonstrated under compost application in wheat-fallow rotations in Washington State."
- Ball, K.R., **Yorgey, G.G.**, and **Hills, K.** 2022. Eighth International Symposium on Soil Organic Matter. (Oral) "The missing link: how coordinated soil health programs can successfully mechanize carbon farming initiatives on agricultural land, a US perspective"
- **Haghighi-Mood, S., M. Ayiania**, H. Cao, O. Marin-Flores, **Y. Jefferson Milan, M. Garcia-Perez. 2021.** Nitrogen and Magnesium Co-doped Biochar for Phosphate Adsorption. Biomass Conversion and Biorefinery, https://doi.org/10.1007/s13399-021-01404-1.
- Mainalis K, **Haghighi Mood S**, Pelaez-Samaniego MR, Sierra-Jimenez V, **Garcia-Perez M**: Production and Applications of N-doped Carbons from Bio-Resources: A Review. Accepted in Catalysis Today, 2023
- **Mood SH**, Pelaez-Samaniego MR, **Garcia-Perez M**: Engineered Biochar for Environmental Applications: A review. Energy & Fuels, 2022, 36, 15, 7940-7986

Relevant technical reports include:

- Seman-Varner, R, Hassebrook, C, Zilberman, D, Brown, R, Paul, B, Winstel, L, Odom, L-K, Moebius-Clune, B, Laird, D, and **Amonette, J.** 2022. Scaling sustainable biochar research & commercialization for agriculture and conservation: A summary from a stakeholder convening [white paper]. American Farmland Trust, Foundation for Food & Agriculture Research, & National Center for Appropriate Technology, Washington, DC. PNNL-33709. 36 p. https://farmlandinfo.org/publications/biochar-convening-summary/

3.4 Impacts of technology transfer, outreach, and extension activities

In total, extension efforts resulted in an estimated 774 opportunities for in-person and virtual "real time" interactions with key stakeholders who work either primarily on organics management in the region, or whose work touches on sustainable organics management in various ways. Our efforts also resulted in 24,801 views of Waste to Fuels Technology reports, publications, blog posts, recordings, and other extension resources that were funded (either fully or in part) via the partnership. Work carried out in the previous and current biennium was used to leverage an additional $3.6 million in this biennium to support work in areas related to Waste to Fuels Technology priorities.