CHAPTER 7:

Biochar Produced and Utilized at Municipal Compost Facilities

Mark R. Fuchs, B. Thomas Jobson, Douglas P. Collins, Edward Wheeler, and Bruce Springsteen

OVERVIEW

Background and Motivation

Composting, the biological breakdown of biomass to more stable organic matter, is a broadly applied method to reduce landfill disposal of the organic fraction of municipal solid waste and to create a useable and sustainable process for recycling organics. The diversion of organic waste generated in urban areas from landfills to compost facilities has multiple benefits including preserving landfill capacity, reducing greenhouse gas (GHG) emissions (in particular, methane; Jobson & Khosravi 2019), as well as providing environmental benefits associated with application of finished municipal solid waste compost to agricultural lands (Martinez-Blanco et al. 2013).

Composting facilities process a significant amount of woody biomass that makes its way into the solid waste collection system. This woody biomass is suitable for biochar production and, thus, presents an opportunity for integrating these two organic waste treatment strategies—composting and biochar production—to advance the biochar industry in the Pacific Northwest. Facilities could capitalize on efficiencies of co-location and existing markets for soil amendments, while providing benefits to the composting process in terms of odorous and GHG emission reduction. In addition, there are indications that adding biochar to traditional feedstocks at the beginning of the composting process, also called "co-composting" can yield a soil amendment that is superior to biochar or compost alone.

In this chapter, we describe the potential that compost facilities represent for biochar production in terms of wood recovery. Next, we discuss the potential benefits of co-composting with biochar. Third, we address some of the characteristics of compost facilities that are important to consider in siting co-located biochar production. Finally, we discuss barriers to co-location of biochar production with compost facilities and make recommendations for overcoming these barriers.

Wood Recovered and Recycled in Compost

Composting of organic wastes has been underway for over 30 years in Washington, Oregon, and California. As an example of these systems, we will describe the situation in Washington. Figure 7.1 shows a map of the 60 compost facilities listed in the Washington Department of Ecology annual report database for 2018. Two dozen of these locations primarily compost municipal organic feedstocks, including yard debris, land clearing debris, food waste, sawdust and shavings, other wood debris, and mixed food-yard debris. Figure 7.2 shows the composition of feedstocks (sum of all facilities) from 2010 to 2017, though there is substantial variation between facilities.

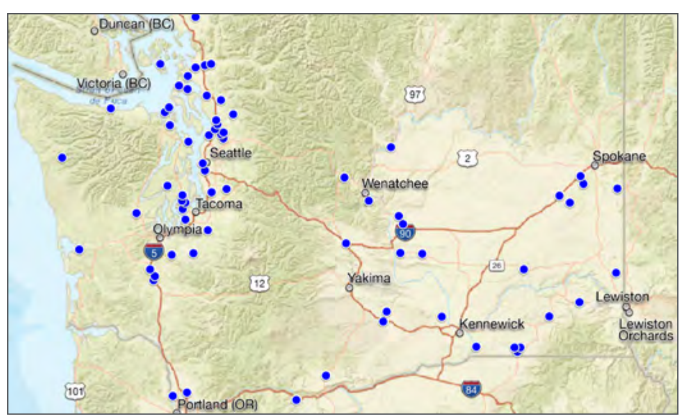

Figure 7.1. *Compost Facilities in Washington State (Source: Ecology n.d.).*

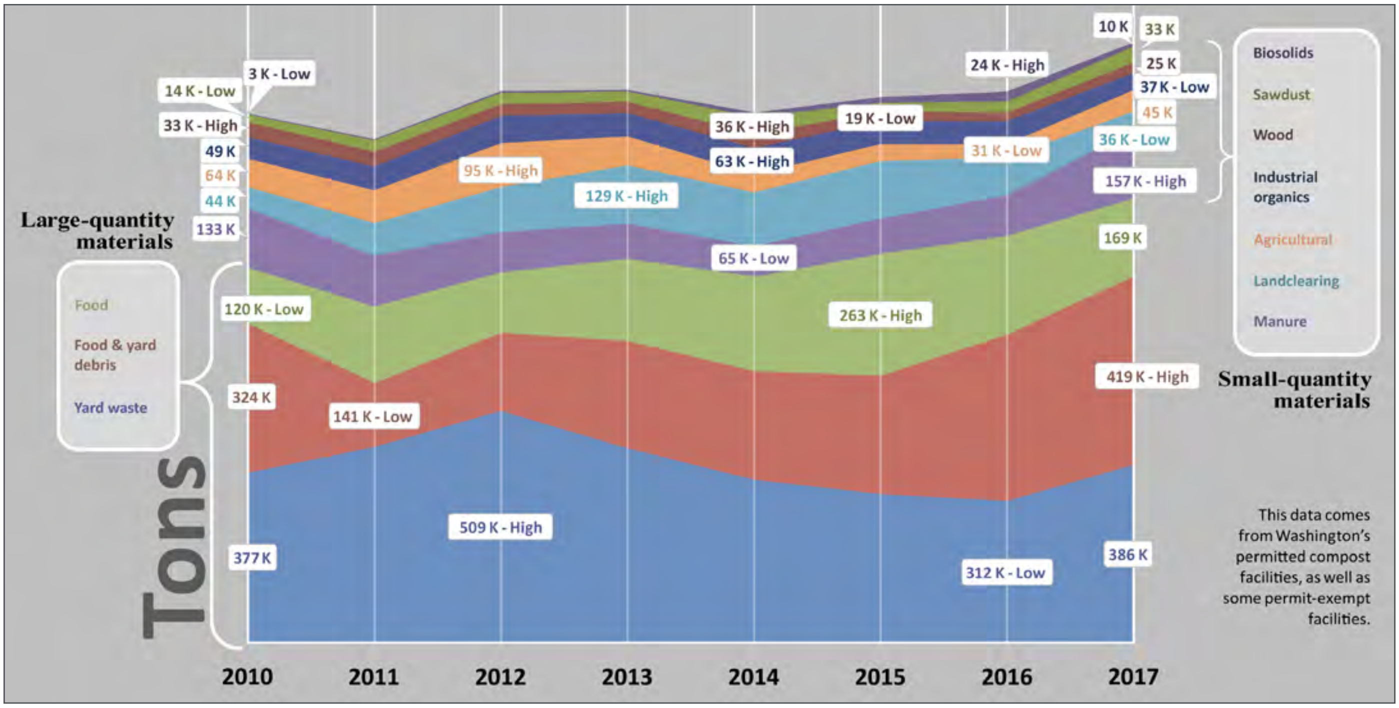

Figure 7.2. *Materials composted in Washington annually 2010 to 2017. (Source: Ecology n.d.)*

Washington, because of its urban and agricultural centers, generates a variety of feedstocks, including pre- and post-consumer food wastes, agricultural residuals, wood waste, biosolids, and other organic and woody materials. Wood waste, however, represents a small portion of the component of the total composted materials in Washington (Figure 7.2). In 2017, Washington compost facility annual reports show that wood biomass including land clearing and wood debris represent about 5% of the feedstock composted at all locations. Up to roughly 10-15% of yard debris and yard waste is wood waste, as confirmed with several compost operators (Scott Deatherage & Edward Wheeler, personal communication). Estimates of urban wood waste in the region are presented in *Chapter 9: Biomass Supply*.

Many composters mechanically reduce the size of limbs and woody biomass to a diameter of four inches or smaller. The woody biomass is further shortened and provides a bulking agent in the compost operation that promotes the movement of atmospheric oxygen into and through the piles. These large wood pieces do not disintegrate quickly and, when composting is complete, are screened out from the finished product. These "overs" along with other large uncomposted debris are re-used as bulking agents to improve porosity in new compost piles. Compost overs are a potential source of biomass for biochar production on the facility premises. A schematic showing potential integration of biochar into a compost facility is shown in Figure 7.3.

CO-COMPOSTING WITH BIOCHAR

The following section explores in more detail the benefits of why a compost facility might want to co-compost with biochar; subsequent sections outline factors that compost facilities both have to consider generally and those more specific elements that should be evaluated when considering co-locating biochar and compost facilities.

Growth and Yield Benefits

Recent literature suggests that there are agricultural benefits to the application of biochar that has been composted with other traditional compost feedstocks (Gang 2018). While co-composted biochar generally benefits plant growth and yields, results range widely and likely depend on the combination of biochar properties, soil, and crop type.

Plant growth trials on regionally relevant specialty crops have shown promise. For example, studies at Washington State University (WSU) with sweet basil grown in greenhouse pots show that basil grown in field soil blended with co-composted biochar (2.5% and 5% biochar by volume) enhanced growth rates and yields. No impact on growth rates was observed when pure biochar or pure compost were mixed together at the same ratios (Gang et al. 2018).

Since the Gang et al. report, a growing number of studies, many of which are relevant to agriculture and the composting industry, have shown the potential agronomic benefits of co-composting with biochar (Godlewska et al. 2017; Agegnehu et al. 2017; Sanchez-Monedero et al. 2018; Akdeniz 2019; Wang et al. 2019). At rates of 5% to 10% addition of biochar by volume at the beginning of the compost process, significant benefits were observed. Most of the studies were co-composting with animal manures, principally chicken, pig, and cattle, and involved small scale lab trials rather than full scale composting. There are far fewer studies where biochar has been added to the organic fraction of municipal solid waste (Malinowski et al. 2019), something that deserves more study. Co-composted biochar appears to be a better soil amendment than compost or biochar alone (Schultz et al. 2013; Agegnehu et al. 2017; Wang et al. 2019) as demonstrated through evaluation on crop plant growth and the aforementioned yields in potted plant experiments and field trials. Adding biochar may thus enhance the commercial value of composts produced in urban markets—but more studies are needed on biochar co-composting with the organic fraction of municipal solid waste. In addition, more definitive trials with co-composting biochar with animal manures are also needed.

Nutrient Capture

One explanation for the exceptional soil amendment properties of co-composted biochar is the ability of biochar to capture nutrients (nitrogen, phosphorus, potassium) from the composting process, allowing for their long term release into the soil (Kammann et al. 2015). Microscale surface chemical analysis of the co-composted biochar shows that nutrients are captured both in the biochar pore space and as an organo-mineral "plaque" formed on exterior surfaces (Hagemann et al. 2017). Biochar thus appears to be chemically modified by the composting process.

The addition of biochar to composting material has been noted as one of the most effective methods for reducing nitrogen loss (Sanchez-Monedero et al. 2019). A number of studies with manure composts have demonstrated that co-composting with biochar increased total available nitrogen in the resulting material (Chen et al. 2010; Prost et al. 2013; Khan et al. 2014; Kammann et al. 2015; Lopez-Cano et al. 2016).

The capture of nutrients also has important environmental benefits. For example, the capture of nitrogen could mitigate environmental losses such as:

- Nitrate (NO_3^-) into surface and ground waters which contributes to eutrophication of waterways

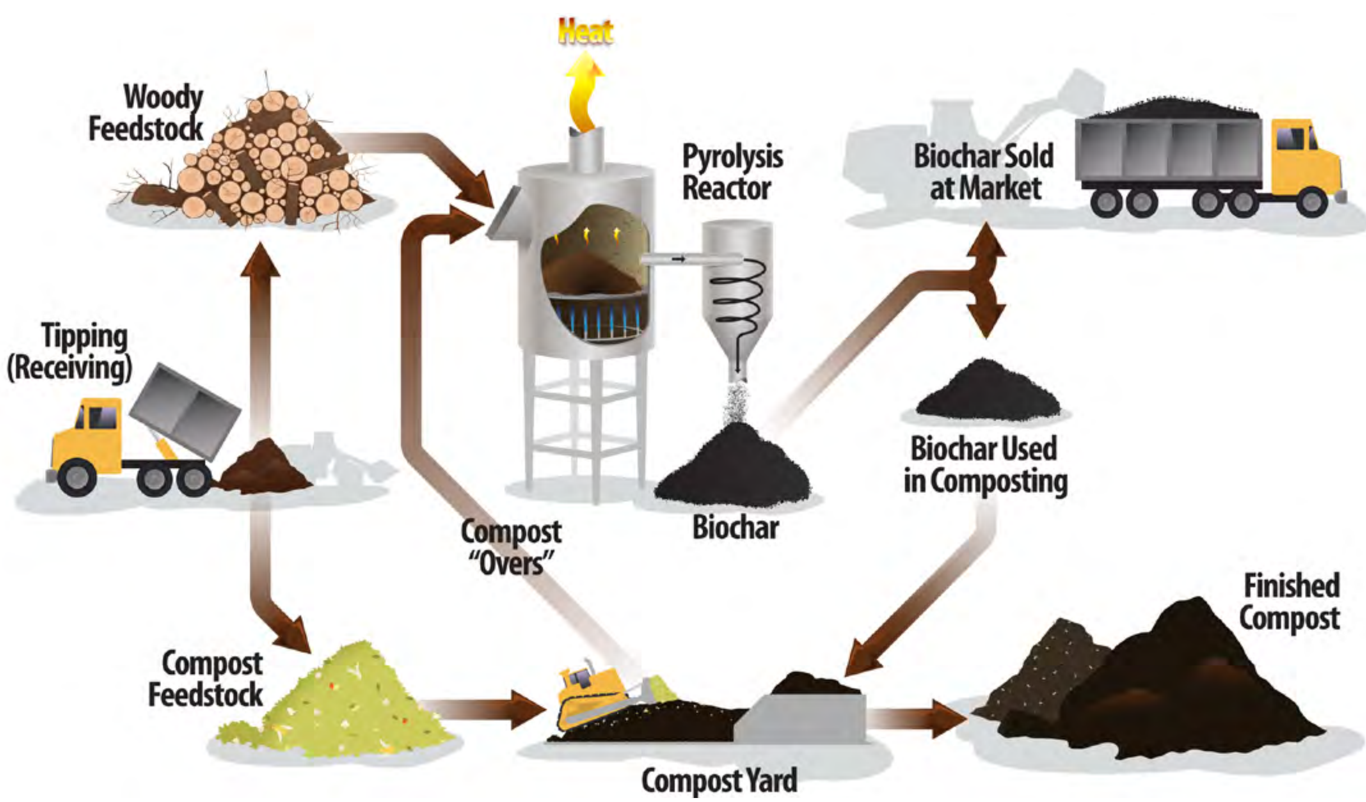

Figure 7.3. *A schematic showing concept for integration of biochar production into a compost facility. (Credit: Andrew Mack, Washington State University)*

- Gaseous emissions of ammonia (NH_3) which can cause odor problems and contribute to particulate matter pollution ($PM_{2.5}$) through formation of aerosol ammonium nitrate (Paulot & Jacob 2014).
- Nitrous oxide (N_2O) emissions which is both a potent GHG (GWP_{100} = 293) and a major contributor to stratospheric ozone loss through production of NOx in the stratosphere as a result of N_2O photochemical degradation (Ravishankara et al. 2009).

Modification and Acceleration of the Composting Process

Biochar is not consumed in the composting process, and it has been noted that it appears to modify the composting process in as yet inexplicable ways. One hypothesis suggests that biochar provides habitat for microorganisms within its pore structure (Zhang & Sun 2014; Gang 2018). One aspect relevant to commercial composters is that biochar accelerates the active composting phase. This acceleration has been noted for turned windrows at California facilities (Rick Wilson, Agromin Inc. and Josiah Hunt, Pacific Biochar, personal communication). For turned windrow systems, accelerating the active composting phase increases facility throughput and thus has economic value. Biochar has also been perceived to help the composting process during seasonally wet conditions (Josiah Hunt, personal communication). Benefits of biochar have also been noted for aerated static pile composting. Preliminary data from an Agromin Inc. facility shown below (Figure 7.4) suggests biochar accelerated composting for negatively aerated static piles. In this case, 6% biochar by volume (Rogue Biochar, Oregon Biochar Solutions) was added and the maturation level of the compost was followed as determined by the Solvita index once per week. For this facility, an index of 6 is indicative of a compost that has gone through its active composting phase. The addition of biochar rapidly accelerated the composting process for this facility.

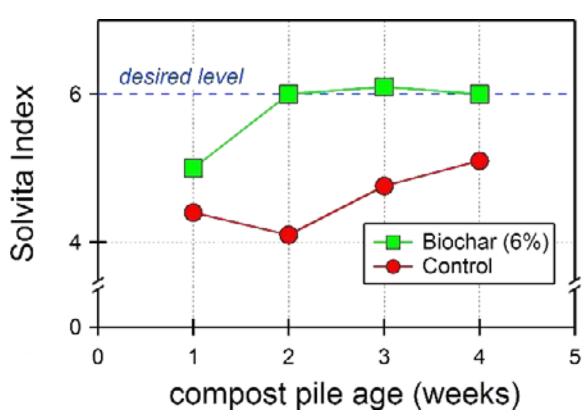

Figure 7.4. *Example of the impact of biochar on composting time for a commercial facility in California (Courtesy of Rick Wilson, Agromin Inc.)*

Another observed improvement is an increase in humus formation. The addition of biochar is thought to improve the composting process by acting as a support structure for microbial growth (bio-colonization). This enhances organic matter degradation, increasing the production of humic acids. Production of humic acids is also aided by biochar's role as an ion exchange material for sorption of ions (Kammann et al. 2015; Sanchez-Monedero et al. 2018). The increase in humification produces a better quality compost that is more stable in soils (Senesi 1989; Senesi & Plaza 2007). For example, Yu et al. (2019) followed the concentrations of humic and fulvic acids in a compositing trial with straw biochar and pig manure for different biochar additions of 1-10% by wet weight. Piles with greater biochar content displayed higher concentrations of these compounds over time. The presence of biochar appears to modify organic matter formation in the composting process yielding a better soil amendment. Operators at commercial compost facilities in California using biochar have also noted improved appearance of the compost (Josiah Hunt, Pacific Biochar, personal communication), likely reflecting the same processes.

Reduction in Gas Emissions

A growing number of reports of co-composting with biochar have noted that the presence of biochar reduces gas emissions from the composting process, most notably NH_3 and the GHGs N_2O and methane (CH_4) (Sanchez-Monedero et al. 2019). Significant reductions (47%) in NH_3 volatilization have been reported when 3% biochar by volume was added to poultry litter (Steiner et al. 2010), and a 30% reduction was observed when 10% biochar by volume was co-composted with poultry manure (Agyarko-Mintah et al. 2017). These results suggest biochar addition could also reduce NH_3 volatilization losses in composted cow manure. Wang et al. (2013) reported a 25% reduction in N_2O emissions from pig manure when co-composted with 3% biochar by volume. Collins et al. (2020) found that biochar at 20% and 40% (by volume) reduced nitrogen loss by 7.5% and 15% compared to the control. Collins et al. found that following active composting, control piles contained more ammonia and biochar-containing piles contained more nitrate. Godlewska et al. (2017) proposed the enhancement of ammonium (NH_4^+) oxidation rates to NO_3^- by nitrifying bacteria is the mechanism for reduced nitrogen loss in co-composting. The mechanistic details of the biochar / microbe / nutrient interaction are still not well understood.

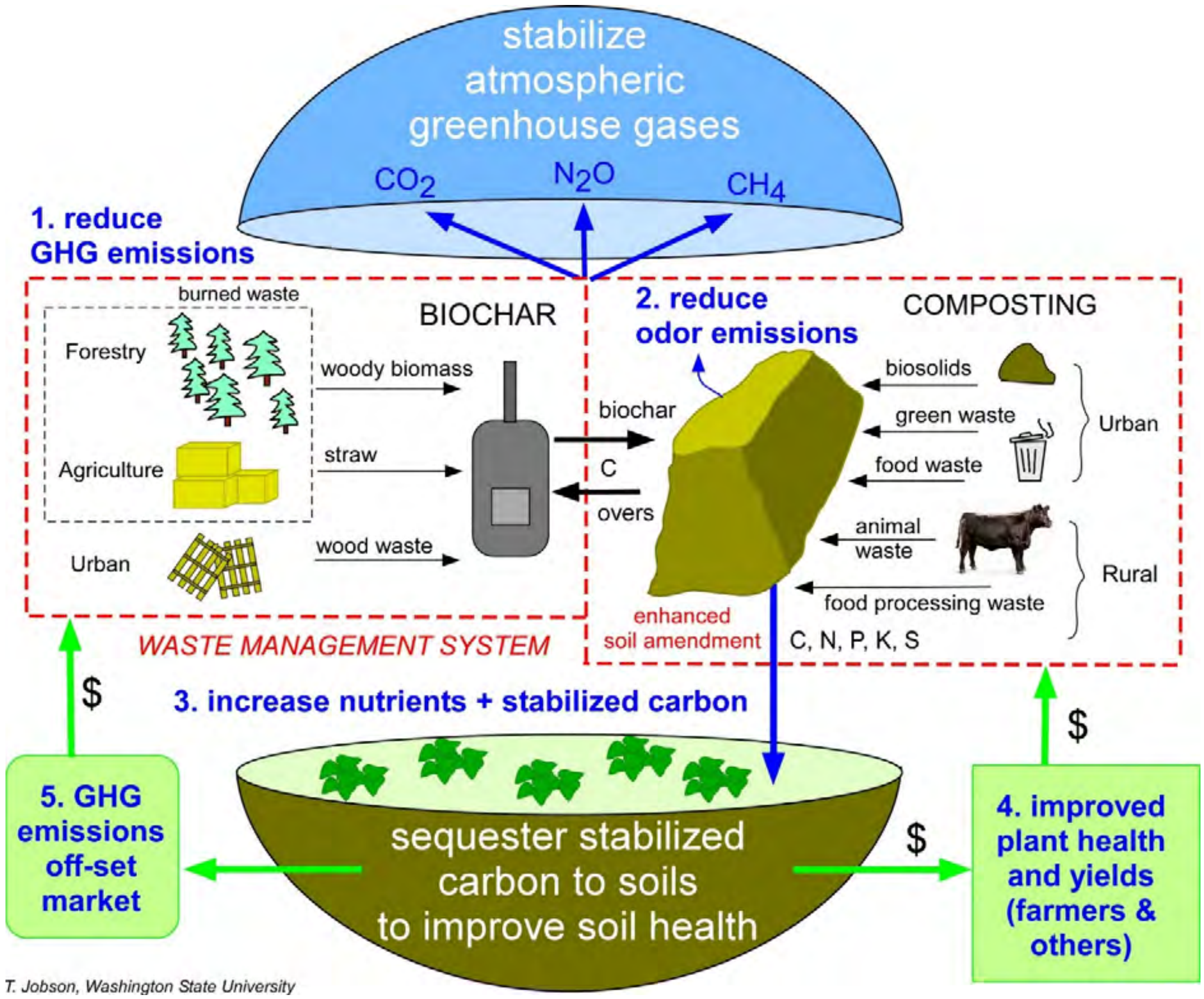

Figure 7.5. *Incorporation of biochar in composting operations can yield multiple benefits.*

While most of the experiments noting reductions in gas emissions have been done at small scale, Vandecasteele et al. (2016) reported significantly reduced CH_4 emissions for a commercial scale pile using 10% biochar by dry weight co-composted with a mix of green waste and the organic fraction of municipal solid waste. Cumulative emissions of CH_4 were reduced by 95%, while for N_2O a 14% reduction was observed over 90 days of pile aging. It is important to demonstrate the benefits at full scale commercial facilities as the impact of biochar on emissions is likely variable due to differences in materials and process conditions (e.g., temperature, pH, oxygen levels). To summarize co-composting benefits, Figure 7.5 illustrates how biochar production could be integrated into both urban and dairy waste management systems to capitalize on the noted benefits of co-composting with biochar. Additional revenue streams are possible for the waste management systems through carbon offset markets and production of a more valuable soil amendment for urban landscaping and commercial agriculture.

Reduction in Volatile Organic Compound Emissions

The composting process can emit a wide range of volatile gases, some of which have unpleasant odors, and the emissions of odors and volatile organic compounds (VOCs) can be a regulatory issue in compost facility permitting (Jobson & Khosravi 2019). Reductions in odor compounds and VOCs emitted during composting have also been noted in studies of co-composting with biochar (Steiner et al. 2010; Hwang & Lee 2018; Sanchez-Monedero et al. 2019). Addition of biochar may be a means of helping reduce odor issues from compost facilities and be a benefit to operators, though Hwang & Lee (2018) noted that different chars had different capacities for removing odor-causing sulfur compounds.

Measuring VOC emissions rates for commercial scale composting has not occurred widely due to the cost and complexity of sampling. Emissions from the surfaces of compost piles are typically measured using a surface flux isolation chamber—an approach used to determine VOC emission rates from several California facilities that utilize static windrows (CARB 2007; CARB 2015). There are also significant challenges in measuring emissions from large piles because of the wide variability that can exist in surface emissions rates. This variability in surface emission rates, obscures trends and makes comparisons between biochar treated and untreated piles difficult (Gang et al. 2019)

The complexities can be reduced by composting at smaller scales in the lab. An example of this is recent work conducted at WSU comparing emission from manure composts treated with biochar from Oregon Biochar Solutions (Jobson & Khosravi 2019). Approximately 400 lbs. (wet weight) of material was composted in two tanks: a tank with 10% biochar by volume and a control tank with no biochar. Emissions were continuously measured from the two tanks over two weeks. The tank with 10% biochar displayed lower emissions of some odorous sulfur containing gases such as dimethyl disulfide (DMDS) as shown in Figure 7.6. Addition of biochar may help control odor compound emissions at compost facilities, another potential benefit to composters.

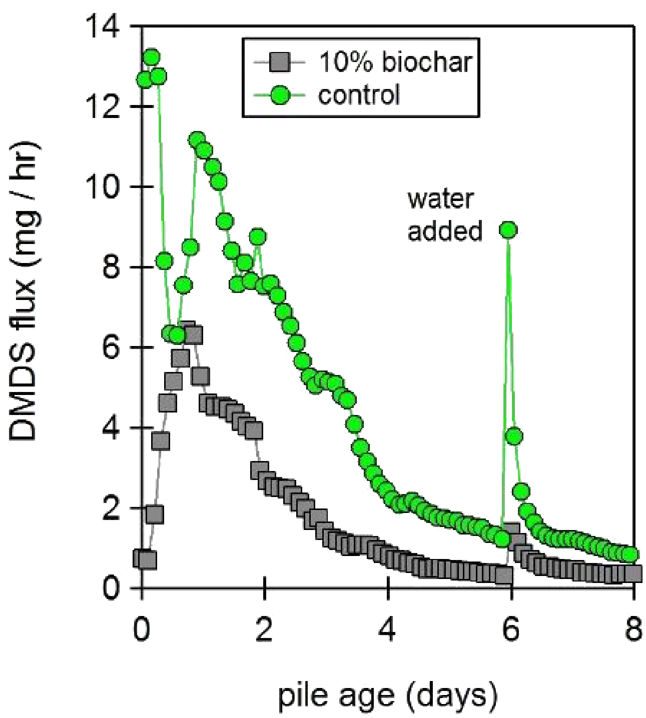

Figure 7.6. *Showing lower emissions of dimethyl disulfide from a 10% biochar co-compost of dairy manure (400 lbs. initial weight material) compared to regular compost. (Source: Jobson & Khosravi 2019)*

A clear recommendation for demonstrating gas emissions reductions when co-composting with biochar is to expand the research that has been done at commercial scale facilities so that real world composting conditions are documented. For facilities that use mechanical forced air flow aeration techniques, such as positive aeration, there are not clearly established methods for sampling. In lieu of finding the support of a cooperating commercial facility, a pilot scale composting plant, utilizing mechanical aeration processes, could be another valuable research facility.

GENERAL CONSIDERATIONS FOR COMPOST FACILITIES

Capacities and Equipment

Compost facilities in Washington and Oregon range from very small, processing only a few tons of materials each year, to quite large facilities processing hundreds of thousands of tons annually. In 2018, the smallest compost facility in Washington processed three tons of organics while the largest processed 235,000 tons. Just eight of these facilities handled 70% of all organics composted in Washington, and were able to because of their sizeable processing capacities. In general, large compost facilities already employ loaders, grinders, screeners, emission control systems, and other ancillary equipment that could also be used to operate a biochar production facility. The cost for this type of equipment can range between a few hundred thousand dollars to over a million dollars per facility depending on its capacity. Maintenance can range from a few thousand dollars a year to hundreds of thousands of dollars annually per piece of equipment. These capital and maintenance costs make co-locating composting and biochar production, and the consequent sharing of equipment and resources, extremely important to the financial feasibility of biochar production. Although facility capacity is just one of many factors to consider, the authors of this section see 50,000 tons per year as a minimum size for co-locating a commercial biochar production facility. At this scale, the facility is large enough to have the operating capacity and equipment to consider biochar production.

Location and Siting

The location of these large compost facilities is varied. In Washington, for example, two are located in rural areas in eastern Washington and six are located in rural or industrial areas in western Washington. The location of a compost facility can have a significant effect on how well a biochar facility might be suited for co-location. Zoning, ambient air quality, surface and ground water, surrounding land use, local population densities, availability of resources and utilities, and available organic residuals, are some of the conditions that need to be assessed to understand whether or not a biochar production unit may make sense at a compost facility.

SPECIFIC CONSIDERATIONS FOR COMPOST FACILITIES CO-LOCATING BIOCHAR PRODUCTION

Continuous feed pyrolysis significantly improves energy efficiency and reduces pollution emissions in comparison with batch kilns and seems well suited for compost facility operation. Pre-treatments and alterations in biochar production can generate "engineered" biochars to meet certain needs but would require the co-located site to maintain additional equipment or undertake additional processes. General information on biochar production is provided in *Chapter 11: Biochar Production*. The following factors should be considered specifically for biochar production at compost facilities.

Flow Through Rather Than Batch Processing

An additional unit process can be a significant impact to footprint of a compost facility. Batch processors require space and time to load, process, cool and unload. A flow through system, however, will require a minimum of space and the final biochar is produced in a single unit.

Biomass Pre-Treatment and Sizing

The flow through system should be capable of processing a wide range of feedstock sizes and shapes with minimal pre-milling or grinding. Current flow through biochar systems require homogenous feedstock (in size and geometry) to eliminate variations in dryness and VOC off-gassing.

Heating and Emissions Considerations

In order to create the lowest air pollutant emissions profile, the biochar production equipment should be designed to utilize the produced synthesis gases for the process heat to pyrolyze or gasify the biomass. Volatiles generated by pyrolysis are combusted by an afterburner, the heat from which can then be used to dry the biomass feedstock will yield the best carbon stabilization, with the most controllable emissions. In such a process the "flame" does not contact the biomass.

Tailoring Biochar Properties and Production for Co-Composting

Feedstock selection and pyrolysis temperature affect physicochemical properties of the final biochar product (Oliveira et al. 2017). Adjustments to the chemical environment during pyrolysis have been shown to affect char function and reactivity in the environment. Ayiania et al. (2019) demonstrated that with appropriate pre-treatment and pyrolysis with biochar produced in the presence of nitrogen and magnesium, both phosphate ion (liquid systems) and sulfur compounds (gas emissions) can be reduced. Other researchers have shown that biochar can be functionalized both with direct chemical and thermal processing and with exposure of biochar to other gases and steam treatment. For example, addition of air during biochar production (Suliman et al. 2016) or exposure to ozone following pyrolysis (Kharel et al. 2019) can add oxygenated functional groups and increase cation exchange capacity. There is great potential for the design and production of engineered chars, but there has been little systematic development in this area.

Co-located compost and biochar facilities could include processes to further activate, or functionalize the char, yielding engineered biochar with properties desirable for co-composting or specialty biochar markets.

Sizing

Finished biochar can be sized for appropriate uses with simple rollers or crushers requiring a minimal capital and footprint cost for use either within the composting operation for co-composting or sold as biochar into specific markets.

PERMITTING COMPOST FACILITY BIOCHAR PRODUCTION

A consistent issue across biochar production regionally is the permitting of a particular technology and facility. Biomass conversion to biochar has often been accomplished using open burning techniques. This has given regulatory agencies the incorrect perception that this is the only technology available for manufacturing biochar. In reality, there are a multitude of technologies available to create biochar, each with its own positive and negative attributes. To mitigate regulatory issues, technologies that minimize regulated emissions during operations should be prioritized. The challenge to the commercial biochar sector is also to produce and implement testing and assessment methodologies that clearly demonstrate the emissions outcomes, carbon stabilization outcomes, and GHG reductions for any pyrolysis process.

Biochar production technology and its understanding among regulators and potential biochar production facility owners is a barrier. Until regulators better understand the various biochar production technologies and their differences with respect to emissions, permitting will be complex. Until potential facility owners better understand the attributes and deficiencies of the process investors will be hesitant.

There are a variety of factors that will drive regulatory requirements. The size and location of the facility, feedstock designation, site land use zoning and permit structure, regulating jurisdiction, and local environmental conditions, are some of the major considerations that need to be identified and assessed. Depending upon these conditions, sites may require air permits, storm water permits, state waste discharge permits, solid waste permits, conditional use permits, and other environmental review. Conditions for these other permits can be highly variable depending upon location, regulatory authority, and scope of the project. A thorough assessment of these conditions is beyond the scope of this report. However, the air permitting process is further detailed in *Chapter 12: Air Pollutant Emissions and Air Emissions Permitting for Biochar Production Systems*.

BIOCHAR PRODUCTION BEYOND THE COMPOST FACILITY: BIOREFINERIES

We have discussed the benefits of co-locating biochar production with a compost facility, both from the perspective of efficiently utilizing woody biomass, and for the potential benefits of co-composting with biochar. However, coupling more than these two technologies to further optimize valorization of organic waste streams is a primary motivation of the biorefinery concept developed by a range of researchers (Bell et al. 2014; Mountraki et al. 2016; Jungmeier et al. 2014). Washington State University researchers have proposed a regional solid waste handling biorefinery (Figure 7.7). The biorefinery emphasizes the synergistic use of technologies beyond composting to effectively treat specific organic waste streams while maximizing co-product generation and providing environmental benefits (e.g., local fertilizer production, GHG emissions reduction).

A similar idea for a centralized biomass center could provide a way to test and verify the processing capabilities of new biochar processors. The facility would need be located near biomass sources, and have the necessary truck and rail transport access, and access to grid power This center is proposed to investigate new technologies appropriate at different scales and test their capacities to reduce emissions and produce stable carbon with various functionalized configurations.

STRATEGIES TO OVERCOME BARRIERS

Perceptions and Marketing

Economic barriers associated with capital and operating costs will not be overcome until more full-scale facilities are built and become successful at selling their products. Successful marketing of biochar will be dependent upon how customers "view" or "feel" about the product and the general understanding of the benefits of biochar. An effective action that can be taken at this time is to develop market-level literature that educates the general public on the virtues of biochar use. This would be effective in an urban or suburban environment, particularly in cities that have food waste recycling programs. Markets exist for lawn and garden products where biochar and co-composted biochar products could be sold and provide a means to educate the public.

Regulatory and Societal

Regulatory barriers are complex and varied but the most prominent issue is air permitting. Producing unambiguous technology descriptions that define regulatory categories associated with biochar production technologies is the most effective action that can be taken at this time. These descriptions would need to fit into the regulatory categories of the National Emission Standards for Hazardous Air Pollutants for Source Categories (40 CFR Part 63) and associated rules.

Technology acceptance barriers by regulators will be partially overcome by using syngas to power biochar production, as this would lower overall process emissions. Standardization of emissions quantifying and reporting for each technology will allow for comparison by regulators and other interested parties. Further acceptance will occur when working facilities are more prominent. Acceptance by potential facility

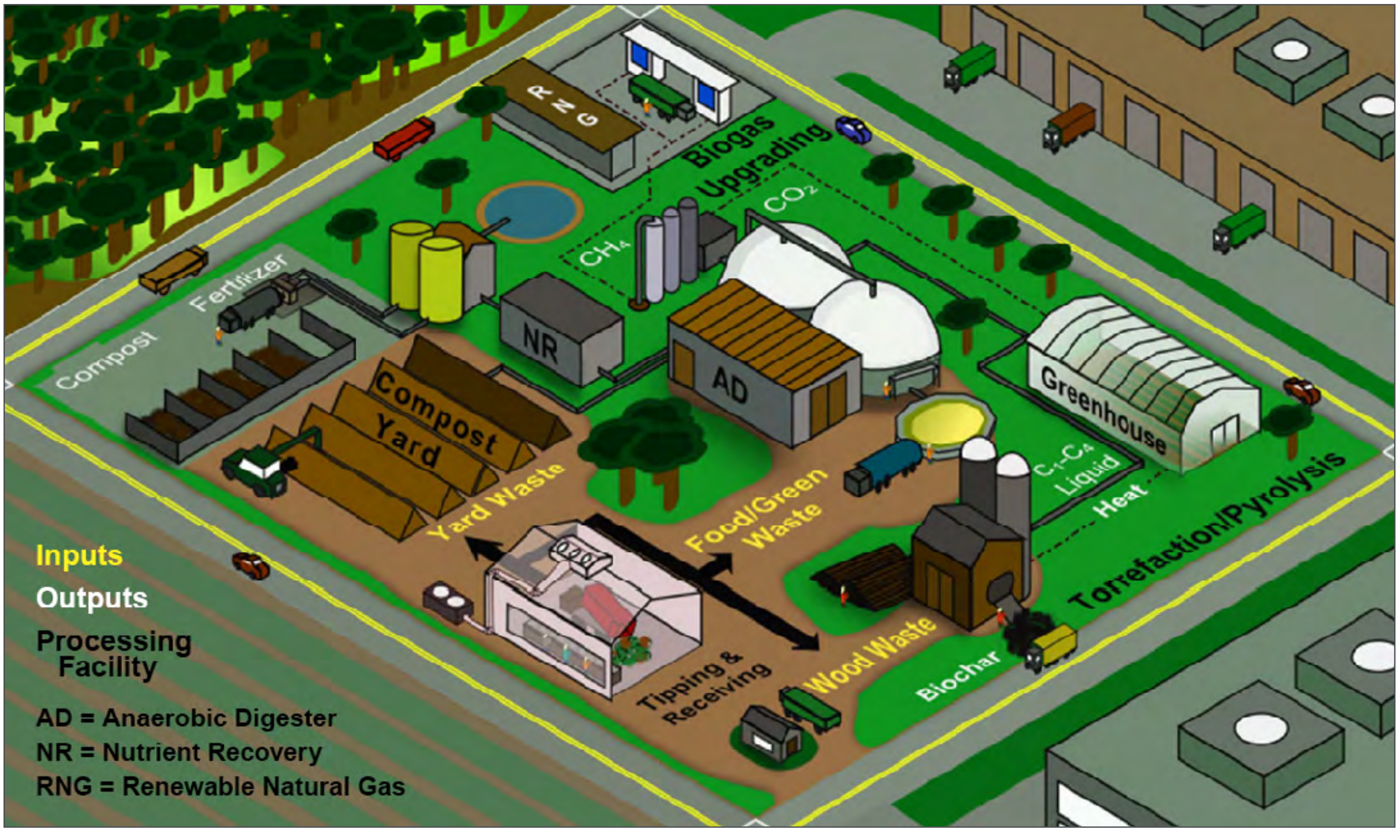

Figure 7.7. *The biorefinery concept for processing organic waste (Source: Hills et al. 2019).*

owners will also be partially overcome through wide-spread use. The most effective action that can be taken at this time is to have regulatory agencies do reviews of technologies and provide guidance documents that indicate potential acceptance of technologies or process conditions. This is likely to make potential facility owners more interested in pursuing this type of business opportunity.

Regulatory agency review and acceptance will also serve to help overcome societal acceptance barriers. Research and educational institution trials are also a method of creating social acceptance.

SUMMARY OF RECOMMENDATIONS

The benefits of co-locating biochar production with compost facilities are both environmental and economic. In order to overcome the regulatory, economic, and public perception barriers of biochar, we make the following recommendations:

1. Accurately identify and quantify emissions during biochar production (see *Chapter 12, Air Pollutant Emissions and Air Emissions Permitting for Biochar Production Systems* for more background information):
   - Conduct a thorough review of air quality permit issues and recommendations for biochar production systems, monitoring, and emissions tests.
   - Develop a near term case study on biochar production that is not based on regulatory identification as incinerators, but as a separate category (e.g., biomass thermal treatment). In the longer term advance a proposal to establish a new category of permitting “carbon stabilizers” based on significant advances in design, operation, and monitoring. These would both be supported by thorough monitoring and testing to demonstrate emissions outcomes carried out on any apparatus.
   - Include criteria air pollutants (particulate matter, carbon monoxide, sulfur dioxide, nitrogen dioxide, ozone forming constituents) and other regulated volatile gases in air emissions research on biochar production. Emissions of GHGs will also be important to support life cycle analysis of biochar production. This is needed to support the air permitting process.

2. Conduct comprehensive studies into the attributes of biochar and co-compost and its end uses.
   - Characterize biochar adequately in research. Standardize biochar attributes with a common set of metrics. International Biochar Initiative (IBI) standards should be followed at a minimum, including reporting feedstock materials, moisture content, pre-treatment, pyrolysis process and temperature. Many papers report the study of biochar in a particular setting without discussion of the biochar properties.
   - Develop a research program to thoroughly understand biochar characteristics and functional properties that reduce compost emissions by capturing valuable nutrients (i.e., nitrogen, phosphorus, sulfur), reducing environmental impacts from leaching and gas emissions. This would also improve compost nutrient quality.
   - Support field research that evaluates biochar and co-composted biochar in soil end use settings. This could be undertaken in conjunction with or separately from the ten year multi-site research effort proposed in Chapter 3.
   - Support near-term research into the uses of biochar and co-composted biochar in field trials in the Pacific Northwest with various crop and soil combinations.
3. In conjunction with the National Renewable Energy Laboratory (NREL) and universities, develop a comprehensive capability to use computer models to evaluate biomass to biochar production systems and outcomes at three scaled levels: load-fed kilns and pyrolyzers, moderate-scale on-site pyrolyzers/gasifiers, and central facility gasifiers/boilers.
4. Provide systematic and ongoing biomass to biochar production process equipment design, engineering, and monitoring support at all levels of biochar production to meet the goals of lowest possible emissions and highest possible biochar production efficiency at minimum cost through a combined research and commercialization effort.
5. Establish a regional bio-processing center (biorefinery) in which composting is the primary organic fraction of municipal solid waste treatment, but that also has ancillary treatment processes and the capacity to test various biochar production systems.

REFERENCES

Agegnehu, G., Sirivasta, A.K., & Bird, M.I. (2017). The role of biochar and biochar compost in improving soil quality and crop performance: A review. *Applied Soil Ecology*, 199, 156-170. http://dx.doi.org/10.1016/j.apsoil.2017.06.008

Agyarko-Mintah, E., Cowie, A., Van Zweiten, L., Singh, B.P., Smillie, R., Harden, S., & Fornasier, F. (2017). Biochar lowers ammonia emission and improves retention in poultry litter composting. *Waste Management*, 61, 129-137. http://dx.doi.org/10.1016/j.wasman.2016.12.009

Akdeniz, N. (2019). Systematic review of biochar use in animal waste composting. *Waste Management,* 88, 291-300. https://doi.org/10.1016/j.wasman.2019.03.054

Ayiania, M., Haghighi Mood, S., Milan, Y.J., & Garcia-Perez, M. (2019). Production of Engineered Biochars for Phosphate Removal from Waste Lignocellulosic Materials: First, Second, and Third Generation Engineered Products. A technical report completed as part of the Waste to Fuels Technology Partnership. 71 pp. https://csanr.wsu.edu/wp-content/uploads/sites/32/2019/08/Production-of-Engineered-Biochars.pdf

Bell, G., Schuck, S., Jungmeier, G., Wellisch, M., Felby, C., Jorgensen, H., & Spaeth, J. (2014). IEA Bioenergy Task42 Biorefining. Wageningen.

CARB (2007). Emissions Testing of Volatile Organic Compounds from Green Waste Composting at the Modesto Compost Facility in the San Joaquin Valley, Publication #442-07-009, and California Integrated Waste Management Board, October 31, 2007.

CARB (2015). ARB Emissions Inventory Methodology for Composting Facilities, California Environmental Protection Agency, Air Resources Board, March 2015 https://www.arb.ca.gov/ei/areasrc/index2.htm, retrieved March 2019.

Chen, Y-K., Huang, X.D., Han, Z.Y., Hunag, X., Hu., B., & Wu, W.X. (2010). Effects of bamboo charcoal and bamboo vinegar on nitrogen conservation and heavy metals immobility during pig manure composting. *Chemosphere*, 78, 1177-1181. https://doi.org/10.1016/j.chemosphere.2009.12.029

Collins, D.P., Stacey, N., Tea, T., Bary, A., & Myhre, L. (2020). Biochar feedstock influences compost pile temperature and available nitrogen. US Composting Council Conference.

Ecology (n.d.). Washington Department of Ecology Compost webpage. https://ecology.wa.gov/Waste-Toxics/Reducing-recycling-waste/Organic-materials/Managing-organics-compost, accessed August 2020.

Gang, D.R. (2018). Impact of Biochar on Composition and Properties of Herbs: A Review. Ch. 9 in Chen et al. *Advancing Organics Management in Washington State: The Waste to Fuels Technology Partnership 2015-2017 Biennium*, Publication no. 18-07-010, June 2018. Solid Waste Management Program, Washington Department of Ecology, Olympia, WA.

Gang, D.R., Berim, A., Long, R., Cleary, J., Fuchs, M., Finch, R.W., Garcia-Pérez, M. & Jobson, B.T. (2018). Evaluation of Impact of Biochar-Amended Compost on Organic Herb Yield and Quality. Ch. 10 in Chen et al. *Advancing Organics Management in Washington State: The Waste to Fuels Technology Partnership 2015-2017 Biennium*, Publication no. 18-07-010, June 2018. Solid Waste Management Program, Washington Department of Ecology, Olympia, WA.

Gang, D., Collins, D., Jobson, T., Seefeldt, S., Berim, A., Stacey, N., Khosravi, N., & Hoashi-Erhardt, W. (2019). Integrating Compost and Biochar for Improved Air Quality, Crop Yield, and Soil Health. Ch. 2 in Hills et al. *Advancing Organics Management in Washington State: The Waste to Fuels Technology Partnership 2017-2019 Biennium*, Publication no. 19-07-027, December 2019. Solid Waste Management Program, Washington Department of Ecology, Olympia, WA.

Godlewska, P., Schmidt, H.P., Ok., Y.S., & Olescezuk, P. (2017). Biochar for composting improvement and contaminant reduction: A review. *Bioresource Technology*, 246, 193-202. https://doi.org/10.1016/j.biortech.2017.07.095

Hagemann, N., Joseph, S., Schimdt, P-H., & Kammann, C.I. (2017). Organic coating on biochar explains its nutrient retention and stimulation of soil fertility. *Nature Communications*, 8, 1089. https://doi.org/10.1038/s41467-017-01123-0

Hills, K., Garcia-Perez, M., Amonette, J.E., Brady, M., Jobson, T., Collins, D., Gang, D., Bronstad, E., Flury, M., Seefeldt, S., Stöckle, C.O., Ayiania, M., Berim, A., Hoashi-Erhardt, W., Khosravi, N., Haghighi Mood, S., Nelson, R., Milan, Y.J., Pickering, N., Stacey, N., Tanzil, A.H., Zhang, J., Saari, B., & Yorgey, G. (2019). *Advancing Organics Management in Washington State: The Waste to Fuels Technology Partnership 2017-2019 Biennium*, Publication 19-07-027. Solid Waste Management Program, Washington Department of Ecology, Olympia, WA.

Hwang, O., & Lee, S-R. (2018). Efficacy of different biochars in removing odorous volatile organic compounds (VOCs) emitted from swine manure. *Sustainable Chemistry and Engineering*, 6, 14239-14247. https://doi.org/10.1021/acssuschemeng.8b02881

Jobson, T., & Khosravi, N. (2019). Emissions from Washington State Compost Facilities: A Review of Volatile Organic Compound Data, and an Estimation of Greenhouse Gas Emissions. Ch. 2 in Hills et al. *Advancing Organics Management in Washington State: The Waste to Fuels Technology Partnership 2017-2019 Biennium*, Publication no. 19-07-027, December 2019. Solid Waste Management Program, Washington Department of Ecology, Olympia, WA.

Jungmeier, G., van Ree, R., de Jong, E., Stichnothe, H., De Bari, I., Jorgensen, H., Wellisch, M. et al. (2014). Facts, Figures and Integration of Biorefineries in a Future BioEconomy—Findings in IEA Bioenergy Task 42 "Biorefining." https://doi.org/10.5071/22n-dEUBCE2014-4DO.9.1

Kammann, C., Schimdt, H-P., Messerschimdt, N., Linsel, S., Steffens, D., Muller, C., Koyor, H-W., Conte, P., & Koseph, S. (2015). Plant growth improvement mediated by nitrate capture in co-composted biochar. *Scientific Reports*, 5, 11081. https://doi.org/10.1038/srep11080

Khan, N., Clark, I., Sanchez-Monedero, M.A., Shea, S., Meir, S., & Boolan, N. (2016). Maturity indices in co-composting of chicken manure and saw dust with biochar. *Bioresource Technology*, 168, 245-251. https://doi.org/10.1016/j.biortech.2014.02.123

Kharel, G., Sacko, O., Feng, X., Morris, J.R., Phillips, C.L., Trippe, K., Kumar, S., & Lee, J.W. (2019). Biochar surface oxygenation by ozonization for super high cation exchange capacity. *ACS Sustainable Chem. Eng.*, 7, 16410-6418. https://dx.doi.org/10.1021/acssuschemeng.9b03536

Lopez-Cano, I., Roig, A., Cayuela, M.L., Alberquerque, J.A., & Sanchez-Monedero, M.A. (2016). Biochar improves N-cycling in composting of olive mill wastes and sheep manure. *Waste Management*, 49, 553-559. https://doi.org/10.1016/j.wasman.2015.12.031

Martínez-Blanco, J., Lazcano, C., Christensen, T.H., Muñoz, P., Rieradevall, J., Møller, J., Antón, A., & Boldrin, A. (2013). Compost benefits for agriculture evaluated by life cycle assessment. A review. *Agronomy for Sustainable Development*, 33(4), 721-732. https://doi.org/10.1007/s13593-013-0148-7

Mountraki, A., Tsakalova, M., Panteli, A., Papoutsi, A.I., & Kokossis, A.C. (2016). Integrated Waste Management in Multiproduct Biorefineries: Systems Optimization and Analysis of a Real-Life Industrial Plant. *Industrial and Engineering Chemistry Research,* 55, 3478–3492. https://doi.org/10.1021/acs.iecr.5b03431

NEOS Corp. (1994). Urban tree residues: Results of the first national inventory. Final rep. Lakewood, CO: International Society of Arboriculture Research Trust, Allegheny Power Service Corp. and National Arborists Foundation. NEOS Corp. Sept.

Oliveira, F.R., Patel, A.K., Jaisi, D.P., Adhikari, S., Lu, H., & Khanal, S.K. (2017). Environmental application of biochar: Current status and perspectives. *Bioresource Technology*, 246, 110–122. https://dx.doi.org/10.1016/j.biortech.2017.08.122

Paulot, F. & Jacob, D.J. (2014). Hidden cost of U.S. agricultural exports: Particulate matter from ammonia emissions. *Environmental Science and Technology*, 48, 903-908. https://dx.doi.org/10.1021/es4034793

Prost., K., Borchard, N., Seimens, J., Kautz, T., & Moller, J-M. (2013). Biochar affected by composting with farmyard manure. *J. Environmental Quality*, 42, 164. https://doi.org/10.2134/jeq2012.0064

Ravishankara, A.R., Daniel, J.S., & Portman, R.W. (2009). Nitrous oxide: the dominant ozone-depleting substance emitted in the 21st century. *Science*, 326, 123-125. https://doi.org/10.1126/science.1176985

Sanchez-Monedero, M.A., Cayuela, M.L., Roig, A., Kindo, J., Mondini, C., & Bolan, N. (2018). Role of biochar as an additive in composting. *Bioresource Technology*, 247, 1155-1164. https://doi.org/10.1016/j.biortech.2017.09.193

Sanchez-Monedero, M.A., Cayuela, M.L., Roig, A., Kindo, J., Mondini, C., & Bolan, N. (2019). Biochar reduces volatile organic compound emissions during chicken manure composting. *Bioresource Technology*, 288, 121584. https://doi.org/10.1016/j.biortech.2019.121584

Schultz, H., Dunst, G., & Glaser, B. (2013). Positive effects of composted biochar on plant growth and soil fertility. *Agronomy for Sustainable Development*, 33, 817-827. https://doi.org/10.1007/s13593-013-0150-0

Senesi, N. (1989). Composted materials as organic fertilizers. *Science of the Total Environment*, 81, 521-542. https://doi.org/10.1016/0048-9697(89)90161-7

Senesi, N. & Plaza, C. (2007). Role of humification processes in recycling organic wastes of various nature and sources as soil amendments. *Clean Soil, Air and Water*, 35, 26-41. https://doi.org/10.1002/clen.200600018

Steiner, C., Das, K.C., Melear, N., & Lakley, D. (2010). Reducing nitrogen loss during poultry litter composting using biochar. *J. Environmental Quality*, 39, 1236-1242. https://doi.org/10.2134/jeq2009.0337

Suliman, W., Harsh, J.B., Abu-Lail, N.I., Fortuna, A.-M., Dallmeyer, I., & Garcia-Perez, M. (2016). Modification of biochar surface by air oxidation: Role of pyrolysis temperature. *Biomass and Bioenergy* 85, 1–11. https://dx.doi.org/10.1016/j.biombioe.2015.11.030

Vandecasteele, B., Sinnico, T., D'Hose, T., Nest, T.V., & Mondini, C. (2016). Biochar amendment before and after composting affects compost quality and N losses but not P plant uptake. *Journal of Environmental Management*, 168, 200-209. https://doi.org/10.1016/j.jenvman.2015.11.045

Wang, C., Lu, H., Dong, D., Deng, D., Wang, H., & Wu, W. (2013). Insight into the effects of biochar on manure composting: Evidence supporting the relationship between N2O emission and denitrifying community. *Environmental Science and Technology*, 47, 7431-7349. https://doi.org/10.1021/es305293h

Wang, Y., Villamil, M.B., Davidson, P.C., & Akdeniz, N. (2019). A quantitative understanding of the role of co-composted biochar in plant growth using a meta-analysis. *Science of the Total Environment*, 685, 741-752. https://doi.org/10.1016/j.scitotenv.2019.06.244

Yu, H., Xie, B., Khan, R., & Shen, G. (2019). The changes in carbon, nitrogen compounds and humic acid substances during organic-inorganic aerobic composting. *Bioresource Technology*, 271, 228-235. https://doi.org/10.1016/j.biortech.2018.09.088