BIOCHAR + COMPOST

By Charlie McIntosh and Josiah Hunt | January, 2023

Biochar is often blended with compost when applied in agricultural soils resulting in benefits beyond what either amendment would supply if used alone. What has become clear from research studies is that biochar can dramatically improve the composting process when added at an early stage and in turn the biochar is improved as well. Amending early stage compost with biochar (co-composting) can result in enhanced nutrient conservation, reduced odors and greenhouse gas emissions, improved habitat for microbiology, and higher compost maturity and stability indices. During composting, biochar surfaces are coated with compost residues, resulting in increased functionality and nutrient loading. Co-composting with biochar can mitigate environmental risks as well as avoid unfavorable emissions associated with commercial composting and manure management operations, while producing a higher quality compost product with improved agronomic performance.

NUTRIENT CONSERVATION [1, 2, 3, 4, 8, 10, 11, 17, 23, 25]

Charcoal (biochar) is well known as a filter for gases and liquids. When biochar is added to compost, this filtration characteristic is directly related to measured results of lowered leaching and volatilization of plant nutrients, particularly nitrogen. The surfaces of biochar can adsorb nutrients; reducing losses and increasing the fertilizer value of the finished compost. Studies consistently show that co-composting with biochar can reduce losses of nitrogen by more than 50% while also shifting nitrogen speciation; favoring nitrogen in the form of nitrate over ammonia/ammonium. Biochar's porous structure improves aeration in the compost pile and provides a degree of moisture buffering, creating a more uniform and favorable environment during the thermophilic phase of composting that supports specific groups of microbes involved in nutrient cycling. These mechanisms help biochar to conserve nutrients in the compost in forms that can help promote soil health and plant vigor.

REDUCED ODORS & GHG EMISSIONS [7, 8, 9, 14, 15, 17, 21, 22, 23, 25, 26, 28]

Odors and greenhouse gas emissions from composting are inescapable. Biochar presents a tool to help mitigate the issue, and with additional benefits. Of particular interest are the emissions of nitrous oxide (N2O), methane (CH4), and ammonia (NH3), all of which can be reduced with prudent use of biochar. In many cases, where biochar is used in composting, greenhouse gas emissions can be reduced by more than half with some studies showing reductions of CH4 by more than 80%, reductions of N2O by more than 50%, and reductions in NH3 emissions by up to 60%. CH4 and N2O are both extremely powerful GHGs with an impact ~25x and ~300x more potent than CO2, respectively, in terms of global warming potential over 100 years. Similarly, emissions of NH3 from composting operations can be a major source of undesirable odors as well as being a significant source of harmful atmospheric volatile organic compounds (VOCs). Applying wood-based biochar at 5-10% by weight at an early stage has been shown to be sufficient to achieve the above-mentioned results; reducing GHG emissions and undesirable odors while increasing the retention of plant nutrients like nitrogen in the compost pile. In the experience of the authors, having worked with biochar in commercial composting operations for many years, the reduction in human-detectable ammonia smell can be rapid and profound.

ENHANCED MICROBIAL ACTIVITY [1, 5, 6, 7, 9, 12, 14, 22]

In the compost environment microorganisms transform raw organic materials into stable aggregates. Biochar provides superb habitat for these microorganisms. The diversity of pores and functional surfaces in biochar particles form a structure on which microorganisms can easily thrive. Biochar's unique physicochemical characteristics provide access to air, water, nutrients, protection from predation, and a favorable environment for metabolic reactions. Because biochar modifies the micro-environment within the compost pile it tends to support specific groups of microorganisms while suppressing others, for example, in some cases biochar has been shown to support increased diversity and relative abundance of fungal populations while simultaneously altering the dominant bacterial populations. An example of this microbial support is the proliferation of nitrifying bacteria in compost piles where biochar has been added; resulting in nitrogen retention and altered NH_4^+ / NO_3^- ratios, favoring NO_3^- forms over NH_4^+ and NH_3, and leading to improved fertilizer value as well as nitrogen bioavailability. These results demonstrate that biochar can influence the functional gene expression of specific groups of microorganisms, such as those primarily responsible for denitrification, leading to reduced losses of nitrogen and reduced emissions of N_2O. Studies have also found that additions of biochar can suppress populations of methanogenic bacteria; responsible for generating CH_4 under anaerobic conditions, while stimulating populations of methanotrophic bacteria; responsible for consuming CH_4 under aerobic conditions.

COMPOST MATURITY & STABILITY [1, 5, 6, 12, 16, 17]

Compost amended with biochar is regularly reported to mature faster. This maturity is often observed in the field as more quickly reaching a sweet smell and pleasant hand feel. For some compost producers, this factor can be incredibly important, reducing the processing costs that accumulate with time. In lab analyses of the finished compost, it is common to find maturity indices such as lower respiration rates, higher concentration of humic substances, and lower ratio of ammonia/ammonium to nitrate in biochar amended compost when compared to non-amended material. Biochar's porosity plays a major role in enhancing the composting environment by increasing aeration, reducing bulk density, and buffering moisture throughout the pile. When conditions are overly wet, compost piles can develop anaerobic zones producing undesirable odors and emissions with the potential for significant losses of nutrients, a problem that biochar has been observed to mitigate. In review articles published over the past decade, research studies consistently show that additions of biochar to composting at an early stage can increase the humic extractable carbon, improve ratios of humic to fulvic acids, and decrease water soluble carbon content; all positive signs of increased humification and improved compost maturity.

By providing such a favorable habitat for microorganisms, biochar also impacts how rapidly organic matter decomposes into humic substances in the composting environment. Co-composting with biochar can increase composting temperatures as well as the duration of the thermophilic phase resulting in increased organic matter degradation and humification. However, the overall flux of CO2 derived from microbial respiration appears to be comparable to composting controls without biochar. Thus, despite significantly stimulating microbial activity, studies show that biochar does not cause additional losses of carbon from the compost pile and may actually stimulate additional carbon sequestration by increasing microbial populations and adsorption of water-soluble carbon on biochar surfaces.

BIOCHAR SURFACE FUNCTIONALITY [3, 4, 8, 24]

Aged biochar, as opposed to raw biochar, consistently shows better characteristics for aiding in plant growth in field trials. The aging of biochar can happen relatively fast in a compost environment when compared to aging in soil. In applying biochar amended compost, studies have shown immediate (first season) and dramatic increases in plant growth response beyond what the comparative compost provided without biochar. During the composting process biochar surfaces become weathered, building up an organic coating composed of minerals, organic compounds, and microorganisms. The organic coating formed during composting has been shown to further enhance surface functionality, cation exchange capacity, and biochar's capacity to bind anions such as nitrate and phosphate. Studies analyzing the organic coating have shown that it is primarily composed of small carbon compounds (i.e. dissolved organic carbon, carbonates, and aromatic carbon structures) complexed with minerals and metals (i.e. Fe, Al, and Si) as well as plant nutrients (i.e. Ca, Mg, K, phosphate, nitrate, and ammonia). Biochar's functionalized surfaces can also adsorb and "lock-up" potentially toxic compounds, organic pollutants, and heavy metals. In the experience of the authors the weathering phenomena can be visibly observed as a reduced reflectiveness of the biochar, as its originally shiny surface begins to develop an organic coating.

AGRONOMIC BENEFITS [1, 2, 13, 18]

Biochar's impact on plant growth and agronomic performance has been well studied in the scientific literature (see "Agricultural Benefit of Biochar" on Pacific Biochar's website), however, studies on the agricultural impact of co-composted biochar are less common. A recently published review of the research found that "COMBI" (co-composted biochar) demonstrates improved agricultural productivity when utilized as a co-composted product over blending the two materials post-composting. The study found that the agricultural impacts of COMBi included: increases in crop yields, soil organic carbon (SOC), available nutrients, cation exchange capacity (CEC), and soil biological activity in addition to stabilizing soil aggregates, improving water retention and drought tolerance, and reducing emissions of N2O from the soil. These results indicate that biochar co-composting has the potential to improve agronomic value above what compost generally provides without the addition of biochar.

CO-COMPOSTING & MANURE MANAGEMENT [5, 12, 16, 17, 19, 20, 21, 22, 27, 28]

Biochar utilization in co-composting and manure management could have a profound impact on composting and livestock operations, specifically with regard to retaining nutrients, mitigating undesirable emissions, supporting beneficial microorganisms, and enhancing the agronomic value of the finished material. However, the incentives for widespread adoption depend upon making biochar both affordable and accessible at an appropriate scale for wide-spread use in commercial composting operations.

Biochar has already proven to be an economically feasible, durable solution for large-scale carbon dioxide removal (CDR), with associated credits driving recent growth in biochar production. An opportunity exists to develop additional methodologies to measure and quantify GHG Emissions Reduction (ER) when biochar is used in composting and manure management operations. A recent study published in 2022 by researchers from UC Merced, focused on manure management in California's dairy industry, found that utilizing wood-based biochar in dairy manure composting alone could mitigate 1.59 million metric tons of CH4 globally on an annual basis, equivalent to roughly 39.75 million metric tons of avoided CO2 emissions every year. Extrapolating these results outside of the dairy industry and factoring in the reduction of other GHG emissions, as described above, could have a significant global impact reducing environmental risk factors while improving the agronomic value of finished compost and manure products.

CONCLUSIONS

In summary, compost benefits from additions of biochar and biochar benefits from the composting process, plant growth response and soil health can be improved, and all of these benefits can be both economically and ecologically valuable with significant impacts on mitigating undesirable odors and GHG emissions, improvements to the composting process, as well as enhancing the agronomic value of the finished material. In the experimental observations of the authors, and well documented in the scientific literature, additions of wood-based biochar at 5% to 10% by weight are generally sufficient to achieve these results in commercial composting and manure management operations.

References:

1. Fischer, Daniel, and Bruno Glaser. “Synergisms between Compost and Biochar for Sustainable Soil Amelioration.” Management of Organic Waste, 2012, doi:10.5772/31200.
2. Kammann, Claudia I., et al. “Plant Growth Improvement Mediated by Nitrate Capture in Co-Composted Biochar.” Scientific Reports, vol. 5, no. 1, 2015, doi:10.1038/srep11080.
3. Joseph, Stephen, et al. “Microstructural and Associated Chemical Changes during the Composting of a High Temperature Biochar: Mechanisms for Nitrate, Phosphate and Other Nutrient Retention and Release.” Science of The Total Environment, vol. 618, 2018, pp. 1210–1223., doi:10.1016/j.scitotenv.2017.09.200.
4. Hagemann, Nikolas, et al. “Organic Coating on Biochar Explains Its Nutrient Retention and Stimulation of Soil Fertility.” Nature Communications, vol. 8, no. 1, 2017, doi:10.1038/s41467-017-01123-0.
5. Sanchez-Monedero, M.a., et al. “Role of Biochar as an Additive in Organic Waste Composting.” Bioresource Technology, vol. 247, 2018, pp. 1155–1164., doi:10.1016/j.biortech.2017.09.193.
6. Jindo, Keiji, et al. “Chemical and Biochemical Characterisation of Biochar-Blended Composts Prepared from Poultry Manure.” Bioresource Technology, vol. 110, 2012, pp. 396–404., doi:10.1016/j.biortech.2012.01.120.
7. Yuan, Yinghong, et al. “Is Biochar-Manure Co-Compost a Better Solution for Soil Health Improvement and N_2O Emissions Mitigation?” Soil Biology and Biochemistry, vol. 113, 2017, pp. 14–25., doi:10.1016/j.soilbio.2017.05.025.
8. Hestrin, Rachel, et al. “Fire-Derived Organic Matter Retains Ammonia through Covalent Bond Formation.” Nature Communications, vol. 10, no. 1, 2019, doi:10.1038/s41467-019-08401-z.
9. Li, Shuqing, et al. “Linking N_2O Emission from Biochar-Amended Composting Process to the Abundance of Denitrify (*nirK* and *nosZ*) Bacteria Community.” AMB Express, vol. 6, no. 1, 2016, doi:10.1186/s13568-016-0208-x.
10. Hagemann, Nikolas, et al. “Nitrate Capture and Slow Release in Biochar Amended Compost and Soil.” Plos One, vol. 12, no. 2, 2017, doi:10.1371/journal.pone.0171214.
11. Steiner, Christoph, et al. “Reducing Nitrogen Loss during Poultry Litter Composting Using Biochar.” Journal of Environment Quality, vol. 39, no. 4, 2010, p. 1236., doi:10.2134/jeq2009.0337.
12. Godlewska, P., Schmidt, H.P., Ok, Y.S., Oleszczuk, P., Biochar for composting improvement and contaminants reduction. A review, Bioresource Technology (2017), doi: http://dx.doi.org/ 10.1016/j.biortech.2017.07.095
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21. Pattey, E., Trzcinski, M.K. & Desjardins, R.L. Quantifying the Reduction of Greenhouse Gas Emissions as a Result of Composting Dairy and Beef Cattle Manure. Nutr Cycl Agroecosyst 72, 173–187 (2005). https://doi.org/10.1007/s10705-005-1268-5
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28. Kebreab, E., & Feng, X. (2021). Strategies to reduce methane emissions from enteric and lagoon sources. Contract 17RD018, 57.

Reference section, with content notes added:

1. Fischer, Daniel, and Bruno Glaser. “Synergisms between Compost and Biochar for Sustainable Soil Amelioration.” Management of Organic Waste, 2012, doi:10.5772/31200.
    a. Biochar and compost both contribute to the pool of stable soil carbon held in soil organic matter.
    b. Compost contains a majority of “labile” carbon, available for microbial respiration, with a small portion of “stable” carbon, contained in humus complexes, as well as “living” carbon contained in the bodies of microorganisms.
    c. Biochar contains a small portion of labile carbon with the majority being present as stable carbon in the form of poly-aromatic condensed carbon compounds with a high degree of recalcitrance.
    d. Biochar made from woody feedstocks at high temperatures contains more stable carbon and less labile carbon when compared to biochar produced at low temperatures and from feedstocks such as manure.
    e. Biochar made from materials like manure contains a higher mineral content and contributes additional fertilizer value while supplying labile carbon available for microbial respiration.
    f. Biochar reduces leaching and volatilization of nutrients, specifically nitrogen species, during composting thereby increasing the nutrient value of biochar amended compost and reducing greenhouse gas emissions.
    g. Biochar improves aeration, water retention and infiltration, reduces bulk density, and provides habitat for supporting increased populations of microorganisms.
    h. Symbiotic relationships between biochar and free living nitrogen fixing bacteria and arbuscular mycorrhizal fungi have been observed along with increased root nodulation in legumes following biochar application.

2. Kammann, Claudia I., et al. “Plant Growth Improvement Mediated by Nitrate Capture in Co-Composted Biochar.” Scientific Reports, vol. 5, no. 1, 2015, doi:10.1038/srep11080.
    a. Biochar has been shown to produce a range of plant growth responses both enhancing and reducing aboveground biomass primarily as a result of nutrient loading occuring before or after soil application.
    b. It has been shown that applying “raw” biochar directly to soil prior to planting can produce a negative plant growth response due to nutrient loading of biochar surfaces occuring in the soil and thus reducing the availability of plant nutrients.
    c. In contrast, nutrient loading prior to soil application (i.e. co-composting biochar with organic waste) demonstrated a dramatic increase in aboveground biomass.
    d. In this study quinoa was used to assess plant growth response to soil applications of biochar using woody biochar produced at 700 ºC.
    e. Co-composting biochar resulted in an aboveground biomass yield increase of 305% while applying “raw” biochar resulted in a yield decrease to 60% of the control; demonstrating the enhanced benefits of biochar nutrient loading prior to soil application.

3. Joseph, Stephen, et al. “Microstructural and Associated Chemical Changes during the Composting of a High Temperature Biochar: Mechanisms for Nitrate, Phosphate and Other Nutrient Retention and Release.” Science of The Total Environment, vol. 618, 2018, pp. 1210–1223., doi:10.1016/j.scitotenv.2017.09.200.
    a. Co-composting biochar alters functional surfaces by complexing with organomineral compounds including humic substances, carbon nanoparticles, and inorganic minerals, clays, and metals present during the composting process.
    b. During co-composting bichar surfaces develop additional functionality demonstrated by changes in the C-O moieties resulting primarily from interactions with organic and inorganic compounds and soluble nutrients with little evidence of direct oxidation of biochar surfaces.
    c. Co-composting facilitates entrainment of nutrient-rich water within micropores, enabling charged compounds to be held tightly with water by capillary action and osmotic forces within small inner pores within the biochar matrix.
    d. Nitrate and phosphate retention is enhanced by the organomineral complexing that occurs during co-composting, increasing pore diversity and functional surfaces capable of adsorbing and retaining anions in solution.
    e. Release of nutrients loaded on biochar surfaces during co-composting to plants occurs across a concentration gradient in the soil (high concentration within biochar particles move toward low concentrations around plant roots) and within the biochar matrix subject to pore clogging, electrostatic and H-bonding forces.

4. Hagemann, Nikolas, et al. “Organic Coating on Biochar Explains Its Nutrient Retention and Stimulation of Soil Fertility.” Nature Communications, vol. 8, no. 1, 2017, doi:10.1038/s41467-017-01123-0.
    a. Surface oxidation plays a minor role in enhancing biochar functionality when compared with the organic coating resulting from co-composting.
    b. Organic coating alters biochar surfaces non-homogeneously with hotspots around outer surfaces and inner pores.
    c. Co-composting altered the elemental composition of the organic coating on biochar surfaces reducing the abundance of CHO and increasing CHON bearing compound classes while an extraction of the organic coating and subsequent analysis revealed enrichment of nitrate, organic carbon, carbonate, Ca, and K when compared with non-composted pristine biochar.
    d. NMR spectroscopy revealed that the differences in organic carbon speciation observed in co-composted biochar versus pristine biochar cannot be explained by transformation of the existing biochar carbon alone and must result from the introduction of new carbon species from the composting process
    e. Co-composting does not substantially affect biochar bulk carbon speciation and therefore carbon stability is unaffected by the composting process.
    f. The organic coating may actually help preserve aromatic carbon structures from oxidative degradation leading to increased longevity in soils.

   g. Biochar nanoparticles created during co-composting associate with compost organic matter to form and shape the porous organic coating
   h. The organic coating increases overall porosity while also contributing to pore clogging by a build-up of humic-like organic compounds on the inner surfaces of pores, restricting water mobility and contributing to water adsorption and soluble nutrient retention.

5. Sanchez-Monedero, M.a., et al. “Role of Biochar as an Additive in Organic Waste Composting.” Bioresource Technology, vol. 247, 2018, pp. 1155–1164., doi:10.1016/j.biortech.2017.09.193.
   a. Biochar improves multiple aspects of the composting process including stimulating microbial activity, increased aeration, nutrient retention, and water conservation
   b. A number of biochar properties can enhance compost by increasing porosity, reducing bulk density, improving water holding capacity, and preventing nutrient loss by adsorption onto biochar surfaces.
   c. Biochar has been shown to increase temperatures of the thermophilic phase of the composting process and accelerate compost maturity due to the stimulation of compost microbiology.
   d. Application rates in composting systems have varied from 3-50% biochar (dry-weight) with optimal conditions achieved at 10% and significant benefits realized at application rates as low as 3-5%.
   e. The composting process alters properties of biochar by modifying surface functionality, increasing reactive oxygen-containing groups, cation exchange capacity, and microporosity.
   f. Biochar provides improved habitat for microorganisms, specifically bacteria, actinomycetes, and fungi by providing moisture, nutrients, and a favorable environment for metabolic reactions.
   g. The varied porosity, macro and micropores, of biochar particles provide a physical structure available for colonization and utilization by soil biology.
   h. Biochar’s charged pore surfaces can facilitate metabolic functions performed by soil organisms and can protect extracellular enzymes from denaturing effects.

6. Jindo, Keiji, et al. “Chemical and Biochemical Characterisation of Biochar-Blended Composts Prepared from Poultry Manure.” Bioresource Technology, vol. 110, 2012, pp. 396–404., doi:10.1016/j.biortech.2012.01.120.
   a. Effect of 2% (v/v) biochar addition to poultry manure composting resulted in a 10% increase in extractable carbon from humic and fulvic acids, a 30% decrease in water soluble carbon, and a 30-40% increase in enzyme activity despite decreased amounts of microbial biomass in biochar-amended composts.
   b. Biochar-amended compost hosted a higher diversity of fungi when compared to non-amended compost

   c. Biochar-amended compost reached higher temperatures during active composting and contained lower concentrations of labile carbon during the thermophilic phase and after maturation.
   d. The higher concentration of humic extractable carbon and higher ratio of HA/FA in biochar-amended compost show increased humification and compost stability at maturation.
   e. Changes observed in the organic matter degradation rate were minimal, however, the composition of organic matter in biochar-amended compost was altered such that indices of compost stability and maturation were significantly increased.

7. Yuan, Yinghong, et al. "Is Biochar-Manure Co-Compost a Better Solution for Soil Health Improvement and N_2O Emissions Mitigation?" Soil Biology and Biochemistry, vol. 113, 2017, pp. 14–25., doi:10.1016/j.soilbio.2017.05.025.
   a. Biochar-amended chicken manure compost showed reduced emissions of CO_2 and N_2O during the composting process.
   b. Biochar suppressed microbial nitrification as demonstrated by a reduction in the abundance of glucosaminidase enzyme activity and nirK gene expression.
   c. Biochar addition to chicken manure stabilized carbon in the compost demonstrated by an increase in peroxidase activity.
   d. Biochar can stabilize carbon, reduce CO_2 and N_2O emissions, and alter microbial functional gene expression to reduce nitrogen losses in composting of high nitrogen materials like chicken manure

8. Hestrin, Rachel, et al. "Fire-Derived Organic Matter Retains Ammonia through Covalent Bond Formation." Nature Communications, vol. 10, no. 1, 2019, doi:10.1038/s41467-019-08401-z.
   a. Biochar acts as a sink for ammonia gas forming covalent bonds between ammonia N and biochar C
   b. The nitrogen retention capacity of biochar (180 mg N/g) resulted in a higher nitrogen content than any unprocessed plant material and many manures, making it a valuable nitrogen fertilizer.
   c. During biochar weathering, nitrogen retention capacity increased six-fold
   d. Ammonia N was retained primarily by chemisorption over physisorption where covalent interactions dominated over electrostatic interactions.
   e. The study reveals that ammonia retention mechanisms differ from ammonium retention in that ammonium N is adsorbed in stoichiometric balance with ammonium H while ammonia N is not, implying that ammonia is bound covalently while ammonium is bound electrostatically.

9. Li, Shuqing, et al. "Linking N_2O Emission from Biochar-Amended Composting Process to the Abundance of Denitrify (*nirK* and *nosZ*) Bacteria Community." AMB Express, vol. 6, no. 1, 2016, doi:10.1186/s13568-016-0208-x.

- a. Biochar significantly reduces N_2O emissions during manure composting by suppressing *nirK* gene expression.
- b. Biochar alters gene expression related to bacterial nitrification/denitrification leading to reduced emissions of N_2O gas.
- c. Biochar reduced emissions of N2O by 54% when compared to the control

10. Hagemann, Nikolas, et al. “Nitrate Capture and Slow Release in Biochar Amended Compost and Soil.” Plos One, vol. 12, no. 2, 2017, doi:10.1371/journal.pone.0171214.
    - a. Biochar amendments in mixed manure composting showed slower release of nitrate, with up to 30% being released after the first hour compared with the control where all nitrate was extracted after one hour.
    - b. Extractable nitrate from all samples (compost and soil) amended with biochar showed an increase up to double the total extractable nitrate over controls.
    - c. Nitrate held in biochar may be underestimated in many studies because of the long time necessary to fully extract all nitrates.

11. Steiner, Christoph, et al. “Reducing Nitrogen Loss during Poultry Litter Composting Using Biochar.” Journal of Environment Quality, vol. 39, no. 4, 2010, p. 1236., doi:10.2134/jeq2009.0337.
    - a. Biochar additions to poultry litter composting reduced emissions of ammonia gas by up to 64% and reduced N losses by up to 52% at the highest biochar application rate of 20% on a dry weight basis.
    - b. Biochar was made from pine chips without further modification.

12. Godlewska, P., Schmidt, H.P., Ok, Y.S., Oleszczuk, P., Biochar for composting improvement and contaminants reduction. A review, Bioresource Technology (2017), doi: http://dx.doi.org/10.1016/j.biortech.2017.07.095
    - a. Compost maturity indices include: temperature, C/N ratio, dissolved organic carbon (DOC), oxygen use rate (OUR), NH4+/NO3- ratio, HA/FA ratio, germination capacity (GI), and biochemical composition
    - b. Because biochar is composed of highly stable carbon compounds that are not available for microbial decomposition, the C/N ratio of biochar amended compost may be skewed higher than is normally considered ideal for mature compost
    - c. During the thermophilic phase, biochar amended compost reaches maximum temperatures 6-7 days earlier, in part due to improved aeration and the stimulation of microbial populations
    - d. Biochar buffers the moisture content of both wet and dry compost piles reducing losses of water and nutrients to evaporation and leaching
    - e. Compost pH can be altered by additions of biochar, often increasing pH at least initially, however, as biochar surfaces become oxygenated its pH tends to decrease as biochar ages in the compost pile
    - f. Organic matter degradation rates in compost piles are often increased by additions of biochar due to increased aeration and microbial activity as well as sorption of compounds that inhibit or reduce decomposition rates

   g. Biochar helps compost reach a higher level of stability of humic substances and the chemical structure of fulvic acids
   h. Nitrogen compounds tend to shift from NH4+ to NO3- with improved nitrification processes caused by enhanced habitat for nitrifying bacteria, and total nitrogen tends to be increased
   i. Fertilizer value of compost is improved by retention of plant nutrients on biochar surfaces in addition to the minerals provided by the biochar itself, nutrients are also observed to be more bioavailable in biochar amended compost
   j. Biochar's affinity for heavy metals results in reduced mobility (i.e. volatilization and leaching) and reduced bioavailability when applied to soil
   k. Biochar can lower emissions of CO2, CO, CH4, NH3, and N2O from the composting process, particularly when composting materials such as manure and sewage sludge

13. Antonangelo, J. A., Sun, X., & Zhang, H. (2021). The roles of co-composted biochar (COMBI) in improving soil quality, crop productivity, and toxic metal amelioration. Journal of Environmental Management, 277, 111443. doi:10.1016/j.jenvman.2020.111443
    a. COMBI (co-composted biochar) demonstrates significant benefits to both the compost and biochar as well as improved agricultural productivity when utilized as a co-composted product over blending the two materials post-composting
    b. Biochar loading rate at 10-15% w/w is optimal for co-composting
    c. Biochar produced from woody biomass and agricultural residues at 400-700C demonstrate ideal properties for co-composting (i.e. SSA, porosity, functional groups, CEC, & WHC)
    d. Biochar amended compost tends to achieve higher maximum temperatures, often faster, and can result in an extension of the thermophilic phase of composting
    e. Biochar can buffer the moisture content of composting piles adding water holding capacity that prevents drying-out as well as improving aeration in water-logged compost piles
    f. Biochar can stimulate microbial activities; providing protective habitat in marco- and micro- pores, improving OM degradation, forming stabilized humic substances, retaining DOC on biochar surfaces, improving nitrification, and suppressing methanogenesis
    g. Biochar can reduce gaseous emissions from composting (i.e. ammonia, methane, and nitrous oxide)
    h. Biochar helps to retain minerals, reduce nitrogen losses, and immobilize heavy metals / organic pollutants in compost piles
    i. Agricultural impacts of COMBi include increased crop yields, SOC, available nutrients, soil CEC, and soil biological activity as well as stabilizing soil aggregates, improving soil water retention and drought tolerance, and reduced emissions of N2O
    j. COMBI shows significant potential to improve amelioration of soils contaminated with PTMs (potentially toxic metals) over biochar or compost used separately or as a blend post-composting

14. Sonoki, T., Furukawa, T., Jindo, K., Suto, K., Aoyama, M., & Sánchez-Monedero, M. Á. (2013). Influence of biochar addition on methane metabolism during thermophilic phase of composting. Journal of basic microbiology, 53(7), 617-621.

    a. Biochar additions (at 10% w/w) to manure composting at early stage resulted in reduced populations of methanogenic organisms and increased populations of methanotrophic organisms during the thermophilic phase.
    b. Microbial communities associated with methane metabolism are assessed by measuring levels of mcrA (methanogen) encoding methyl coenzyme M reductase subunit alpha and pmoA (methanotroph) encoding particulate methane monooxygenase using qPCR analysis.

15. Chen, W., Liao, X., Wu, Y., Liang, J. B., Mi, J., Huang, J., ... & Wang, Y. (2017). Effects of different types of biochar on methane and ammonia mitigation during layer manure composting. Waste Management, 61, 506-515.
    a. Different biochars added at 10% w/w to layer hen manure compost in small-scale laboratory composters
    b. Cornstalk, bamboo, woody, and coir biochars reduced ammonia emissions by 24.8, 9.2, 20.1, and 11.8 % respectively, reduced methane emissions by 26.1, 15.5, 22.4, and 17.1% respectively, and reduced total nitrogen losses by 29.4, 17.9, 25.4, and 13.9% respectively
    c. Cornstalk and woody biochar showed reduced levels of NH4+(N) and increased levels of NO3-(N) when compared with the control and other biochars, demonstrating that these biochars create a favorable environment for nitrifying bacteria

16. Guo, X. X., Liu, H. T., & Zhang, J. (2020). The role of biochar in organic waste composting and soil improvement: A review. Waste Management, 102, 884-899.
    a. Biochar increases porosity and aeration, accelerates OM degradation, stimulates microbial activity, increasing thermophilic phase duration and max temperatures, while decreasing emissions of ammonia, methane, and nitrous oxide
    b. Compost quality is affected by biochar additions; increasing/accelerating maturation, stabilization, and humification; total N is increased as well as CEC; and increasing germination indices

17. Xiao, R., Awasthi, M. K., Li, R., Park, J., Pensky, S. M., Wang, Q., ... & Zhang, Z. (2017). Recent developments in biochar utilization as an additive in organic solid waste composting: A review. Bioresource Technology, 246, 203-213.
    a. Biochar impacts the physicochemical properties of the compost pile reducing pile density and improving aeration, reducing the occurrence of clumping and anaerobic zones that can reduce compost quality, and enhancing the thermophilic phase of the composting process
    b. Biochar influences microbial communities in the compost pile by providing an optimal habitat in variable sized pore spaces with access to oxygen and moisture and supplying nutrients
    c. Biochar effects GHG emissions from composting operations; reducing ammonia, methane, and nitrous oxide emissions
    d. Biochar improves compost quality by reducing N losses, shifting nitrification index (NH4+ / NO3-) favoring NO3-, enhancing formation of humic substances, and improving germination indices

18. Sánchez-Monedero, M. A., Cayuela, M. L., Sánchez-García, M., Vandecasteele, B., D'Hose, T., López, G., … Mondini, C. (2019). Agronomic Evaluation of Biochar, Compost and Biochar-Blended Compost across Different Cropping Systems: Perspective from the European Project FERTIPLUS. Agronomy, 9(5), 225. doi:10.3390/agronomy9050225
    a. Study spanning 3 years focused on field-scale applications of biochar alone and with organic residues and/or compost in four cropping systems: olive groves (Spain), greenhouse tomatoes (Spain), an arable crop rotation (Belgium), and three vineyards (Italy)
    b. Biochar was derived from oak wood (slow pyrolysis) and compost was derived from olive wastes (Spain), sheep manure (Spain), and bio-waste / green waste (Belgium & Italy)
    c. Treatments increased soil C by an average of 11% for compost, 20% for biochar-blended compost, and 36% for biochar
    d. Compost and biochar-blended compost treatments enhanced soil fertility; increasing extractable organic C by 25%, extractable N by 44%, available K by 26%, soil respiration by 26%, and 2-4 enhancement of denitrifying activity
    e. Compost and biochar-blended compost treatments enhanced crop quality in grapes; increasing grape must acidity by 9% and grape weight by 16%, as well as increasing tomato diameter by 9% and fruit hardness by 8%

19. Ba, S., Qu, Q., Zhang, K., & Groot, J. C. (2020). Meta-analysis of greenhouse gas and ammonia emissions from dairy manure composting. biosystems engineering, 193, 126-137.
    a. Static, turning, windrow, and silo composting methods for managing dairy manure were evaluated for greenhouse gas emissions based on 41 scientific articles (153 treatments)
    b. Common gaseous emissions from manure composting include CO2, N2O, CH4, and NH3 which can account for 46% and 67% of the initial nitrogen and carbon content of the original manure substrate, respectively
    c. CO2 was the primary pathway for carbon losses, while NH3 accounted for most of the nitrogen losses
    d. Although GHG emissions varied significantly across the studies; turning composting resulted in the highest GHG emissions while silo composting resulted in the lowest GHG emissions
    e. CH4 emissions were positively correlated with moisture content, TC, and TN while N2O emissions were positively correlated with TC, TN, and temperature

20. Harrison, B. P., Gao, S., Gonzales, M., Thao, T., Bischak, E., Ghezzehei, T. A., ... & Ryals, R. A. (2022). Dairy Manure Co-composting with Wood Biochar Plays a Critical Role in Meeting Global Methane Goals. Environmental Science & Technology.
    a. Based on 35-day field scale co-composting study comparing biochar-composting with wood-based biochar applied at ~20% on a dry-weight basis and composting without biochar versus stockpiling (not studied) of dairy manure
    b. Biochar co-composting using woody biochar in dairy manure composting can reduce CH4 emissions by 79% versus composting without biochar
    c. Biochar co-composting resulted in reduced life-cycle GHG emissions of 0.535 tCO2e per metric ton of manure

    d. Utilizing biochar in manure composting could mitigate 1.59 million metric tons of CH4 per year globally
    e. In CA, biochar utilization in dairy manure composting could replace the need for 132 anaerobic digesters while still meeting the methane reduction requirements for dairies adopted with SB 1383 (40% CH4 reduction below 2014 levels by 2030)

21. Pattey, E., Trzcinski, M.K. & Desjardins, R.L. Quantifying the Reduction of Greenhouse Gas Emissions as a Result of Composting Dairy and Beef Cattle Manure. Nutr Cycl Agroecosyst 72, 173–187 (2005). https://doi.org/10.1007/s10705-005-1268-5
    a. Comparison of GHG emissions from dairy and beef cattle manure stored in three different methods: slurry, stockpile, and passively aerated compost
    b. Composting resulted in the lowest levels of GHG emissions as determined by combined N2O-CH4 emissions in CO2 equivalents followed by stockpiled manure, with slurry manure storage resulting in the largest combined emissions

22. Yin, Y., Yang, C., Li, M., Zheng, Y., Ge, C., Gu, J., ... & Chen, R. (2021). Research progress and prospects for using biochar to mitigate greenhouse gas emissions during composting: a review. Science of The Total Environment, 798, 149294.
    a. Common greenhouse gas emissions from composting include methane (CH4), carbon dioxide (CO2), nitrous oxide (N2O) and ammonia (NH3)
    b. Biochar can significantly reduce GHG emissions from composting with the greatest impact resulting from biochars produced at high temperatures, from crop residues and woody biomass, and applied at 10% (w/w)
    c. Microbial micro-habitat is enhanced by biochar's immense surface area where surface functional groups can further enhance the activities of microorganisms and improve adsorption capacity
    d. Biochar affects nitrogen in the composting environment by inducing changes in nitrogen speciation by capturing nitrogen (NH3, NH4+, and N2O) adsorbed to surface functional groups and shifting ammonia to nitrate ratios in favor of nitrate, augmenting microbial gene expression linked to enzymes that catalyze N2O production / consumption (*nirK/nirS* and *nosZ*), and changing the nitrogen-associated microbial community structure during composting and resulting in increased nitrogen retention and reduced emissions of N2O
    e. Biochar's porosity increases water holding and aeration in manure composting, resulting in reduced anaerobic conditions, reducing the effectiveness of methanogenic and denitrifying bacteria to produce CH4 and N2O, while enhancing conditions for methanotrophic bacteria to transform CH4 into CO2

23. Agyarko-Mintah, E., Cowie, A., Van Zwieten, L., Singh, B. P., Smillie, R., Harden, S., & Fornasier, F. (2017). Biochar lowers ammonia emission and improves nitrogen retention in poultry litter composting. Waste Management, 61, 129-137.
    a. Green waste biochar added to poultry litter composting showed reduced ammonia volatilization (60%) and reduced losses of nitrogen (51%)

24. Archanjo, B. S., Mendoza, M. E., Albu, M., Mitchell, D. R., Hagemann, N., Mayrhofer, C., ... & Joseph, S. (2017). Nanoscale analyses of the surface structure and composition of biochars

extracted from field trials or after co-composting using advanced analytical electron microscopy. Geoderma, 294, 70-79.
    a. Biochar extracted from multi-year field trials and co-composting experiments was found to contain organo-mineral complexes on internal and external surfaces that form porous structures at the carbon-mineral interface modifying the biochar's surface functionality
    b. Mineral complexes appear to be composed of Fe, Al, Si, K, P, Mg, and Ca (including oxide/hydroxide groups, carbonates, phosphates, and alumina-silicates) forming micro-aggregates and -agglomerates on biochar surfaces and within pores

25. Vandecasteele, B., Sinicco, T., D'Hose, T., Nest, T. V., & Mondini, C. (2016). Biochar amendment before or after composting affects compost quality and N losses, but not P plant uptake. Journal of environmental management, 168, 200-209.
    a. Biochar added (10% w/w dry-basis) at the beginning of the composting process, with common compost feedstocks of green waste and organic fraction of municipal solid waste, showed increased decomposition rates and decreased GHG emissions (CO2 -53%, CH4 -95%, and N2O -14% respectively)
    b. Biochar added during compost storage significantly increased the carbon content of finished compost material while biochar added during composting significantly increased organic matter degradation and reduced GHG emissions

26. Sánchez-Monedero, M. A., Sánchez-García, M., Alburquerque, J. A., & Cayuela, M. L. (2019). Biochar reduces volatile organic compounds generated during chicken manure composting. Bioresource technology, 288, 121584.
    a. Oak biochar added at 3% (w/w) to poultry manure composting significantly reduced emissions of oxygenated volatile organic compounds (VOCs) as well as nitrogenous VOCs during the thermophilic phase

27. Akdeniz, N. (2019). A systematic review of biochar use in animal waste composting. Waste Management, 88, 291-300.
    a. Biochar applied at 5-10% in animal waste composting can decrease the duration of the thermophilic phase of composting, reduce finished compost pH, prevent the formation of compost leachate, and reduce emissions of ammonia, methane, and nitrous oxide.

28. Kebreab, E., & Feng, X. (2021). Strategies to reduce methane emissions from enteric and lagoon sources. Contract 17RD018, 57.
    a. Agricultural activities account for ~18% of anthropogenic GHG emissions globally with methane from enteric and manure sources responsible for 40% of all agricultural emissions, livestock emissions are the largest source of anthropogenic methane emissions globally
    b. The most effective manure management additive to reduce methane emissions is biochar, capable of reducing methane emissions from manure compost by up to 82.4%