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Operative Utilization of Agricultural Wastes for Amending Pyrolysed Carbonaceous Feedstock, or Biochar, in a Simulated Unindustrialized Agricultural Setting

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Biochar—pyrolysed organic material—has the capacity to sequester recalcitrant carbon, making it a viable method of carbon capture and storage internationally. Biochar can also be used as a soil amendment, as it has many benefits to plants when in the soil; however, biochar must be treated properly for its agricultural benefits to be realized. This investigation tests the efficacy of four composted agricultural wastes with biochar to grow corn and soybeans, as compared with controls of no biochar or amendment during a fourteen-day pot trial. The biochar and fertilizers were produced and composted locally, using replicable, unsophisticated methods. It was predicted that biochar, a known nutrient sink, would delay initial growth in all soils; however, plants in soil only amended with biochar had higher germination rates and grew taller than those without biochar. This gives evidence that biochar alone may give a benefit to plants.

Keywords: agriculture, biochar, corn, soybean, climate, botany

Introduction

Biochar is the name commonly given to a form of close-to-pure carbon for agricultural use.[1-3, 5-6, 10] It is produced by the destructive distillation, or pyrolysis, of organic material in high-temperature, low-oxygen environments.[1-2, 5, 7] It has received widespread interest for its potential in long-term carbon sequestration and sustainable soil improvement.[2-4] Among its benefits when applied to soil are moisture retention, greater prevalence of soil biota, and efficient retention of fertilizer that both minimizes leaching and facilitates nutrient uptake into plants.[1-3, 5, 7] Because biochar acts as a nutrient sink and not as a direct fertilizer, the full agricultural benefits of biochar are not realized until the material has been amended with a fertilizer.[10] This is usually urea or another chemically-derived nitrogenous fertilizer. Raw biochar can be produced cheaply, and is scalable from small family farms to industrial operations[2]; however, the chemical fertilizers used to amend biochar, as well as other refined agricultural techniques, are often not present in developing nations and small farms. In order for biochar used in agriculture to make a significant impact on the global climate, it would need to be implemented more broadly than chemical treatment and production methods currently allow. This study seeks to investigate whether prevalent agricultural wastes such as manure and greenwaste can provide nutrients with which to charge biochar in many of the areas in which chemical fertilizers are unavailable or impractical and to document the interactions between biochar and composted agricultural wastes as measured by crop germination and growth. This study is relevant and highly necessary, as most of the research currently done with biochar tends to use chemical fertilizer as urea, while little data exists on the use of biochar with alternative nutrient sources that are more sustainable and produce fewer environmental problems than chemical fertilizers. The ultimate objective of this study is to establish recommended practices for rural and unindustrialized farmers such that they can more assuredly and effectively apply biochar with resources more likely to be available to them, thereby increasing the global sequestration potential of biochar.

Background

The word "biochar" broadly describes the black carbon produced from heating a feedstock in the absence of diatomic oxygen.[1-2, 5] Feedstocks, the substances that become biochar after processing, can consist of any carbon-rich substance; however, due to economic considerations, biochar is most often produced from some form of biomass, especially agricultural residues.[2] These include rice husks, sugarcane bagasse, corn stalks, and peanut shells. Biochar is chemically indistinct from charcoal, as it is produced by similar methods using similar feedstocks.[5] The principal difference between the two is usage; charcoal is black carbon often used as a heat source, while biochar is black carbon used as a soil amendment or sequestration vector.

The thermochemical process by which biochar is made is called pyrolysis, during which the water and volatile organic compounds in feedstock are driven off as incompletely combusted vapour, leaving black carbon behind.[5] The released vapour can either complete its combustion in an oxygen-rich environment, such as an afterburner, or can be condensed and cooled into a composite liquid known as pyroligneous acid, which can be further refined into chemical products, including acetone and methanol.[17-18] Other names for pyrolysis include "gasification" and "destructive distillation", while pyroligneous acid refined for fuel or heating are often called "syngas" or "wood gas".[17-18] It ought to be noted that an oxygen-free environment is critical to the production of these products.[5] When biomass is heated in open, oxygenated air, it is allowed to completely combust the feedstock. This yields mostly ash, which does not have the soil benefits offered by biochar.

Literature Review

In the scientific community that conducts research into biochar, there are two primary categories of study: climate science research and agricultural science research. Biochar research from a climate science perspective attempts to justify biochar as a stable tool for carbon capture and storage. Biochar research from an agricultural science perspective is largely concerned with the agronomic benefits of biochar application, and the ability to increase land productivity, fertilizer efficiency, or other factors with direct relevance to the health and productivity of crops. The following review, intended as a primer for the current scientific understanding of biochar, seeks to first establish the benefits of biochar for carbon sequestration, then to discuss biochar from the perspective of agricultural science, the field to which this study aims to directly contribute. This was done to justify the broad implementation of biochar not just as an agricultural aid, but as a method of carbon capture and storage. It must be noted at the outset that this review is limited and narrowed to the use of biochar from plant-based feedstocks with little standalone fertility, and does not detail the emerging field of research into directly pyrolysing animal wastes to create nutritive biochars.

The independent scientific disciplines of agricultural and climate science investigate biochar for different purposes and with different goals in mind, but a paper entitled "sustainable biochar to mitigate climate change" published in *Nature* by D. Woolf et al. has become a landmark study that is relevant to both primary categories of biochar study.[1] This was a collaboration among researchers at Swansea University, Pacific Northwest National Laboratory, the University of New South Wales, and Cornell University in departments relevant to materials science, agricultural science, and climate engineering. The study bolsters hundreds of citations, and represents a strong convergence and intersection of different fields of science to examine the subject of biochar through the lenses of many independent scientific disciplines. Utilizing and synthesizing the body of work that had been done on biochar, the team[1] sought to calculate the "maximum sustainable technical potential of biochar to mitigate climate change." To perform this synthesis, the researchers[1] used not only climate science research, but considered the agronomic application of biochar to promote and ensure food security. They concluded that a maximum of twelve percent of annual human emissions could be offset by biochar without any negative consequences to the environment or to global food security.[1] This indicates that although biochar cannot be the only method used to fully solve Earth's climate problems, it will certainly be an invaluable tool in the goal of offsetting human impact on the global climate. This gives further justification into researching biochar application methods, as it demonstrates that biochar could be safely implemented on much greater scales than it currently is. This was the first comprehensive biochar-related study to be accepted into such a prestigious scientific journal, and represents the point in time in which biochar reached a broader audience within the related scientific communities, causing it to become more widely researched.

The validity and importance of biochar as a carbon sequestration tool has been recognized by the Intergovernmental Panel on Climate Change, or IPCC.[2] This international aggregate of researchers and scientists forms a world authority on the science concerning climate change, and is actively used to shape public policy related to carbon emissions. In the eleventh chapter of their 2014 publication on the most current strategies for the mitigation of climate change, a segment was dedicated to detailing the promising research into biochar, wherein the benefits of the substance not only for carbon sequestration, but for agriculture and heat production were laid out.[2] The IPCC classifies biochar as one of their recommended land-based mitigation strategies,[2] and even identify biochar-manure interactions as an underexplored area of study.[2] This is a highly credible organization of scientists, researchers, and policy-makers, and their identification of biochar-manure interactions – the focus area of the study described in this paper – as being insufficiently researched is a reliable indication that a shortage of knowledge exists on the subject.

The claim that biochar is chemically stable, or recalcitrant, in soil is central to its usefulness as a means of carbon sequestration. A collaborative study[3] among researchers at the University of Göttingen in Germany, Nanjing Agricultural University in China, and Kazan Federal University in Russia conducted a meta-analysis of dozens of biochar-related studies in an attempt to discover trends regarding the degradation of biochar to accurately characterize its stability. They found that a 97% majority of biochar's mass is biologically inaccessible, which means it is not subject to degradation by normal biological processes in the soil.[3] Biochar, therefore, has a high degree of recalcitrance, which is a necessary component for the longevity of biochar in soils. In addition, the researchers[3] found that biochar degradation decreased logarithmically, even in the short-duration studies they examined. This shows that after a short period, most likely to do with the oxidation of biochar after its production, biochar becomes extremely stable in soils. They were also able to confirm that biochar enhances soil fertility by promoting the propagation of beneficial bacteria and fungi.[3] This research suggests that biochar is, in fact, stable in soils, albeit after a brief integration period.[3] This is key to the usefulness of biochar for carbon capture and storage.

Although the popularity of biochar has been increasing rapidly over the course of the past few decades, it is by no means a new invention. There is evidence to suggest that biochar was used by Amazonians several thousand years ago.[4] Bruno Glaser and Jago Jonathan Birk from the Soil Physics Group at the University of Bayreuth in Germany conducted a review[4] to summarize the current understanding of a certain type of highly fertile soil, *terra preta*, found scattered throughout central Amazonia. They concluded that the high concentration of aromatic carbon found in *terra preta* was the result of biochar.[4] Glaser and Birk concluded that biochar applied to farmland "has the potential to combine sustainable agriculture with long-term CO_2 sequestration".[4] This further justifies the interdisciplinary approach to biochar as both a climate mitigation strategy and as an agricultural technology, and provides evidence that biochar truly is recalcitrant in soils over longer periods than can be experimentally simulated. It also suggests a correlation between increased black carbon content and soil fertility. While other studies[1, 3] have examined the stability and concentration of biochar in newly produced biochar amended soils, this review[4] was advantaged in that it was able to examine the recalcitrance of biochar amended soils thousands of years after its creation. This provides evidence suggesting that biochar can be relied upon as a highly-recalcitrant and effective method of carbon capture and storage around the world. Given the unsophisticated methods and limited resources the ancient Amazonians would have produced these soils with, it simulates the sorts of soils produced for the experiment in this paper's study.

Having explained the benefits of biochar for the global climate,[1-2] the question of implementing its use must be addressed. Biochar has a number of benefits to soil, including the aforementioned increases in soil biota and aromatic carbon,[3] which makes it a valuable substance for farmers. One key benefit offered by biochar is its ability to efficiently distribute existing nutrients to plants through cation exchange.[5] This claim was reviewed by researchers with expertise in biochar and soil science writing for the scientific journal *Biology and Fertility of Soils.*[5] Through a meta-analysis of several independent studies of biochar performance in agricultural fields, the researchers sought to find, through synthesis, a consensus on the impact of biochar on nutrient retention and distribution, and explain the chemical and physical properties of biochar that cause these benefits. They found that biochar application in conjunction with other fertilizers consistently improved nutrient uptake into plants. They also noted that the application of biochar had a noticeable regulatory effect on soil pH. In addition to this, they concluded that the aromatic structures and carboxyl groups found on biochar, mostly produced as a result of post-production oxidation, were largely responsible for the nutrient holding and exchanging properties of biochar. This property is the mechanism by which biochar conditions the soil to which it is added,[5] and is therefore of vital importance to any investigation of biochar interactions with different nutrient-rich soil amendments. This research also confirms that biochar application is correlated with increased microbial activity in soils, which is beneficial to plant growth.[5] This is corroborated by the aforementioned collaborative study between German, Chinese, and Russian researchers, which stated in their conclusion that biochar "stimulates microbial activities" in soil.[3] The pH regulation performed by biochar was also noted by a separate team of researchers.[6] In their study, biochar from several plant-based feedstocks was combined with several different soil types to test for a variety of chemical and physical properties including water holding capacity, soil carbon content, and nitrogen mineralization.[6] Although the impact of biochar on these soils varied quite substantially, the researchers state in their conclusion that "biochars, regardless of origin, significantly raised the pH of all soil types".[6] This is known to compensate for the pH-lowering effect of increased nitrogen in soil, and is yet another benefit conferred by biochar to agricultural soils.[5, 6]

The key benefit of biochar for agriculture is as a soil conditioner. The current scientific consensus is that biochar made from plant-based feedstocks provides little direct nutrient benefit to the soil.[7] Research published in the journal *Soil Science* details an incubation study wherein soils containing biochar were chemically analyzed against control soils [7]. This was done by directly analyzing the leachate after the 67-day study. It was found by this study that biochar application increased soil organic carbon,[7] which is an unsurprising result given that biochar is almost entirely composed of aromatic carbon.[1-3] They found, as did other studies, a number of oxygenated functional groups on the surface of the biochar after incubation that would likely contribute to soil fertility.[3, 7] The important finding of this study, however, was that biochar did not substantially increase the nitrogen content of the soil to which it was added.[7] This is indicative of the function of biochar as a nutrient distributor, rather than as a source of nutrient itself. The concentration of certain micronutrients in the leachate from biochar soils indicated that biochar absorbs these substances, and decreases their availability in soil during the integration and oxidation period. This may explain any stagnation of, or indeed drop in, productivity of plants in biochar-only soils as opposed to soils amended with a fertilizing substance. The means by which biochar is incorporated into soil is also likely to impact the leaching of nutrients.[8] In a study designed to simulate rain-induced leaching, a 20% loss of total phosphorus was recorded when the fertilizer-amended biochar had been applied on top of, rather than mixed into, the soil.[8] Although biochar can reduce leaching of fertilizer,[7] it must be incorporated into the soil properly in order to function in this capacity. This emphasizes the importance of not only producing biochar with the correct chemical properties and fertilizer additions, but of the physical properties as well.

Other research, from researchers writing for the *Journal of Environmental Quality,*[9] provides evidence that certain feedstocks yield biochar with non-negligible levels of nitrogen and other macronutrients. Most of these nutritive feedstocks are manures, and are therefore outside the scope of this review. Pyrolysed peanut hulls, however, are an outlier; their nitrogen content of 30kg per tonne is similar to the nitrogen content of some pyrolysed manures.[9] Despite this, the trend is for biochar from plant-based feedstocks not to be used in a nutritive capacity.[7]

The most important type of research for the study conducted for this paper is research that incorporates a plant growth element to test the efficacy of biochar. The results of a similar study to the one conducted here was published in the *Australian Journal of Soil Research*, and was produced by a team of researchers – predominately Australian – with expansive portfolios on biochar research, especially Lukas Van Zwieten.[10] This research tested the effect of biochar alone, as well as biochar amended with a nitrogenous chemical fertilizer, on the yields of radishes. The pot trial was conducted with different concentrations of biochar measured in tons per hectare as an application rate, and different concentrations of nitrogenous fertilizer. The team found that a number of soil fertility factors– including cation exchange capacity, loam, and organic carbon– were positively correlated with the presence of higher concentrations of biochar in the soil.[10] There was a 266% increase of plant mass in the highest-concentration biochar pots, as opposed to the 95% increase observed in pots with fertilizer alone.[10] More importantly, they found that, "application of biochar to the soil did not increase radish yield even at the highest rate", meaning that biochar provided little benefit on its own.[10] This source informs the research conducted in this paper's study by providing a precedent for the way in which biochar-amended plots will influence the growth of a food crop; however, their use of chemical fertilizers and pot trials, as well as the crops used is where the studies differ. Similar research, produced by multiple USDA researchers, also emphasizes the positive interaction between a fertilizer source and biochar.[11] Although the study focuses mostly on soil gas exchange, it recommends in its conclusion that biochar be used in conjunction with a fertilizer rather than on its own because "it eliminated potential yield reductions from biochar".[11] This relates to my study's area of inquiry; the fertilizer source used was bovine manure, and separate trials were conducted for biochar-only, manure-only, and manure-and-biochar soils. Their results strengthen the notion that the best agricultural usage of biochar is when applied in conjunction with a fertilizer.

Materials and Methods

To measure the interactions between biochar and different composted fertilizers, two crops with different nutrient requirements,[12] namely Early Sunglow corn and Envy soybeans, were grown during a fourteen-day indoor pot trial. These crops were selected for their widespread international use.[13] The one-hundred total plants, fifty plants each of Envy soybean and Early Sunglow corn, were divided into ten rows, each containing a distinct blend of biochar and agricultural wastes. There were two control blends. The first, containing sandy soil and nothing else, controlled for the absence of both biochar and compost. The second control, containing sandy soil and biochar, controlled for the absence of compost. The eight remaining blends were the four compost sources, each having a blend with and without biochar. Given the small sample size of five plants of each species per blend, the inclusion of statistical analysis was not recommended. This limitation was caused by the limited resources available for this study. The height of each plant was measured daily in millimetres, as well as plant death or non-emergence. During the growing period, the soil temperature was maintained at 30°C, the plants were exposed to twelve continuous hours of light provided by a 60W grow light, and were watered by mist twice a day. This was done to better simulate ideal growing conditions, and to control for extraneous confounding factors. These trials are similar to those conducted in the aforementioned radish trial published in the *Australian Journal of Soil Research.*[10] The Australian study served as a useful model for the conduction of pot trials such as the one used in this study. Time constraints prevented any yield analysis in this study, so plant height was used as a growth metric instead.

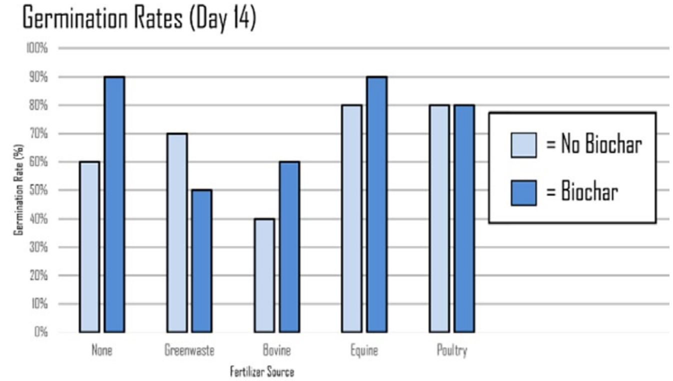
The soils were produced by layering nitrogenous (green, or manure) and carbonaceous (brown) materials in approximate ratios pursuant to the Berkeley composting method,[14] being left covered in black plastic for a shorter-than-normal two week period due to seasonal time constraints. In the compost plots for biochar soils, the brown layers were composed of biochar. In the compost plots for non-biochar soils, the brown layers were composed of shredded dry oak leaves. The three types of animal manures used in this study– bovine, equine, and poultry– were sourced from a local farm in Seminole County, Florida. The greenwaste used in this study was manually harvested and shredded Indian goosegrass, chosen for its regional abundance. These materials were chosen not only for their availability, but for their varying nutrient content [15]. Poultry manure has the highest nutrient concentration, followed by equine and bovine manures respectively [15]. Greenwaste is known to be less nutrient dense than all of these because lower nutrient contents are associated with soils incorporating greenwaste rather than animal manures as a fertilizer [16]. The soil used was a nutrient-poor sandy soil with no prior history of cropping, and was mixed with the manure and greenwaste before the two-week composting period. After composting, the layers were manually broken up and each blend was mixed well. This was done not only to ensure a uniform distribution of soil constituents in each pot, but to minimize the potential leaching that may result from top-dressed application of biochar.[8]

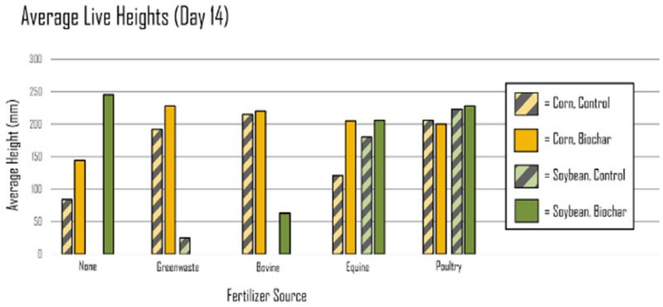
The biochar used in this study was produced in a custom-built pyrolytic reactor. The design was based on similar reactors, called Top-Lift Up-Draft (or TLUD) kilns. These are operated by starting a fire on the top of the bottom subunit, establishing a coal bed, and putting an afterburner subunit on top to finish combusting the volatile organic compounds rather than collecting them or releasing them as smog. This style of reactor employs a thermochemical process called slow pyrolysis, which was chosen for its relatively high feedstock conversion efficiency compared to other thermochemical methods.[9] The reactor was designed such that welding was not necessary, as the limited funds were insufficient for advanced manufacturing to be used. The pyrolytic reactor was constructed from two 55-gallon steel drums without an interior epoxy coating. One barrel formed the top, afterburner region. The other barrel formed the bottom, reactor region. Vents were bored around the bottom rim of the bottom barrel. This was done by striking the barrel with a pickaxe to produce holes with diameters of approximately 1cm each, at approximately 3cm intervals. The top of the bottom barrel was cut along its diameter four times to create eight triangular tabs, which were manually bent upwards to serve as a stable coupling between the top and bottom barrels. The bottom of the top barrel was entirely cut out and sanded, allowing the two barrels to couple correctly. The top of the top barrel was cut identically to the top of the bottom barrel. The triangular tabs were kept only partially bent upwards, as this seemed to allow the exiting gases to mix better when trial operations were conducted.

Manually split and chopped oak branches were the feedstock used to produce all the biochar in this study. Oak was chosen for its local abundance. After loading the bottom barrel with feedstock, the top was set aflame and left to burn openly until the first signs of glowing coals could be observed, at which point the second barrel would be set on top of the first. This served as a combustion chamber for the exiting vapours. As the heat radiated downwards towards the bottom vents, the feedstock in the bottom barrel was gradually pyrolysed over the course of approximately two hours. After the reactor had finished pyrolysing its contents, it was extinguished by sealing the vents with wet sand and dousing the coals in water. This was the most expeditious method of extinguishing the coals in this design, though other designs could simply be sealed and left to cool overnight.

Results

The control soils without fertilizer, as well as those with bovine and equine manure, showed an increase in germination rates for all plants in the presence of biochar when contrasted with the no-biochar controls. The greenwaste and poultry soils were outliers. The germination rate of plants in greenwaste-amended biochar soils was 20% lower than the germination rate of plants in the greenwaste no-biochar control. There was no observed difference in germination rates of plants in poultry-amended soils.





In most cases, the presence of biochar in the soil was correlated with an increased average height. For corn, a positive biochar-height correlation was true of greenwaste, bovine manure, equine manure, and no-fertilizer control soils. For soybeans, this was true of equine manure, poultry manure, and no-fertilizer control soils. A small decrease in average corn height was observed for plants in poultry manure soils. No soybeans germinated in the greenwaste-amended biochar soils; however, while no soybeans germinated in the absence of biochar in no-fertilizer control and bovine manure soils, germinations were recorded for plants in the corresponding biochar-amended soils. The highest average live height was for soybean plants grown in the biochar-amended no-fertilizer control soils.

Discussion

This study yielded some noteworthy results regarding the impact of different fertilizer sources with biochar on the average height and germination rate of the resulting plants. The addition of biochar to otherwise untreated soils appears to have increased both the germination rate and height of resulting plants. If it can be established through further study that wood-feedstock biochars can reliably increase germination rates, it would be possible to create a new class of biochar-based germination aids. This result was not anticipated, since plant-feedstock biochar produced via slow pyrolysis is not generally thought to provide a nutritive benefit.[8-11] Although certain feedstocks yield nutritive biochar, wooden feedstocks such as the oak used in this study are not thought to be nutritive.[9] This means that either the non-nutritive properties of biochar account for this increase in germination and height, or the current characterisation of wood-feedstock biochars as being minimally nutritive is incorrect or incomplete. Some non-nutritive properties that may be hypothesised to increase germination rates are increased water retention and increased aeration through porosity.[1-3, 5, 7] Further research is needed to discover the reasons for the increase in germination rates observed in this study.

Biochar also appears to aid germination in soils amended with bovine and equine manures, and hinders germination in soils amended with greenwaste. The increase observed in soils containing bovine and equine manure were anticipated; positive interactions between biochar and fertilizers are already found in the literature.[10-11] The decreases seen in greenwaste-amended biochar soils, however, were unexpected. The possibility of contamination cannot be eliminated, meaning that experimental error may be sufficient to explain this difference. There is, however, another possibility; given the relatively low nutrient density of greenwaste when compared with the other soil blends, it is likely that biochar, as a nutrient sink, had absorbed nutrients from the soil and left little for the plants' initial growth.[16] The relative abundance of nutrients in other soil blends, such as those containing bovine and equine manure, would likely have compensated for this effect. To ensure that biochar is not applied to the detriment of agricultural productivity, the full reasons for the observed decrease in germination rates observed in the greenwaste-amended biochar blend must be investigated and identified.

Biochar has no confirmed effect on germination in soils amended with poultry manure. Poultry manure had the highest nitrogen content of all the soils tested in this study, which means that it is possible that the biochar's absorption of nutrients, and the distribution of those nutrients to the plants, was overshadowed by the sheer abundance of nutrients available for the plants regardless of biochar application.[15] The addition of biochar to soils is correlated with a greater average height of corn and soybean plants in this study, with the significant exception of greenwaste-amended soils, where biochar appeared to have an inhibiting effect on the growth of soybeans.

It may be argued that the purity of materials in this study, the relative imprecision of the technologies used, and the non-exact soil volume measurements would present confounding factors that would decrease the reliability of the results; however, the aim of this study was to work with only the degree of precision that would be practiced by a farmer using rough guidelines and unsophisticated techniques. The results displayed here, therefore, are more likely to be representative of the sort of growth achievable by using biochar and composted agricultural wastes in unindustrialized settings, which is reflective of this study's ultimate objective. Using nutritive biochar was also outside the scope of this study. One possible direction for future research would be an investigation of soil fertility of slow-pyrolysed manure contrasted with fresh manures. Such a study might provide a better model for which nutrients are lost or concentrated as a result of pyrolysis, and could help to better explain the results of this study. In order to broadly implement biochar without unintended reductions in soil fertility, the causes for the disparate greenwaste result in this study must be identified, and a more comprehensive model of biochar interactions must be created.

Conclusion

Almost without exception, biochar is demonstrated by this study to have a positive or neutral effect on the height of corn and soybean plants during the first fourteen days of growth. Interactions between greenwaste and biochar were detrimental to plant growth, meaning that biochar does not have a consistent benefit across all fertilizer sources. The results of this study appear to indicate that the addition of biochar to otherwise untreated soils is correlated with an increase in the germination rate and height of resulting plants. An explanation for this result is not forthcoming, and in fact contradicts some of the existing literature on the use of biochar.[8-11] Perhaps further investigation into and replication of the procedures used here will yield valuable data on the production of positive-benefit standalone plant-feedstock biochar, and transform our presently held understanding about its use.

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Glossary

Biochar: black carbon produced for agricultural use.[1-11, 17-18]

Carbon sequestration: the act of removing carbon-containing compounds from the atmosphere by adding them to the carbon sink.[1-3, 8-11]

Combustion: an exothermic reaction wherein a substance is combined with oxygen.[17-18]

Feedstock: a carbonaceous substance that can be pyrolysed to produce biochar.[1-11, 17-18]

Greenwaste: an organic fertilizer derived from decomposed herbaceous plant materials.[10, 15]

Leach: to drain a soluble substance from its substrate.[5, 8]

Pyroligneous acid: a collection of condensed vapours produced through pyrolysis or similar thermochemical processes.[17-18]

Pyrolysis: the thermochemical process by which a substance is broken down by heat in the absence of oxygen.[1-11, 17-18]

Recalcitrance: the measure of chemical stability and resistance to degradation.[1, 3-4]

Urea: a common nitrogenous compound that is often used as a fertilizer.[10, 16]