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Utilization of Biochar to Accelerate Aerobic Decomposition and Increase Compost Quality in the Presence of Plastic and Microplastic Pollutants

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Abstract

Plastic and microplastic (MP) pollution poses a threat to biological systems worldwide, with high concentrations of plastic ending up in organic agricultural waste due to transportation and collection methods. Composting, a common method for managing organic waste but relying on the proliferation and growth of living organisms, is negatively affected by MPs, limiting its usefulness as a sustainable waste management strategy. This study aimed to investigate the effect that biochar, a biologically-inaccessible form of carbon, had on plastic and MP contaminated cow and horse manure compost. Biochar exhibits beneficial characteristics in composting applications due to its very high surface area to volume ratio and porosity, as well as providing a structure for the proliferation of bacteria and fungi. The experiment investigated two hardwood biochar concentrations of 10% (BC-10) and 20% (BC-20) by dry weight. High density polyethylene plastics (~26%) and microplastics (~74%) were added to each experiment group at a concentration of 0.5% by dry weight. The results demonstrated an increase in pile porosity and aeration in biochar-amended groups, as well as a significant decrease in phytotoxicity ($p < 0.05$) and decreased microbial density. Additionally, the plastic-contaminated group (PC) without biochar demonstrated a significant decrease in pH as compared to plastic-contaminated biochar groups, indicating a successful mitigation of the plastics. Humic acid concentration was also analyzed, demonstrating an increase in BC-20 even with the presence of plastics. These results indicate that biochar may be a promising tool in the mitigation of plastic pollution, especially in large-scale composting operations.

Introduction

Plastic and microplastic (MP) pollution and its effects on environmental and human health are of significant global concern in recent years. Though numerous past studies have focused on plastics in aquatic and animal environments, MP pollution on land especially has garnered increased attention, with publications on MP pollution in soil systems steadily rising in the past seven years (He et al., 2020). Due to their small particle size, large surface area, and hydrophobicity, MPs are effective at adsorbing pollutants, and can contain harmful substances from manufacturing (plasticizers, flame retardants, etc.). As a result, MPs may cause a plethora of health effects in humans and animals such as inflammation and precocious puberty, as well as altering nutrient cycling, enzyme activity, and niches in soil and compost microorganisms (Zhou et al., 2020, He et al., 2020). As the ubiquity of plastics and MPs rises, the need to develop sustainable and effective strategies to mitigate their impact both on humans and agriculture has become a vital step in maintaining the future health of our planet.

Composting has long been recognized as an ecologically superior alternative to landfill disposal, particularly due to its minimal methane emissions attributed to aerobic decomposition (Lou and Nair, 2009). Increasing presence of MPs have been found in compost, largely introduced through the use of plastic bags for waste collection, unsuitable sorting and removal before composting, and from the composting of manure and sewage which has been found to contain high amounts of plastics and other pollutants (Bläsig and Amelung, 2018). In addition, larger plastics are often broken down by industrial composting into MPs (Ng et al., 2018). MPs not only compromise compost quality as a soil amendment but can also negatively affect the composting processes and final compost quality (Song et al., 2022). Overall, this growing amount of plastic in compost greatly limits the feasibility of large scale composting operations and impedes the positive impacts of compost as a soil amendment, especially as compost now stands as one of the largest sources of MPs on farms and fields (Bläsig and Amelung, 2018). Concerns of growing waste as well as the modern ubiquity of MPs demonstrates the necessity of developing strategies that not only improve compost quality but also alleviate the MPs burden in the environment.

The utilization of biochar, a form of stable carbon generated from the pyrolysis of organic biomatter, holds promise as a solution not only for reducing the amount of carbon released by organic materials into the atmosphere but also improving soils and composts. Biochar's potential to serve as a valuable compost amendment is well-documented, exhibiting various benefits such as enhanced water retention, microbial proliferation, nutrient availability, and compost acceleration (Xiao et al., 2017). Furthermore, biochar has shown remarkable efficacy in absorbing pollutants, including those commonly found on MPs , thereby limiting their toxicity and mitigating their ecological impacts (Valizadeh et al., 2021).

This study aims to bridge these two critical objectives: enhancing compost quality and mitigating pollution caused by MPs. Previous studies have shown an increase in enzyme activity and subsequent oxidation and breakdown of organic matter with biochar additions (Lv et al., 2022). By utilizing biochar during the composting process in varying concentrations, we evaluated its potential in improving compost quality while simultaneously reducing the impacts of MPs. In this study cow manure and wheat straw were used as composting feedstock, and mature compost was added in addition in order to enhance organic matter degradation and humification (Yang and Zhang, 2022). This research observed the physicochemical properties of compost under the influence of biochar and MPs, including pH, CO_2 levels, ammonia content, and humic acid concentration. In addition, we assessed the germination index, a metric of compost toxicity, to observe the potential of biochar to limit the phytotoxic quality of microplastic contaminated compost. The research will attempt to show that the integration of biochar will not only improve compost quality but also facilitate the absorption of toxins released by MPs, serving as a comprehensive strategy for enhanced composting and microplastic mitigation.

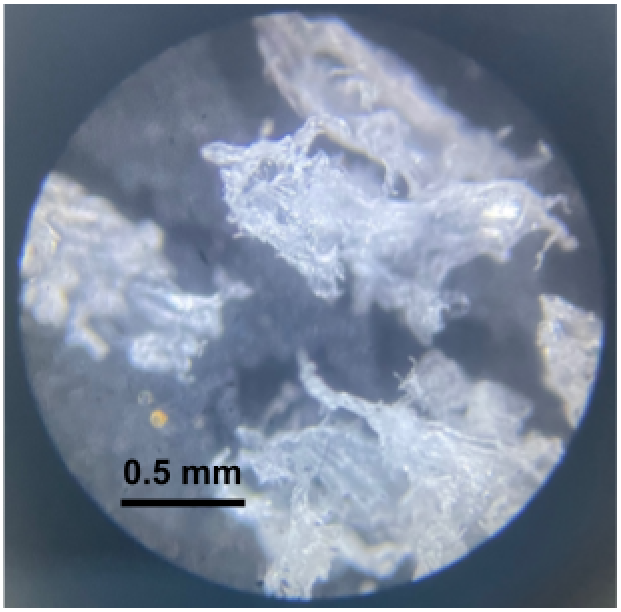
Materials and Methods

Raw materials preparation

Cow manure and wheat straw were gathered from a local farm in Dutchess County, New York. Horse manure was obtained from a stable in New York City, New York. Plastics and microplastics were prepared by the mechanical grinding of a 0.5mm sheet of high density polyethylene (PE), and were then sieved to determine the size composition of the resulting particles, with a final composition of 26.1% > 5mm (macroplastics), 17.9% > 1mm, and 56% < 1mm (fig. 1). Hardwood biochar was purchased from Seneca Farms Biochar in Schuyler County, New York. The biochar was pyrolyzed at a temperature of 950 °F and its pH was initially measured at 9.01. The biochar exhibited a surface area of 304 m^2/g, representing a moderate surface area to volume ratio which is appropriate for composting applications due to its water holding and aerating abilities (Huerta and Pliatsika, 2022).

Figure 1

Macro photograph of mid-sized PE microplastics used in the experiment

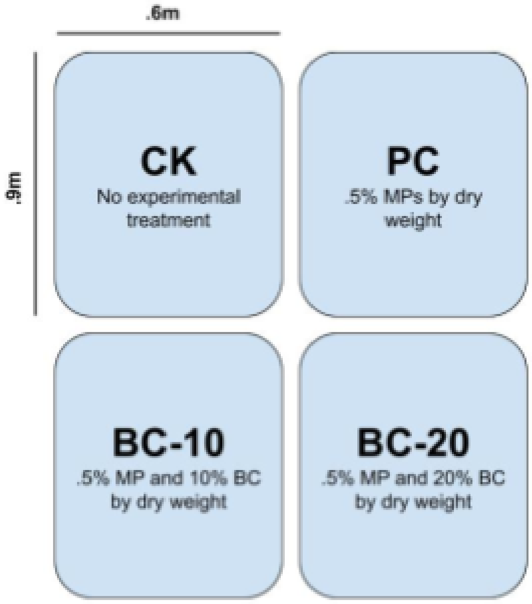


Experimental Setup

Cow manure, horse manure, and wheat straw were weighed and manually turned to create an initial C/N ratio of ~25:1. The initial moisture content of all experimental groups was measured to be ~65%. Mature commercially-available cow manure-based compost with a moisture content of 15% was added at 10% by wet weight of combined feedstock to all groups. After mixing, feedstock was split into four groups and four composting bins (0.9m x 0.6m x 0.6m) were designed and built from untreated cedar wood to hold the compost. PE plastics and MPs were mixed and added to three of the groups at 0.5% of the dry weight of the feedstock, leaving one as a negative control (CK). Biochar was added to two groups at 10% and 20% weight, noted as BC-10 and BC-20 respectively, leaving a positive control with plastics and no biochar, noted as PC (fig. 2). All compost groups were manually turned to incorporate treatments and then again every three days to ensure proper aeration and aerobic decomposition. Groups were left to compost for 58 days, during which compost temperature was measured and recorded every day with a Thermapen digital thermometer by averaging two sites in the center of each pile. Ambient temperature was recorded using the same thermometer outside of the composting bins. On day 25 additional wheat straw was added to each group at 5% of wet weight to correct for high nitrogen content, however this was likely unnecessary due to high levels of nitrogen loss within the first two weeks of experimentation.

Figure 2

Set-up of composting bins



Note. CK as a negative control with no treatments added; PC as a positive control with only plastics and MPs added; BC-10 as an experimental group with plastics and 10% biochar; and BC-20 as a second experimental group with plastics and 20% biochar

pH Analysis

Compost samples were collected and homogenized from each group on days 0, 1, 7, 15, 23, 30, 37, 45, and 58. Distilled water was added to each sample at a 5:1 water to dry weight ratio. Samples were left in jars for 45 minutes, and were manually agitated every 15 minutes by shaking each jar aggressively with the lids closed. The pH of the resulting solution was measured using a calibrated pH meter from APERA® Instruments.

Germination Index

Compost samples were collected on days 1, 7, 14, 20, 27, 37, 48, and 58. Distilled water was added to each sample at a 10:1 water to dry weight ratio. Samples were left in jars for 45 minutes, being agitated every 15 minutes. Then, 10 ml of the resulting solution was used to wet filter paper. Filter paper was placed inside petri dishes, and 10 cabbage (*Brassica oleracea)* seeds were placed onto the filter paper and left to incubate in the dark for 72 hours at 70°C, with distilled water serving as the control. Cabbage was chosen for its relatively quick germination rate in order to shorten incubation time. The germination index of each sample was determined using the following formula:

$$\mathrm{GI}(\%) = \frac{\mathrm{Seedgermination}(\%) \times \mathrm{rootlengthoftreatment}}{\mathrm{Seedgermination}(\%) \times \mathrm{rootlengthofcontrol}} \times 100\%$$

NH_3 and CO_2 Analysis

Thirty cubic centimeters of fresh compost was collected from each group and placed separately in 8 oz jars after being sieved through a 10mm grate. Solvita® gel probes were then placed in the jars, after which the jars were sealed for four hours. Probes were then removed from the jars, and CO_2 and NH_3 concentrations were gathered from the colorimetric reading from the gel.

Humic Substance Analysis

Compost was collected and dried in a low-temperature dehydrator for 24 hours. Samples were sent to TPS labs, an agricultural laboratory in Hidalgo County, Texas, for humic substance analysis.

Statistical Analysis

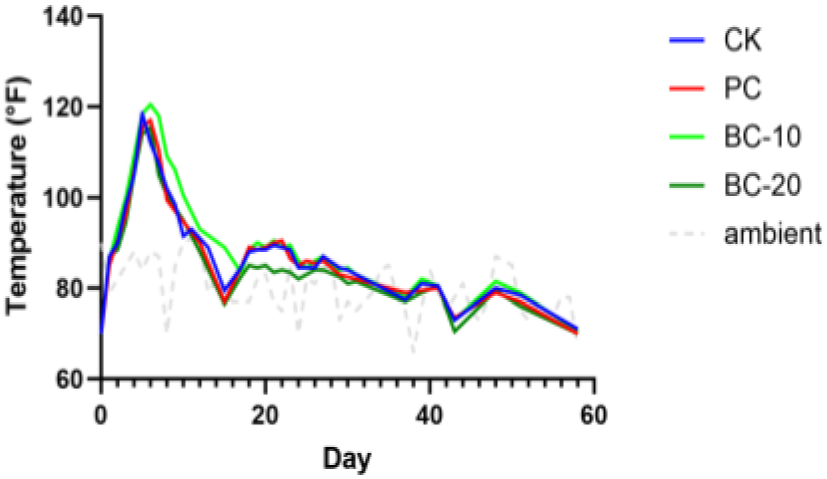
Experimental data were organized in Google Sheets. Data were checked for normality prior to a one-way analysis of variance (ANOVA), to examine significant differences among various treatments and variables, with $p < .05$ representing a significant difference. All statistical analyses were conducted in R Statistical Software (v 4.1.2; R Core Team 2021).

Results

All compost piles exhibited a lower temperature than expected, likely due to the small size of containers along with lack of insulation. Nevertheless, all groups went through mesophilic, thermophilic, cooling, and maturing stages, with CK reaching peak temperatures on day 5 and all other groups reaching peak temperature on day 6. The peak temperature of CK, PC, BC-10, and BC-20 was 118.5 °F, 117 °F, 120.5 °F, and 115.5 °F respectively (fig. 3). After reaching this peak, the temperature of all groups gradually decreased to ambient temperature, reaching ~78 °F at the conclusion of the experiment. BC-20 exhibited a slightly lower temperature over the entirety of the composting period as compared to other groups, with an average temperature 4.2 °F below CK.

Figure 3

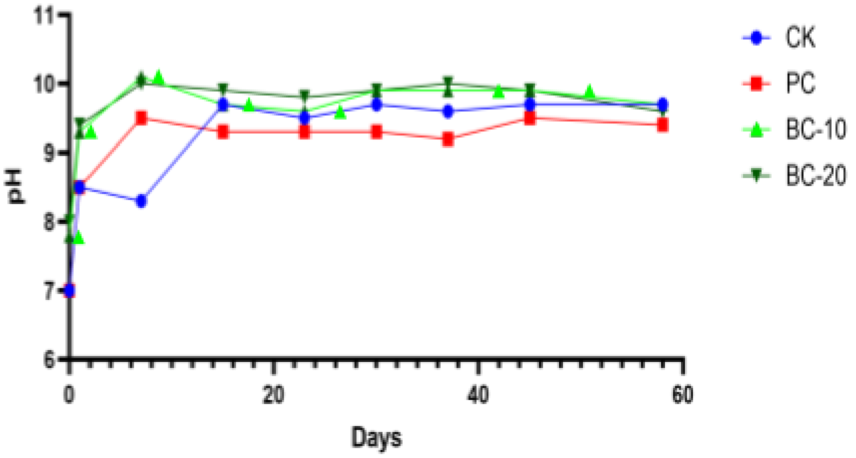
Temperature of all compost groups during experimental period



The pH of each composting group initially spiked, with all groups reaching a pH above 9 on day 15 (fig. 4). All groups maintained this high pH throughout the remainder of composting which very slightly decreased as composting progressed, with CK, PC, BC-10 and BC-20 reaching a final pH of 9.7, 9.4, 9.7, and 9.6, respectively. The pH of PC and CK was significantly lower than the two biochar treatments ($p < 0.05$), however BC-10 and BC-20 were not significantly different from each other.

Figure 4

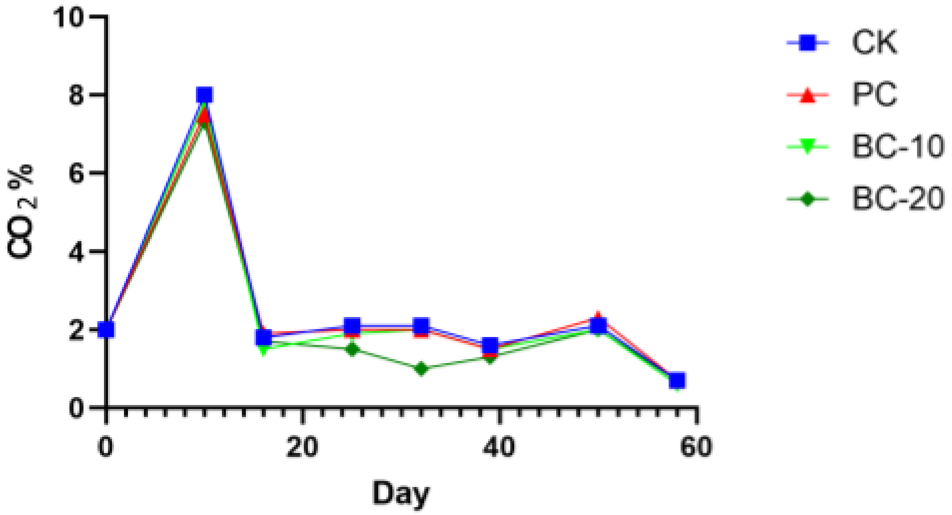
pH of compost during experiment



The ammonia content of each group initially spiked then dramatically decreased after 15 days, leveling out at 20 days after the start of the experiment. Differences in ammonia levels between groups proved insignificant across the experiment. CO_2 levels similarly rose at the beginning of the experiment, with CK, PC, CK-10, and CK-12 reaching a peak of 8.0%, 7.6%, 7.8%, and 7.2% respectively. Though differences in CO_2 levels across all groups in the experiment remained insignificant, CO_2 levels in BC-20 remained consistently lower than other groups (fig. 5).

Figure 5

CO_2 concentrations in compost groups.



Note. CO_2 levels measured as the CO_2 % in the headspace of incubation jars after four hours

The germination index of all groups steadily increased throughout the composting process in all groups, however especially dramatically in BC-10, with the germination index in BC-10 during the first week reaching that of CK after 37 days. Of all physicochemical properties, the germination index demonstrated the most significant difference between treatments ($p < 0.005$), with CK, PC, BC-10, and BC-20 ending with a germination index of 142.9%, 112.5%, 144.6%, and 176.8% respectively (fig. 6). Compared with PC, the germination index of BC-10 and BC-20 were increased by 32.1% and 64.3% respectively. Although they ended with an increased germination index, both biochar treatments demonstrated inconsistent upward trends as compared to CK and PC, most notably a dip in BC-20 of 47.7% on day 37.

Figure 6

Changes in germination index during experiment

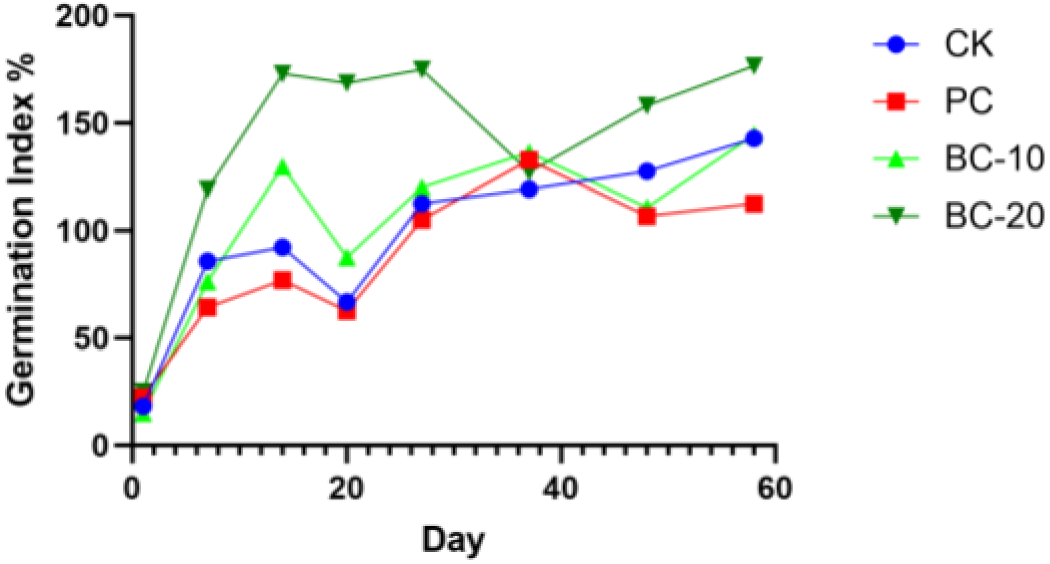
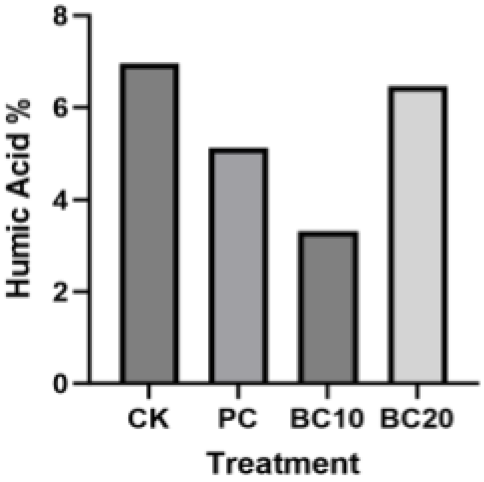


Figure 7 shows humic acid levels measured at the end of the experiment in all composting groups. CK, PC, BC-10 and BC-20 exhibited a final humic acid content of 6.96%, 5.14%, 3.32%, and 6.47% respectively.

Figure 7

Final humic acid content of composting groups at the end of experimentation by dry weight of compost



Discussion and Conclusions

Overall, the temperature of all four treatments demonstrated a progression typical of aerobic composting, albeit with lower temperatures caused by limited pile size. Thermophilic temperatures in the BC-10 treatment were sustained for slightly longer as compared to other groups, indicating increased decomposition rates and proliferation of thermophiles which prefer temperatures between 105-140°F and facilitate rapid degradation of organic matter (University of Florida). This slight increase in temperature was consistent with other publications on biochar amendments to compost over the past 15 years, likely caused by increased porosity and airflow created by the addition of biochar (Xioa et al., 2020). As composting continued, the temperature discrepancies between groups lessened due to the lower aerobic need of more mature compost as well as the saturation of biochar by organic material, decreasing porosity and airflow.

No significant changes in composting temperature were caused by the addition of plastics, consistent with findings by Song et al. in 2022. PC did exhibit a slightly prolonged thermophilic period as compared to CK, possibly due to the plastic's ability to increase porosity and stimulate airflow within the compost pile (Song et al., 2022). Though airflow is vital to the process of aerobic composting, high levels of porosity and airflow may cause excess heat loss and a drop in temperature (Song et al., 2022), a phenomenon which was observed in BC-20. A 20% biochar treatment by dry weight is, compared to previous studies, much greater than typical biochar applications which range from 5-10% (Xiao et al., 2017). As a result, BC-20 exhibited a very high porosity and airflow which led to substantial heat loss, indicated by a consistently lower temperature in the thermophilic and cooling stages of the composting. Additionally, a high ratio of biologically unavailable biochar to organic matter may have effectively diluted the compost, leading to a lower pile density and concentration of microorganisms, causing lower temperatures (Liu et al., 2017).

The pH of compost is crucial to understanding the health and functionality of the composting process, having been shown to affect bacterial activity, diversity, and bioavailability of organic carbon (Sheng and Zhu, 2018; Zhu et al., 2017). In this experiment, pH levels in all compost groups except CK initially rose within the first week and stayed above 9.0 for the duration of the composting period, outside of the range for optimal composting (Moubareck et al., 2023). This may have been due to an initial excess in ammonia which, when being metabolized into ammonia, took up H^+ ions and decreased the pH. Generally, a decrease in pH can be attributed to the creation of organic acids as byproducts of microorganism growth and increases in pH are caused by release of ammonia and breakdown of organic acids (Wang et al., 2022). It is unclear why CK was the only group to drop in pH within the first week, especially due to its sharp rise after the initial drop. It is possible that plastics particles added had a slight negative charge, which, combined with their high surface area, adsorbed H^+ ions, leading to a more alkaline compost initially. After the first week however, the pH of PC proved to consistently be the lowest out of all groups, consistent with findings by Song et al. in 2022, who found a significant decrease in pH in polypropylene microplastic contaminated cow manure compost. It is possible the addition of plastics shifted the structure of bacterial and fungal communities, causing an increase in the amount of nitrifying organisms which may have contributed to a decrease in pH (Deng et al., 2021). Overall, the significant rise in pH in biochar treatments can be attributed to the alkaline nature of the biochar itself, which has been shown to increase pH of compost in many applications (Xiao et al., 2017). Both biochar groups effectively mitigated the decrease in pH caused by plastic contamination, even increasing pH higher than

CK. Although containing twice the amount of biochar, the pH of BC-10 did not exhibit a large increase in pH during experimentation, and even ended with a lower overall pH, suggesting a relationship between high biochar concentrations and organic acid formation in later phases of composting. Further research is needed to determine relationships between pH changes due to biochar additions and plastic contamination, as well as the mechanisms that drive pH changes due to the addition of plastics.

The germination index of compost has been widely recognized as an indicator of compost maturity and phytotoxicity, representing an indirect way to measure changes in the composting process as well as final compost quality (Oktiawan et al., 2018). The GI of all groups initially rose and then leveled off, caused by the initial high ammonia content and organic acid content of the initial feedstock which was later volatilized or formed into NH_4^+, leading to an eventual increase in GI. When the GI of compost reached and maintained a value of over 80%, it was considered mature (Huang et al., 2004). All groups reached maturity quite quickly and exhibited high GI values despite relatively low temperatures in composting, which typically indicate slower breakdown of phytotoxic compounds and decreased humification. This rapid increase was likely due to the rapid volatilization of ammonia caused by poor initial aeration and excess moisture in composting groups, which would have caused a lower nitrogen content and decreased risk of excess nitrogen inhibiting germination rates (Zhang et al., 2020). This explanation is also supported by the fact that ammonia levels in all groups plummeted only a week after the initiation of the experiment. Overall however, the GI exhibited a typical upward trend in all groups. The ending GI value of CK was ~20% higher than that of PC, similar to results found by Song. et al. in 2022. Although also containing the same amount of plastics, BC-10 and BC-20 both demonstrated a higher ending GI compared to CK, indicating a positive remediation of the plastic pollutants. It is unclear, however, how much of this positive effect was due to the general positive effects of biochar in composting applications or its ability to absorb and mitigate harmful molecules released by plastic pollutants (Zhou et al., 2023; Valizadeh et al., 2021; Chen et al., 2010). Further research is necessary to better understand the interactions between biochar and plastics both interacting with each other and when co-composted.

CO_2 emissions are considered a good indicator of microbial activity and oxygen consumption in compost and soil systems, as well as a measure of organic carbon loss during the composting process (Alarefee et al., 2023). The CO_2 levels of all groups initially rose during the thermophilic period to around the same level, and no significant difference was found among CO_2 levels overall ($p > 0.05$). However, both biochar treatments exhibited slightly lower and more inconsistent CO_2 levels throughout composting, indicating a potentially lower microbial density in BC-10 and BC-20 caused by the biologically unavailable biochar causing a decrease in the number of microbes per volume of compost (Li et al., 2023). The lower CO_2 levels in BC-20 especially were consistent with the observed decrease in temperature and porosity, with a decreased temperature indicating lower bacterial activity, in turn indicating a decreased need for oxygen consumption, therefore creating fewer CO_2 emissions. Since CO_2 levels were determined with a CO_2 to volume ratio without taking the mass of the compost into account, we hypothesize that the lower pile density of BC-10 and BC-20 may have negatively skewed results. Ultimately, further testing is required to determine if the addition of biochar and plastics resulted in higher or lower microbial activity and biomass.

Previous studies have shown a decrease in humic acid concentrations with the addition of plastics in composting systems, indicating lowered humification and possibly lower quality compost (Song et al., 2022). This effect was observed in PC, with humic acid concentrations lowered by 1.82% as compared to CK, indicating a lower quality compost caused by plastic contamination. Interestingly, although the humic acid percent of BC-20 was nearly as high as the control, the concentration exhibited in BC-10 was lower than PC. Generally, high humic acid concentrations indicate the conversion of humus precursors and fulvic acid to humic acid as well as increased compost maturity levels (Xi et al., 2020; Zhou et al., 2022). Plastic and MP contamination may limit the activity of bacterial communities responsible for such a conversion, limiting overall compost maturity (Song et al., 2022). The application of 20% biochar seemed to mitigate the effect of plastic contamination, possibly providing habitat for bacterial growth and shifting microorganism communities to produce larger humic acid concentrations. On the other hand, the decrease in humic acid concentrations in BC-10 seemed to do the opposite, exacerbating the effect of plastic contamination in the compost. This discrepancy between biochar amended groups may be due to errors in sampling and homogenization of BC-10 samples, or due to a non-linear relationship between biochar additions and humic acid concentrations. Further research is needed to re-examine shifts in humic acid during the co-composting of biochar and plastics, as well as the interactions between biochar and humic acid-producing microorganisms in order to explain the anomalous findings presented in this experiment.

In this experiment, we aimed to explore the abilities of hardwood biochar to mitigate the negative effects of plastic contamination in horse and cow manure compost. Among all treatments, BC-20 presented the largest decrease in phytotoxicity and decrease in temperature and CO_2 emissions, indicating a lessened microbial density and greater porosity. Expectedly, both biochar treatments significantly increased pH, mitigating the effect of lowered pH from plastic contamination. These results support the application of biochar in commercial composting, especially in applications where temperature can be more easily controlled and porosity/aeration is of higher importance, such as in industrial sized composting facilities. The composting cycle presented in this experiment was irregular in all groups with low temperatures and rapid nitrogen loss due to poor initial aeration and small composting piles. Future research is needed to understand the physical interactions between biochar and small microplastic particles as well as the interactions between pollutant-oxidizing enzymes (such as polyphenol oxidase and peroxidase (Lv et al., 2022)) and biochar which may lead to an increase in plastic degradation.

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