Research Article

Optimizing Biochar Dosage to Improve Physicochemical Properties of Buffalo Dung Compost for Sustainable Agriculture

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Abstract | This study investigates the impact of different biochar addition rates on the quality of buffalo dung compost to identify the optimal level for improving soil fertility and nutrient retention, which is important for sustainable agriculture. Biochar was produced through pyrolysis by heating 100 grams of oven dried biomass in a reactor at 600°C for one hour. After cooling, the resulting biochar was stored in sealed plastic containers. Buffalo dung was collected from a dairy farm and packed in plastic bags. Composting involved mixing ground biochar into the dung at three different rates: 20 grams, 40 grams (reference), and 60 grams per kilogram of dung. The mixtures were placed in mechanical bioreactor vessels, with moisture levels maintained between 40 percent and 60 percent throughout the process. Compost properties, including pH, total nitrogen, potassium, phosphorus, and organic carbon, were analyzed using standard laboratory methods. Analyses revealed notable variations in compost properties. The pH increased from a minimum of 8.7 to a maximum of 9 with increasing biochar doses. Total nitrogen exhibited a range from 1.52% to 1.8%, while potassium levels ranged from 2% to 2.51%. Phosphorus content varied from 1.6% to 1.95%. Notably, organic carbon content ranged from a minimum of 60% to a maximum of 73%. The study reveals that adding biochar to buffalo dung compost improves its chemical composition and nutrient content, leading to higher pH levels, nutrient levels, and organic carbon content. The biochar ratio increased from 20g to 60g, resulting in higher total nitrogen levels and organic carbon percentage. The study suggests the optimizing biochar ratios to improve buffalo dung compost quality and recommends further research to explore its potential for sustainable farming.

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Introduction

Composting is a sustainable method for reducing organic waste and producing nutrient-rich soil amendments (Sharma *et al*., 2019). Though compost is primarily used as a soil conditioner due to its high organic matter content (90–95%), it generally contains lower concentrations of nitrogen, phosphorus, and potassium compared to chemical fertilizers (Goldan *et al*., 2023). It also serves as an effective strategy for managing municipal solid waste by reducing landfill burden by up to 30% and converting organic matter into a stable, less odorous product (Hamid *et al*., 2019; Vaverkova *et al*., 2014). Various organic residues such as manures, crop wastes, and bedding materials are commonly used in compost production, where factors like moisture, aeration, and layering significantly influence microbial activity and composting efficiency (Meena *et al*., 2022).

Recent research has increasingly explored the role of biochar a carbon-rich byproduct of pyrolysis in enhancing composting processes. Biochar's porous structure supports microbial colonization, enhances nutrient retention, and speeds up organic matter decomposition (Vandecasteele *et al*., 2016; Chen *et al*., 2017). It also improves soil water retention, aeration, and carbon sequestration while enhancing humus formation and plant growth (Sohi *et al*., 2010; Liang *et al*., 2006; Castaldi *et al*., 2011). Despite these benefits, biochar alone may release nutrients slowly due to its refractory nature particularly if derived from low-nutrient feedstocks at high pyrolysis temperatures (Al-Wabel *et al*., 2013; Borchard *et al*., 2012). To overcome this, co-composting biochar with organic materials like manure or crop residues has proven effective in improving nutrient availability (Schulz *et al*., 2013; Roberts *et al*., 2007; Jouquet *et al*., 2010).

Combined applications of compost and biochar have shown promise in enhancing soil fertility, particularly under stress conditions like salinity, by improving nitrogen uptake, enzyme activity, and plant growth (Liu *et al*., 2021). However, their synergistic effects depend heavily on biochar properties, pyrolysis conditions, and compost composition. For example, compost from maize residues had pH 8.22 and contained 240 g/kg organic carbon, whereas maize-derived biochar had higher pH (11.0), organic carbon (520 g/kg), and notable NPK levels (Liu *et al*., 2021). Studies report that biochar additions of 40–50% (w/w) significantly enhance compost quality and nutrient availability (Schulz *et al*., 2013).

Nevertheless, more targeted research is needed to assess the effect of varying biochar ratios on compost derived from specific feedstocks, such as buffalo dung. This study aims to address that gap by evaluating how different biochar application rates influence key compost parameters, including pH, nutrient content, and organic carbon levels.

Materials and Methods

Biochar preparation

The biochar was prepared through the pyrolysis process. The 100g of oven dried biomass was put into the pyrolysis reactor. The reactor was tightly closed with nuts and bolts. The reactor was placed in the electric furnace at the 600 °C for one hour under oxygen-limited atmosphere. After one hour, the furnace was shut off and allowed to cool down at room temperature. The reactor was opened, and the biochar was collected and tightly packed in the plastic jar (Bhatt *et al*., 2023).

Composting process

The composting treatments were based on different rates of biochar mixed with buffalo dung. The buffalo dung used for compost preparation was collected from the dairy farm of Sindh Agriculture University, Tando Jam. The dung was weighed and mixed with ground biochar at four treatment levels: T1 = 0 g, T2 = 20 g, T3 = 40 g, and T4 = 60 g of biochar per kg of dung. Each treatment was thoroughly mixed and placed in separate vessels of a mechanical bioreactor. Moisture content was maintained between 40% to 60% throughout the composting process. All treatments were replicated three times.

Testing of compost quality

Total Kjeldahl Nitrogen (TKN): One gramme of oven-dried compost and 12.5 millilitres of concentrated sulphuric acid (H_2SO_4) were combined to calculate the total nitrogen of the produced compost. After being put in sample tubes, the mixture was heated to 350°C to 400°C for 30 minutes in a block digester. 50 cc of distilled water was added to chill the sample once it had finished digesting. After adding eight to ten drops of Tashiro indicator, the samples were put in the Kjeltec distillation apparatus and allowed to distil for seven minutes. Seven to eight millilitres of distillate per minute were produced by adjusting the steam. A 0.1 N hydrochloric acid titration was performed on the material. After that, a formula was used to determine nitrogen concentration.

$$\text{Nitrogen (\%)} = \frac{\text{R-3} \times \text{Normality of Acid} \times \text{Factor}}{\text{Sample taken}}$$

Phosphorus (P) and Potassium (K)

The basic acid digestion method was used to measure the compost's total potassium and phosphorus content. To begin the digestion process, 0.5 g of the oven-dried sample was combined with two distinct acids nitric acid and perchloric acid in varying quantities of 70 ml and 15 ml, respectively. After that, the sample tubes were submerged in a water bath to aid in digestion. Orange-brown fumes were first produced, and as the digestive process went on, thick white odours eventually emerged. The tubes were taken out of the water bath to chill when they had finished digesting. Each sample received two to three milliliters of distilled water before being filtered straight into 50 milliliters volumetric flasks. Distilled water was used to bring the flasks up to capacity. A second 50 ml volumetric flask was then filled with 10 ml of the diluted sample and 10 ml of the color development reagent (CDR), and the mixture was brought to volume with further distilled water. A spectrophotometer was then used to measure the amount of phosphorus in the sample after a quantity had been placed into the cuvette. A flame photometer was used to measure the potassium concentration of the same sample.

$$\text{Concentration \%} = \frac{\text{Spectrophotometer reading} \times \text{Dilution factor}}{10000}$$

Organic carbon

Following the weighing of a 200 mg sample of the dried compost into a 300 ml Erlenmeyer flask, 200 ml of a 0.22 mol/l hydrochloric acid solution (C.4.3) was added. The sample quantity might be raised to a maximum of 2000 mg if the majority of the material was carbonates (such as limestone). The solid's volume portion was seen as insignificant in both situations. As a result, 200 ml was the suspension's volume. A high-velocity homogeniser (precise tool!) was then used to homogenise the whole sample volume over the course of three minutes at rotation speeds ranging from 17,000 to 18,000 min^{-1}, producing a suspension. Following an inert gas purge, the suspension's non-purgeable organic carbon (NPOC) and total organic carbon (TOC) were estimated using the original solid sample as a reference. This was done by taking the mean value from at least four single injections. Before sampling and during purging, the suspension was agitated. The formula was used to determine the mass percentage of organic carbon in the solid sample.

$$\text{TOC} = \frac{\text{Vsus} \times i \times 100}{\text{ms} \times f}$$

Where; TOC= Organic carbon in the solid samples expressed in the percentage (%) mass fraction; i= Instrument-specific measuring value; Vsus=Volume of the suspension expressed in liters (l); ms= Mass of the solid samples expressed in milligrams (mg); f=Calibration factor expressed in liters per milligram (mg).

C:N ratio

The total carbon and nitrogen contents were measured using a CHN analyzer. The C:N ratio was calculated by dividing the total carbon content by the total nitrogen content.

pH and ash content

A pH meter was used to measure the pH of a 1:5 (volume fraction) manure suspension in a 0.01 mol/L calcium chloride solution (pH in $CaCl_2$). Using a reciprocating shaker set to 100 RPM, the sample was shaken for an hour. A glass electrode pH meter with great precision was then used to test the pH. Ash content was determined by combusting a known weight of dried compost sample in a muffle furnace at 550 °C for 4 hours and calculating the residual inorganic matter percentage.

Statistical analysis

The study employed a one-way analysis of variance (ANOVA) to assess the effect of different biochar mixing ratios on the properties of compost derived from buffalo manure. The significance level (α) was set at 0.05. In cases where a significant difference was observed, Tukey's test was conducted for comparisons.

Results

Duration of the compost

Figure 1 shows that the effect of varying biochar additions (0g, 20g, 40g, and 60g per kg) on the duration of the composting process. The results demonstrate that biochar significantly accelerates the decomposition of organic matter. In the control treatment (0g biochar), the composting process required the longest duration, taking 10 weeks to reach maturity. However, with the addition of 20g/kg biochar, the composting duration decreased to 9 weeks. Further increasing the biochar quantity to 40g and 60g per kg reduced the composting period to 8 and 7 weeks, respectively. This trend indicates a direct relationship between biochar dosage and composting efficiency. ANOVA revealed highly significant

(P<0.001) differences in composting duration among treatments. The low coefficient of variation indicates minimal variability, confirming that biochar addition significantly accelerates the composting process, with higher dosages leading to shorter composting times.

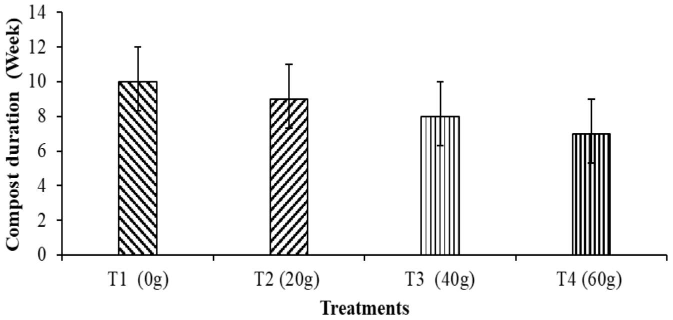

Figure 1: *Effect of biochar addition on composting process. Error bars show the SD (n = 3).*

Yield of compost

Figure 2 shows the effect of biochar addition on the compost yield. The results indicate that incorporating biochar into the composting process enhances the overall yield, with a consistent increase observed as the biochar dosage rises. In the control treatment (0g/kg biochar), the compost yield was 62%. When 20g/kg biochar was added, the yield improved to 68%. Further increases in biochar application, at 40g and 60g per kg, resulted in compost yields of 72% and 75%, respectively. Biochar improves composting by stabilizing organic matter, reducing carbon and nitrogen losses, and retaining nutrients, making it an effective composting additive. Its potential benefits extend to soil fertility and crop productivity. ANOVA confirms a significant (P< <0.001) effect of biochar on compost yield. The moderate CV 20.17% and low error variance ensure result reliability, reinforcing biochar's role in enhancing yield.

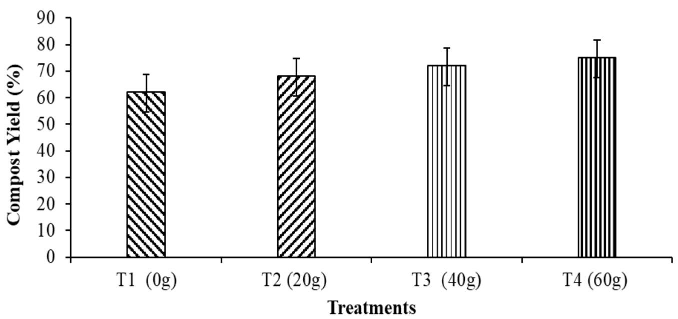

Figure 2: *Effect of biochar addition on yield of compost. Error bars show the SD (n = 3).*

pH of compost

Figure 3 shows that the impact of wood biochar, compost without biochar, and varying rates of biochar on the quality of buffalo dung compost revealed notable changes in pH levels across different ratios. Wood biochar has the highest pH (9.2), indicating strong alkalinity. Compost without biochar has a lower pH of 8.2 but is still alkaline. Adding biochar to compost increases its pH in a dose-dependent manner. With 20g/kg of biochar, the pH rises to 8.7, then to 8.9 with 40g/kg, and 9.0 with 60g/kg, nearing the pH of pure biochar. As the quantity of biochar increased within the compost mixture, there was a discernible rise in pH levels. The differences observed were statistically significant (P< 0.05), indicating that the increasing biochar ratio had a meaningful effect on the pH levels of the compost.

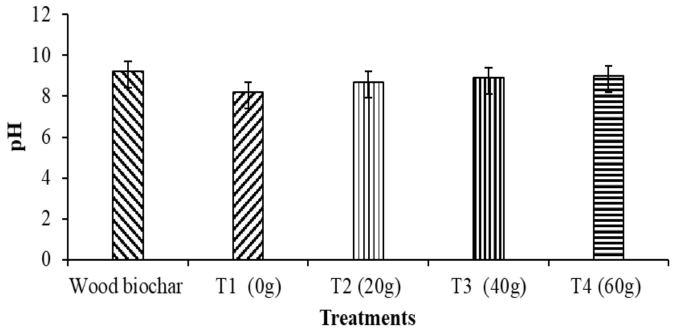

Figure 3: *pH of compost under different biochar ratios. Error bars show the SD (n = 3).*

Total nitrogen, potassium, and phosphorus of compost

Figure 4A-C illustrate the effects of different biochar application rates on the total nitrogen, potassium, and phosphorus contents (%) in wood biochar, compost without biochar, and compost enriched with various biochar ratios during buffalo dung compost production. Wood biochar consistently exhibited the highest nutrient concentrations, with total nitrogen at 2%, potassium at 2.8%, and phosphorus at 2.1%. In contrast, compost without biochar showed lower nutrient values: 1.4% nitrogen, 1.8% potassium, and 1.4% phosphorus. The incorporation of biochar into compost led to incremental increases in all three nutrient levels, indicating its potential to enhance compost quality and soil fertility. At a biochar application rate of 20 g/kg, total nitrogen, potassium, and phosphorus contents were 1.52%, 2.0%, and 1.6%, respectively. Increasing the rate to 40 g/kg further elevated the nutrient levels to 1.6% nitrogen, 2.3% potassium, and 1.75% phosphorus. At the highest rate of 60 g/kg, total nitrogen reached 1.8%, potassium 2.51%, and phosphorus 1.95%. These differences across treatments were statistically significant (P <

0.05), demonstrating that increasing biochar rates had a meaningful and positive effect on the nutrient composition of buffalo dung compost.

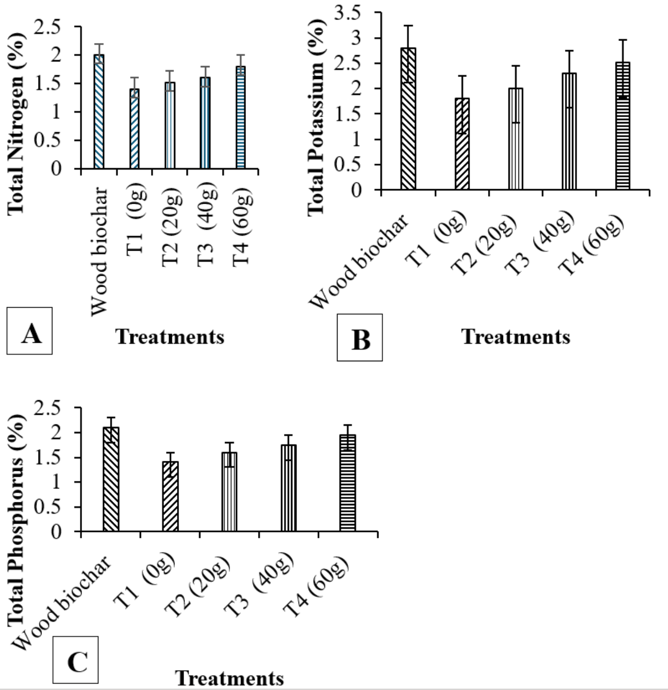

Figure 4: *Total (A) Nitrogen, (B) Potassium and (C) Phosphorus of compost under different biochar ratios. Error bars show the SD (n = 3).*

Organic carbon of compost

Figure 5 shows that the organic carbon content (%) in wood biochar, compost without biochar, and compost enriched with varying biochar ratios on the organic carbon percentage in buffalo dung compost. Wood biochar has the highest organic carbon content at 80%, while compost without biochar contains 55%. Adding biochar to compost increases organic carbon content were observed. At a biochar ratio of 20g/kg, the organic carbon percentage was measured 60%. Increasing the biochar ratio to 40g/kg resulted in a noticeable elevation in organic carbon was recorded at 65%. Subsequently, at the highest biochar ratio of 60g/kg, the organic carbon percentage exhibited a further increase was reported at 73%. The differences in organic carbon percentages across the biochar ratios were statistically significant P< 0.05) confirming that biochar ratios had a significant effect on organic carbon levels.

Carbon nitrogen ratio of compost

Figure 6 shows that the carbon-to-nitrogen C:N ratio (%) in wood biochar, compost without biochar, and compost enriched with different impact of biochar ratios on the buffalo dung compost. Wood biochar has the highest C:N ratio of 41%, while compost without biochar has a lower ratio of 38.5%. The increasing biochar content led to significant changes in the C:N ratio. At 20g/kg biochar ratio, the compost had a C:N ratio of 39.47 %, indicating higher C:N ratio. As the ratio increased to 40g/kg, the C:N ratio increased slightly to 40.63 %, indicating a better balance. At 60g/kg biochar ratio, the C:N ratio slightly decreased to 40.56 %, indicating a stabilization in the relationship. ANOVA confirms a highly significant ($P<0.0001$) effect of biochar on the C:N ratio. The minimal CV (0.07%) ensures reliability, highlighting biochar's role in reducing nitrogen loss and improving carbon stabilization.

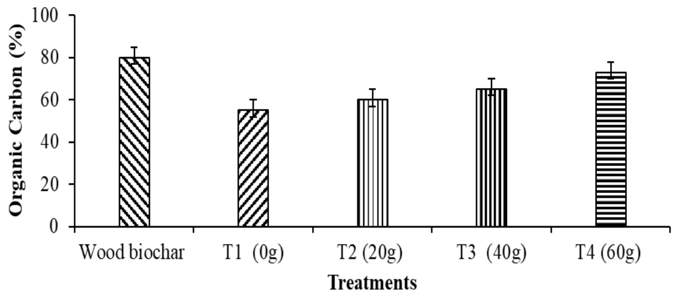

Figure 5: *Organic carbon of compost under different biochar ratios. Error bars show the SD (n = 3).*

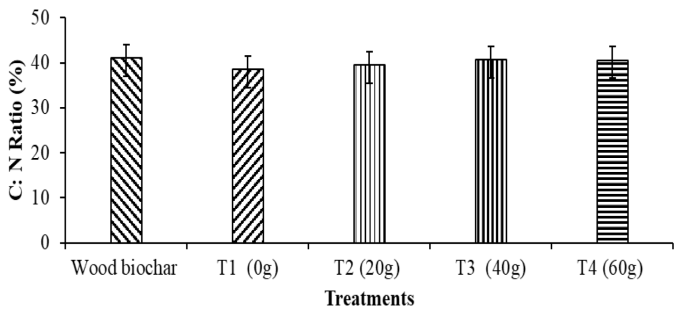

Figure 6: *C:N ratio of compost under different biochar ratios. Error bars show the SD (n = 3).*

Ash content of compost

Figure 7 shows that the ash content (%) in wood biochar, compost without biochar, and compost enriched with varying biochar ratios. Wood biochar shows the highest ash content at 42%, while compost without biochar has a lower ash content of 30%. The addition of biochar to compost increases the ash content was 32% at 20g/kg of biochar. Increasing the biochar ratio to 40g/kg led to a 35% increase, indicating a higher concentration of inorganic minerals. At the highest biochar ratio of 60g/kg, the ash content increased to 38%, indicating that greater biochar additions contribute to an overall increase in the compost's mineral fraction. These results suggest that higher biochar ratios can affect the nutrient availability and structural characteristics of the compost. ANOVA confirms a significant (P<0.0001) effect of biochar on ash content. The low CV 1.18% ensures reliability, indicating biochar enhances the compost's mineral content and potential soil benefits.

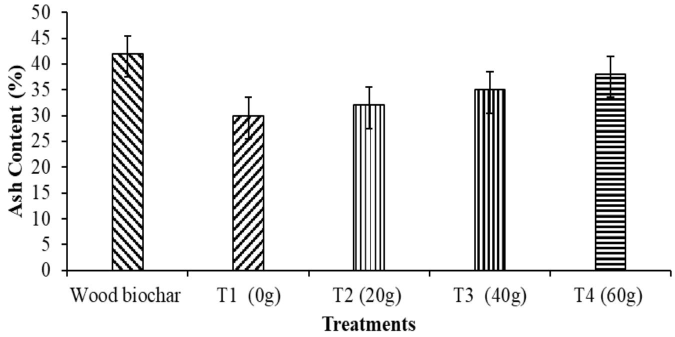

Figure 7: *Ash content of compost under different biochar ratios. Error bars show the SD (n = 3).*

Discussion

Depending on its type, biochar can improve the structure, decrease the bioavailability of contaminants, improve the nutrient status, and increase the efficiency of composting (humification), all of which are known to improve the quality of compost (Godlewska *et al*., 2017; Xiao *et al*., 2017; Guo *et al*., 2020). Therefore, in order to learn more about the process, the addition of biochar to organic waste has been studied in recent years. The impact of different types of biochar on different types of organic waste composts (such as food waste, green waste, non-hazardous wood waste, biowastes, biomass, manures, etc.) and the ideal ratio of biochar additions in relation to the composting process (the impact on organic matter), the availability of heavy metals, and the nutrient status of the compost are of interest (Steiner *et al*., 2011; Godlewska *et al*., 2017; Al-Gheethi *et al*., 2021; Tran *et al*., 2021). The addition of biochar at various stages of the composting process has been studied, and the ratio of biochar addition has typically ranged from 2% to 20% by weight (Xiao *et al*., 2017).

The study revealed that different biochar ratios significantly influenced the physicochemical properties of buffalo dung compost. The pH increased with higher biochar additions, from 8.7 at 20g to 9.0 at 60g, indicating enhanced alkalinity that can affect microbial activity and compost chemistry (Tran *et al*., 2020; Tran *et al*., 2021). Optimal composting typically occurs at pH 6.5–7.5 (Yunus *et al*., 2020; Zainudin *et al*., 2020), but higher pH values can reduce the solubility and toxicity of heavy metals (Li *et al*., 2015). pH shifts may result from ammonification, microbial activity, or CO_2 and fatty acid production during organic matter breakdown (Godlewska *et al*., 2017; Steiner *et al*., 2010). Studies have also shown that biochar can buffer pH through ammonia absorption (He *et al*., 2017), while alkaline biochars used as bulking agents can initially raise compost pH (Dias *et al*., 2010; Vandecasteele *et al*., 2016; Zhang *et al*., 2016; Wong *et al*., 1995; Fang and Wong, 1999).

Nutrient analysis showed biochar positively influenced nitrogen, phosphorus, and potassium content. Total nitrogen increased from 1.52% at 20g to 1.8% at 60g, aligning with findings from Jain *et al*. (2018), who reported enhanced nitrogen retention due to increased organic matter decomposition. Biochar's porosity improves aeration and moisture regulation, facilitating microbial activity and nitrogen conservation (Sánchez-García et al., 2015; Zhang and Sun, 2014). The nitrogen retained is more available for plants, as biochar also immobilizes nitrogen compounds due to its structure (Kastner *et al*., 2009; Steiner *et al*., 2010). Potassium increased from 2.0% to 2.51%, consistent with Khater (2015), Bhattacharyya *et al*. (2007), and Laird *et al*. (2010), who observed potassium enrichment in biochar-amended compost. Nutrient retention is further supported by biochar's surface charge properties (Liang *et al*., 2006). However, losses through leaching and runoff can occur without structural bulking agents like straw or wood chips (Pathak *et al*., 2012; Muhamed and Umer, 2023).

Similarly, phosphorus levels rose from 1.6% to 1.95% as the biochar ratio increased, reinforcing previous findings by Jain *et al*. (2018), Singh and Kalamdhad (2014), and Xu *et al*. (2019), who demonstrated improved P retention in compost with biochar. Phosphorus availability in compost is crucial for microbial metabolism and plant uptake, and bulking agents help reduce phosphorus loss. Biochar amendments also increased concentrations of soluble PO_4, K^+, and Ca^{2+}, enhancing nutrient availability (Zhang *et al*., 2016).

The C:N ratio ranged from 39.47% at 20g to 40.63% at 40g, then slightly decreased to 40.56% at 60g, suggesting a plateau effect. This supports findings by Rahman et al. (2019) and Suliman *et al*. (2018), who noted that moderate biochar additions enhance microbial processes, but excessive amounts may yield diminishing returns. Biochar improves nitrogen retention by creating favorable conditions for nitrifying bacteria (Zhang *et al*., 2014; Wang *et al*., 2015; Cabrera *et al*., 2005; Joy and Kamath, 2017; Nigussie *et al*., 2016).

Organic carbon content also improved, from 60% at 20g to 73% at 60g, likely due to biochar's porous structure that promotes microbial colonization (Khater, 2015; Al-Nawaiseh *et al*., 2021). While TOC levels vary by feedstock, biochar consistently enhances organic carbon retention. Ash content increased with biochar addition from 32% to 38% reflecting the presence of inorganic minerals, which aligns with findings from Sebahire *et al*. (2024), Stacey *et al*. (2021), Matthiessen *et al*. (2005), and Husni and Samsuri (2012), who reported higher ash content with increasing biochar due to accelerated mineralization.

Conclusions and Recommendation

The addition of biochar to buffalo dung compost significantly improved composting efficiency and quality. Composting duration was reduced by up to 30% at the highest biochar application rate (60 g/kg), while compost yield increased by a maximum of 19% at the same rate. As biochar ratios increased, pH levels rose, and concentrations of essential nutrients such as nitrogen, potassium, and phosphorus improved, resulting in higher organic carbon content and better overall compost quality. Total Kjeldahl nitrogen increased from 1.5% to 1.8%, while organic carbon content rose substantially from 60% to 73%. These enhancements suggest that biochar-enriched compost not only accelerates the composting process but also produces a more nutrient-rich product. When applied to soil, such compost can enhance soil structure, fertility, and nutrient retention. Therefore, the use of biochar in composting presents a promising strategy for farmers seeking to improve soil health and support sustainable agricultural practices.

Acknowledgement

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Novelty Statement

This study demonstrated the significant benefits of adding biochar to buffalo dung compost, resulting in a 30% reduction in composting time and a 19% increase in yield. It provides novel insights into how biochar enhances nutrient content (N, P, K), organic carbon, and pH, leading to improved compost quality and greater potential for sustainable soil management.

Author's Contribution

M.S.H.K carried out the experiments under the project which were conceived by the M.L who also supervised the study. While, S.A.B and M.U.M helped in analysis and in preparation of manuscript.

Generative AI and AI-assisted technology statement

After preparing the manuscript, the authors used ChatGPT to reduce similarity and improve the language and readability of the draft. Following the use of this tool, the authors reviewed and edited the content as needed and take full responsibility for the final version of the publication.

Conflict of interest

The authors have declared no conflict of interest.

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