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Synergistic effect of biochar and post-thermophilic stage application of supplemental *Tithonia diversifolia* on compost nutrient dynamics

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Abstract
Composting is a sustainable waste management technique that transforms organic matter into a valuable, soil amendment through processes such as thermophilic decomposition. However, thermophilic composting leads to a loss of important nutrients such as nitrogen by up to 50% in some cases. This is due to low-quality feedstock and loss of labile nutrients caused by high pile temperatures in the early phase of the process. Ultimately, the low quality of compost can potentially reduce soil fertility and crop productivity. We sought to enhance compost quality by biochar addition during heaping and supplemental *Tithonia diversifolia* application during post-thermophilic stages. We did a field setup of four composting treatments; Conventional practice; (Cattle manure + dry maize stalks + *Lantana camara*); L, Biochar compost (Cattle manure + dry maize stalks + *Lantana camara* + Biochar); B, Biochar compost + *Tithonia diversifolia;* post-thermophilic phase *Tithonia diversifolia* supplementation to L (LT) and B (BT). Sampling for physicochemical parameters analysis was done every 21 days over 84 days on each heap. We used assorted functions in the R statistical package (version 4.3.1) to plot the principal component analysis, correlation matrix, and analysis of variance among compost treatments. Total nitrogen exhibited significant positive correlations with all other variables. We also observed significantly higher nutrient levels in biochar-based composts than those without biochar amendment. Supplemental addition of *Tithonia diversifolia* in the post-thermophilic stage significantly increased nitrogen levels (1.59% in BT and 1.32% in LT compared to 1.34% and 1.24% in B and L, respectively). However, this addition led to a rise in pile temperature, prolonging the composting duration. We observed the highest nitrogen and organic carbon levels in BT (1.59% and 24.9%, respectively) at the end of the composting process. Our study recommends applying nutrient-boosting materials such as *Tithonia diversifolia*, in the post-thermophilic stage to minimize nutrient losses during composting.

Keywords Organic amendment · Humus · Nutrient loss · Decomposition · Cattle manure · Co-composting

1 Introduction

The incorporation of compost into soils improves fertility through build-up of organic matter and nutrients while supporting the development of a robust soil microbial community [1, 2]. However, previous studies have shown that compost is sometimes deficient in soil nutrients, crucial for plant growth [3–5]. For example, nitrogen loss has been reported in kitchen waste (8.87–39.37%) [6, 7], poultry manure (16–76%) [8, 9] and cattle manure (13.13–50%) [10, 11] composts. These

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deficiencies are often attributed to the imbalanced nutrient composition of feedstock materials and losses during composting. The losses are also attributed to compost management practices [3, 4, 12]. The main routes of losses for phosphorus and potassium are through leaching. On the other hand, carbon is volatilized as carbon dioxide and methane, while nitrogen is mainly lost as ammonia and nitrous oxide [13–16]. Pile conditions such as temperature, moisture, and aeration substantially influence compost quality, with temperature management being the main non-feedstock influencer of nutrient dynamics [17–19]. This positions the temperature-dependent phases of composting as critical pointers to nutrient dynamics. The losses of nutrients, such as nitrogen and carbon are particularly attributable to the thermophilic phase of composting, characterized by high temperatures [18].

The phytochemical composition of feedstock substantially influences compost succession and ultimately compost quality. For example, simple sugars encourage faster microbial decomposition rates compared to the more recalcitrant materials like cellulose and lignin [20–23]. The complex materials also extend the thermophilic phase and immobilization of nutrients in the ecosystem. Breaking the immobilization barrier of this complex matter in the ecosystems necessitates thermal pretreatments such as biochar addition which have a phytochemical configuration allowing mobilization of nutrients and trapping. This therefore contributes to the reduction of nutrient losses [24–26].

Biochar is an inert carbon-rich organic material produced through the pyrolysis of dry matter under oxygen-limited conditions [27–29]. The biochar matrix stabilizes soil nutrients by trapping volatile nutrient forms such as ammonia and carbon dioxide by providing an aromatic carbon framework that supports the formation of functional groups [30–33]. These functional groups include carboxyl, phenolic, and amino moieties that facilitate nutrient retention in the ecosystems [32]. The positive effect of this medium on compost nutrient retention has not been exhaustively studied; for example, the impact of biochar during cattle manure and *Tithonia diversifolia* co-composting. Existing studies on cattle manure co-compositing with biochar have been done on pilot set-ups e.g. rotary tanks [34, 35] with scanty information on full-scale field experiments. Despite their capacity to refine methodologies, laboratory-scale pilot studies have limitations in their viability for practical composting solutions.

Nitrogen, phosphorus, and potassium are among the important nutrients fortified by adding green matter during cattle manure composting. Conventionally, these materials are co-composted with cattle manure and dry matter [11, 36]. However, these green materials decompose faster with *Tithonia diversifolia* being fully broken down in ten to thirty days compared to the more recalcitrant carbon-rich dry matter [37, 38]. This implies that *Tithonia diversifolia* is fast in nutrient release in forms that plants can take up before the compost reaches full maturity. Conversely, dry matter such as maize stalks, bean biomass, and sawdust fully decomposes only after three months. Consequently, yielded nutrients such as nitrogen are possibly lost due to their ready availability, while the composting period persists. The loss is further compounded by the volatility of nutrients during the early thermophilic phase of composting, where elements like nitrogen are lost in labile forms such as nitrous oxide and ammonia. *Tithonia diversifolia* by itself is also capable of elevating pile temperature but the peak temperatures are less prolonged [38]. On the other hand, organic carbon is mainly lost in gaseous form as methane and carbon dioxide [13, 39, 40].

Nutrient losses during composting potentially affect compost quality. While conventional composting methods often lead to substantial losses of crucial soil nutrients, strategies to minimize these losses are needed. Therefore, we investigated the effect of rice husk biochar addition at heaping and post-thermophilic stage *Tithonia diversifolia* application on the succession of compost physicochemical elements, nutrient losses, and product quality. We hypothesized that adding rice husk biochar during heaping and *Tithonia diversifolia* during the post-thermophilic stages would minimize losses and maintain the compost quality.

2 Materials and methods

2.1 Site description and feedstock sourcing

We set up the field study at the Farming Systems Comparison in the Tropics (SysCom) project trial site at Kandara, Kenya (01° 0.231′ S 37° 04.747′ E) [36] between March and June 2022. The site lies at 1518 m a.s.l, in the upper midland 3 (UM3) agro-ecological zone. Moreover, *Lantana camara* and *Tithonia diversifolia* thrive on furrow land and hedges in the area, offering viable soil fertility options for uptake by farmers in the region.

The feedstock materials included rice husk biochar and fresh cattle manure from a zero-grazing dairy unit close to the site. Dry maize stalks were sourced from the project trial plots, while green materials (*Lantana camara* and *Tithonia diversifolia* twigs) were harvested from hedges- and furrow land around the trial site. On the other hand, rice husk biochar was sourced from commercial fields, in Mwea, Kirinyaga County in Kenya, (50 Kilometers from the project site).

Preparation of rice-husk biochar was done by pyrolyzing dry rice husks in a kiln under limited oxygen conditions at temperatures ranging from 300 to 600 °C; for 5 h. This was followed by cooling in open fields, before transportation to the composting site.

2.2 Treatment selection and pile layering

We rationalized treatments (Table 1) based on common farm-yard composting practices in the tropics [11]. Cattle manure is co-composted with dry maize stalks and green matter (*Lantana camara*) with all materials being heaped at day zero (0). The sources of variation were the addition of biochar during heaping and supplemental green matter (*Tithonia diversifolia*) during the cooling phase (at day 63 of composting).

Maize stalks and *Lantana camara* twigs were individually cut into small pieces (3–5 cm long) using machetes for uniformity and enhanced breakdown. Each compost treatment was replicated thrice and set under a composting shade. Heaping was done by layering the materials as per the common practice of farm-yard composting in sub-Saharan Africa [36]. Heaping individual compost piles began by spreading small dry twigs on a flat surface and sprinkling them with water. This was followed by a layer of chopped dry maize stalks and moisture adjustment to about 60%, then, a layer of cow dung manure followed. Finally, we added a layer of *Lantana camara*. Layering was repeated five times for each pile as described above and a thermostick was inserted diagonally for moisture and complementary temperature monitoring. Compost pile aeration was done by turning it every 4 days during the first 20 days; then weekly until 84 days of composting and moisture levels maintained at about 40%. Fresh chopped *Tithonia diversifolia* twigs were added on the 63rd day of composting for the LT and BT treatments. This was done by incorporating the chopped twigs into the heaps through turning.

2.3 Sample collection for physicochemical analysis

Daily monitoring of temperature from each compost pile and ambient temperature was done using a compost thermometer (model: WIKA 110824862-EN 13190). We collected daily temperature data from three random points on each compost pile by inserting the thermometer halfway between the top and bottom of the pile to the maximum probe depth (45 cm) as described by Matheri et al. [11]. This followed a top-down approach at each sampling point, to ensure a representative sample was collected. The samples from the 3 points were then homogenized in a clean bucket before transportation to the laboratories for analysis. Compost samples for the analysis of other physicochemical parameters were collected every 21 days till the end of the 84-day composting period. Compost samples were collected at 21, 42, 63, and 84 days of composting.

2.4 Laboratory analysis of physicochemical parameters of compost

The pH of compost (1:10 w/v waste: water extract), moisture, mass loss, and microbial carbon dioxide respiration during sampling days (mg CO_2 g-1d-1) were determined as described by Adamtey [41]. Total Kjeldahl Nitrogen (TKN), the total organic carbon, and Olsen phosphorus were analyzed from shade-dried samples using the standard methods described by Okalebo et al. [42]. TKN was quantified through acid digestion, distillation, and titration. On the other hand, Olsen phosphorous was extracted using sodium bicarbonate and quantified colorimetrically. Dichromate oxidation and titration based on the Walkley–Black method were the protocols used for organic carbon quantification. Mineral nitrogen was extracted from fresh compost samples using the KCL method and analyzed spectrophotometrically.

2.5 Statistical data management

We conducted statistical data analysis using R software, v 4.3.1 [43]. We log standardized data with the *decostand* function in the *vegan* package [44] to calculate the distributions of physicochemical parameters. This was followed by plotting a distance matrix and visualization in a PCA plot, representing each variable's direction and contribution to the overall variations of the treatments. We also computed a Pearson correlation matrix using the *corrplot* function in the *corrplot package* [45]. The resulting measurements of all the physicochemical parameters were also individually subjected to a

Table 1 Overview of treatments, feedstock composition, and application timing

Treatment	Feedstock materials	Application time	Abbreviation
Conventional practice (Control)	Fresh cattle manure + Dry maize stalks + *Lantana camara* twigs (4:2:1)	Day 0	L
Biochar compost	Conventional practice compost + 25 kg biochar (5 kg for each 5 layers	Day 0	B
Biochar compost + *Tithonia diversifolia*	Biochar compost + *Tithonia diversifolia*	*Tithonia diversifolia* added at 63 days	BT
Conventional practice compost + *Tithonia diversifolia*	Conventional practice compost + *Tithonia diversifolia*	*Tithonia diversifolia* added at 63 days	LT

Biochar was applied in unsieved form (containing uncharred husks) while fresh Tithonia twigs were used. LT and BT treatments were set up using equal feedstock amounts to the L and B treatments and departure/treatments were applied at 63 days of composting normality test using the Shapiro test and homoscedacity using the *(leveneTest())* function in the *car* package. Data that were not normally distributed were log transformed using *log()* function. This was the followed by analysis of variance (ANOVA) under the a*gricolae* package [46]. A post hoc comparison of the compost treatment means was made per composting day for each physicochemical variable, using Tukey's Honestly Significant Difference (HSD). The analysis of the overall significance of treatment and composting duration effects was also tested. Plotting of daily temperature from all the compost treatments over the composting period was done using *ggplot2* (version 3.5.0) and *ggpubr* (version 0.6.0) packages [47].

3 Results

3.1 Succession of pile temperatures in different compost treatments

All compost treatments achieved a temperature peak above 55 °C by the 4th day of composting till the 8th day (Fig. 1). Biochar-based composts (B and BT) consistently recorded higher pile temperatures than L and LT, respectively. There was also a notable spike in pile temperatures in LT and BT treatments at 63rd day of composting (Fig. 1). This is after the post-thermophilic application of *Tithonia diversifolia* to both treatments. We observed notable unique temperature peaks in B and BT, with these treatments recording higher overall pile temperatures than the other treatments. Overall plateauing of pile temperatures of B and L treatments began after 63 days of composting while LT and BT treatments pile temperatures surged. This indicates that the two latter treatments had prolonged maturation periods, due to the supplemental *Tithonia diversifolia* addition (Fig. 1).

3.2 Contribution of physicochemical parameters to differences in composts

Principal Component 1 (PC1) and Principal Component 2 (PC2) showed 64.4% and 16.1% of the total variance, respectively (Fig. 2). Parameters such as pH, organic carbon, carbon to nitrogen ratio (C: N), and moisture content showed strong positive associations with PC1.

3.3 Compost physicochemical parameters and impact on compost quality and maturity

Most physicochemical parameters were positively correlated with each other (Fig. 3). We found out that total nitrogen exhibited significant positive correlations with all other measured variables. Conversely, Nitrate nitrogen

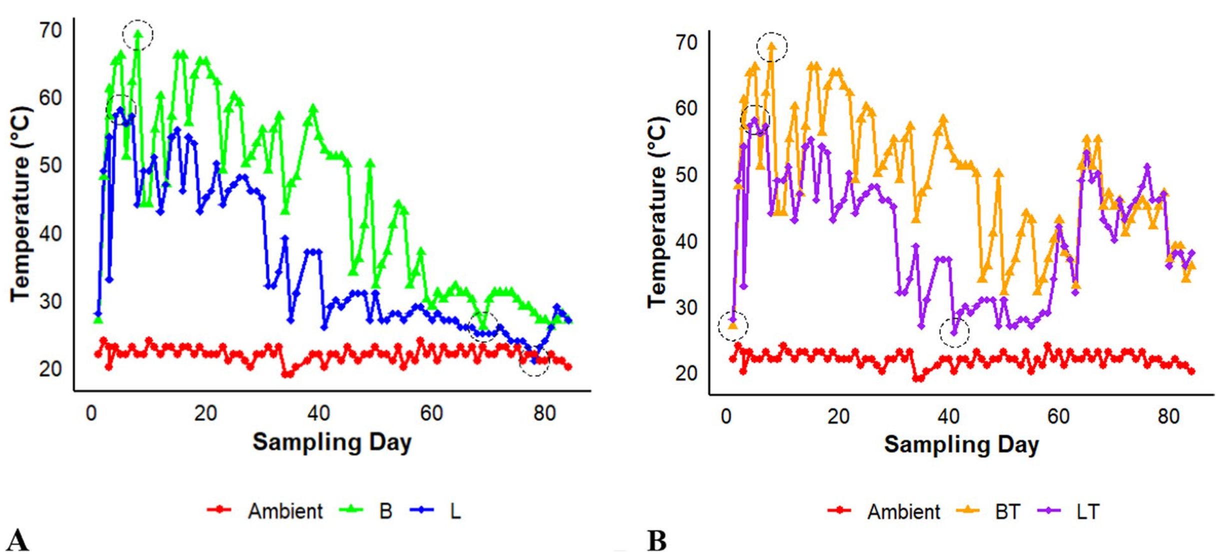

Fig. 1 Temperature plot of changes in B and L composts (**A**); BT and LT composts (**B**)

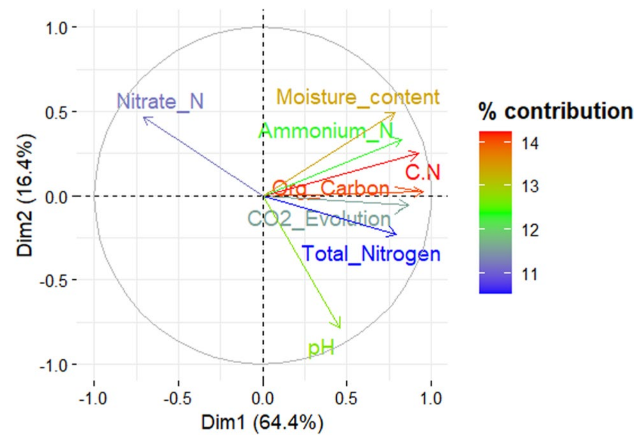

Fig. 2 A biplot of Principal component analysis (PCA) of compost physicochemical parameters. The influence of each variable on sample distribution is represented by the arrows radiating from the center of the PCA plot

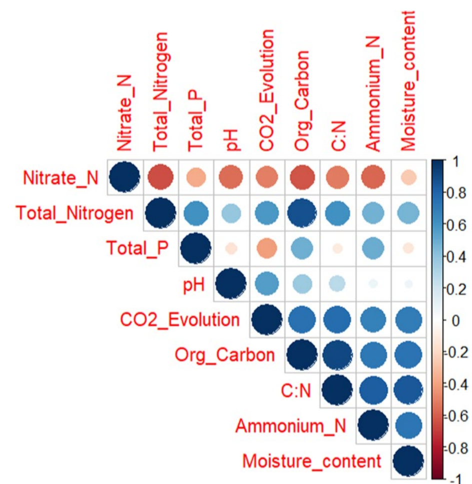

Fig. 3 A Pearson correlation bubble plot depicting correlation among analyzed physicochemical variables. Positive and negative correlations are displayed in blue and red shades, respectively. The size and intensity of matrix circles are proportional to the correlation coefficient

was negatively correlated with all the physicochemical parameters in compost. Notably, total phosphorous was only correlated to organic carbon and ammonium nitrogen.

3.4 Influence of supplemental *Tithonia diversifolia* and biochar on compost physicochemical parameters

The piles pH was similar among all treatments from the beginning of the composting period until the 84th day of composting when the pH of BT and LT treatments had significantly higher pH than other treatments (Table 2). The addition of *Tithonia diversifolia* notably brought about a significant increase in CO_2 evolution in compost. This is associated with the rise in temperature in the respective compost piles. Overall, Biochar-based composts recorded reduced CO_2 emissions compared to composts without biochar addition.

4 Discussion

The conventional way of compost preparation potentially leads to suboptimal nutrient levels in compost limiting its effectiveness as a soil amendment. The high temperature at the thermophilic phase often leads to significant nutrients losses, particularly nitrogen. These losses must be mitigated using practical approaches such as the application of biochar, which is a matrix known to reduce nutrient losses. Moreover, the addition of *Tithonia diversifolia* in post-thermophilic stages of composting has the potential to minimize nutrient losses. *Tithonia diversifolia* is a nutrient-dense supplemental

Table 2 Evolution of compost physicochemical parameter, as influenced by various treatments

Variable	Composting duration	B	BT	L	LT	Significance
pH	21	8.7	8.7	8.7	8.7	Ns
	42	8.57	8.57	8.54	8.54	Ns
	63	8.60	8.60	8.59	8.59	Ns
	84	8.2^{b}	9.2^{a}	8.2^{b}	9.2^{a}	***
C (%)	21	30.7^{a}	30.7^{a}	26.1^{b}	26.1^{b}	***
	42	24.6^{a}	24.6^{a}	18.9^{b}	18.9^{b}	***
	63	21.5^{a}	21.5^{a}	19.3^{b}	19.3^{b}	***
	84	18.7^{bc}	24.9^{a}	17.7^{c}	19.6^{b}	***
Total N (%)	21	1.67^{a}	1.69^{a}	1.43^{b}	1.47^{b}	***
	42	1.54^{a}	1.54^{b}	1.31^{b}	1.31^{b}	**
	63	1.42	1.41	1.38	1.39	Ns
	84	1.34^{b}	1.59^{a}	1.24^{b}	1.32^{b}	***
Nitrate_N (ppm)	21	1.26^{a}	1.26^{a}	0.16^{b}	0.16^{b}	***
	42	13^{b}	13^{b}	34.3^{a}	34.3^{a}	***
	63	7.85^{b}	7.85^{b}	15.70^{a}	15.70^{a}	***
	84	32.1^{b}	3.2^{d}	100^{a}	18.8^{c}	***
Ammonium_N (ppm)	21	84.0^{b}	84.0^{b}	109.1^{a}	109.1^{a}	***
	42	47.2^{a}	47.3^{a}	39.1^{b}	39.1^{b}	***
	63	44.8^{a}	44.9^{a}	41.5^{b}	41.5^{b}	***
	84	11.7^{a}	11.3^{a}	5.8^{b}	10.7^{a}	*
Total phosphorous (%)	84	0.61^{a}	0.61^{a}	0.41^{b}	0.47^{b}	***
CO_2 respiration (%)	21	11.5	14.0	12.1	11.2	Ns
	42	7.1	7.7	7.7	8.0	Ns
	63	4.8^{b}	5.8^{ab}	6.2^{a}	6.5^{a}	**
	84	3.2^{b}	8.7^{a}	4.7^{b}	10.4^{a}	**

C is Organic carbon; Total N is total nitrogen, Nitrate_N is Nitrate nitrogen; Ammonium_N is Ammonium nitrogen. B is biochar-based compost, L is Lantana-based compost, BT is biochar-based compost with post-thermophilic tithonia addition, and LT is Lantana-based compost with post-thermophilic Tithonia diversifolia application

Significance codes: 0 '***' 0.001 '**' 0.01 '*' 0.05

material that easily mineralizes leading to losses especially due to high temperatures. Since the essence of thermophilic conditions is mainly to sterilize and humify manure and dry matter, it is therefore practically feasible to add *Tithonia diversifolia* during cooler phases.

4.1 Influence of biochar and post-thermophilic *Tithonia diversifolia* addition on compost temperature

The attainment of thermophilic conditions in all compost treatments positions all tested feedstocks as capable of pathogen and weed sanitization in cattle manure [48–50]. The thermophilic conditions also quicken nutrient mineralization, stabilization, and humification of organic matter [51–53]. The consistently higher pile temperatures in biochar-based composts (B and BT) than L and LT are attributable to the uncharred husks in the rice-husk biochar. Uncharred rice-husks are colonized by micro-organisms and broken down into simpler sugars accompanied by temperature increase [54, 55]. This potentially hinders the attribution of this observation solely to the biochar. The sudden rise in pile temperatures in LT and BT treatments at 63rd day was brought about by the post-thermophilic application of *Tithonia diversifolia* to both treatments. Among the constituent elements broken down by microbes in *Tithonia diversifolia* are carbon and nitrogen, which are in simpler forms compared to those in *Lantana camara*. We attribute the temperature increase to the carbon breakdown in the applied *Tithonia diversifolia*. This decomposition is mediated by decomposition communities in the compost ecosystem [56, 57]. The rapid decomposition of *Tithonia diversifolia* in nature is attributable to its low lignin content and favorable carbon-to-nitrogen (C:N) ratio, which accelerates microbial activity. This rapid decomposition highlights the potential of *Tithonia diversifolia* as a valuable organic amendment for agricultural systems [58, 59].

4.2 Impact of physicochemical parameters on compost quality

The strong positive associations of pH, organic carbon, and moisture content with PC1 indicates their importance in shaping treatment differences and thus provide a basis for their further exploration of compost quality. Carbon, the C: N ratio and moisture content are key drivers of soil health, impacting microbial activity, organic matter decomposition, and ultimately nutrient cycling. Higher carbon content enhances soil structure and water retention, while an optimal C: N ratio ensures efficient nutrient cycling. Moreover, moisture is essential for these processes, impacting soil fertility and crop productivity [60].

The significant positive correlations of total nitrogen with all other measured variables position nitrogen content as a central factor influencing the overall compost quality. Previous studies have reported that low nitrogen in compost limits microbial growth and slows down the decomposition rate [61, 62]. Moreover, the deficiency of nitrogen shifts the balance to a higher C: N ratio, essentially meaning more carbon is available in the ecosystem. This potentially leads to an increased thermophilic phase [61, 63]. Conversely, nitrate nitrogen was negatively correlated with all the physicochemical parameters in compost. Nitrate nitrogen has been reported to be negatively correlated with pH [64]. On the contrary, most studies on similar matrices such as soil, have reported a positive correlation between nitrate nitrogen and total nitrogen and pH [65–68]. The lack of a positive correlation of phosphorous with multiple variables implies that phosphorus content is relatively independent of the other measured parameters. Thus, indicating that factors influencing phosphorus levels in studied compost regimes might differ from those affecting nitrogen and other key variables.

Our findings highlight the multifaceted nature of compost quality assessment and the importance of considering multiple indicators to gain a comprehensive understanding of compost dynamics [69–71]. The application of organic materials such as biochar, compost, *Lantana camara,* and *Tithonia diversifolia* is critical in maintaining an optimal carbon-to-nitrogen balance in soils. This balance is essential for enhancing overall nutrient availability, improving soil structure, and promoting sustainable crop growth [72–75].

4.3 Influence of supplemental materials on compost quality

The addition of *Tithonia diversifolia* in the two compost treatments; LT and BT at 63rd day, led to the increase in pH. This can be explained by the potential increase in ammonia caused by the high temperatures recorded in these treatments. The addition of *Tithonia diversifolia* to similar matrices has been shown to contribute to a rise in pH [76, 77]. The increase in microbial CO_2 respiration in BT and LT composts after the addition of *Tithonia diversifolia* is associated with the temperature in the respective compost piles. The temperature increase is occasioned by the breakdown of *Tithonia diversifolia*-borne carbon by microbes [11]. *Tithonia diversifolia* contains easily biodegradable carbohydrate polymers and secondary metabolites such as polyphenols whose breakdown by microbes prompts temperature surge [78–80]. Supplemental *Tithonia diversifolia* application increased the total nitrogen in the compost treatments compared to the ones without addition. The phytochemical composition of *Tithonia diversifolia* which includes nitrogen, phosphorus, and assorted secondary metabolites [80] directly influence the breakdown efficiency and compost quality. The reduced microbially respired CO_2 in biochar-based compost until day-63 of composting can be explained by its relatively stable nature, slowing microbial breakdown of carbon in compost. Biochar has been reported by various studies as capable of reducing these emissions by trapping the gaseous emissions from the compost pile [81, 82].

Biochar improves soil nutrient retention by increasing the cation exchange capacity and surface area; thus, reducing nutrient losses [83–85]. The conformation of the biochar matrix also presents it as a sink with higher sequestration capacity, thus reducing losses of gaseous emissions such as CO_2 [86–88]. Biochar from different feedstocks has also been reported as a sequestrant of heavy metals in soil, reducing copper and zinc by up to 14.6 mg kg^{-1} and 117.2 mg kg^{-1} respectively [89]. This confirmed that the two factors are critical for nutrient status and ultimately compost quality. Other studies have also reported that the nature of feedstock and the duration of composting have a major influence on nutrient mineralization, losses, and stability [90–92].

5 Conclusion

The addition of biochar to compost led to lower microbial CO_2 respiration at the end of composting, indicating more stabilized organic matter. Moreover, a combination of biochar and post-thermophilic phase supplementation of *Tithonia diversifolia* contributed to higher nitrogen and organic carbon levels compared to their separate application to compost. This highlights that the synergistic effect of biochar and *Tithonia diversifolia* enhances compost nutrient content compared to the sole addition of the feedstocks to the compost. The combined effect of these two amendments in soil balances the C: N ratio and may ensure the immediate and slow release of important nutrients such as nitrogen. This study has potential for replication with similar substrates but there are potential variations due to the phytochemical quality of feedstock. For example, biochar quality is dependent on the type of material pyrolyzed. Moreover, we appreciate the potential heterogeneity occasioned by the use of unsieved biochar (containing both charred and uncharred rice husks); which is the common composting practice in the area. We therefore recommend further experimentation on standardization of biochar to leverage common practice and practicability of the input to compost improvement with a view to standardize the feedstock and optimize compost quality. The post-thermophilic addition of *Tithonia diversifolia* could potentially have limited its integration with the compost matrix, reducing its effectiveness as an amendment. Therefore, we recommend further composting studies that explore optimizing composting efficiency and nutrient stabilization due to the extended composting periods required when *Tithonia diversifolia* is added at post-thermophilic stage.

Research involving plants Compliance with the IUCN Policy Statement on Research Involving Species at Risk of Extinction and the Convention on the Trade in Endangered Species of Wild Fauna and Flora: None of the plant materials (*Lantana camara, Tithonia diversifolia*, Rice husks, Maize stalks) species used in the field experiment is endangered or at the risk of extinction. Experimental research and field studies on *Lantana camara, Tithonia diversifolia,* Rice husks, and Maize stalks plants are not endangered and, hence, not subject to institutional, national, and international guidelines and legislation. However, the cuttings of *Lantana camara* and *Tithonia diversifolia* were from the hedges of the project trial site as they freely grow. The rice husks were sourced from Mwea, Kirinyaga County in Kenya, (50 Kilometers from the project site) and maize stalks were sourced from the project trial plots. The plant collection and use was in accordance with all the relevant guidelines.

Author contributions F.M and M.K: Conceptualization;F.M, M.K and C.M: Methodology, F.M and D.B: Formal analysis and investigation, F.M and M.K: Writing—original draft preparation, F.M, C.M. D.B. and C.D.:Writing—review and editing; D.B. and M.K. Funding acquisition: D.B. and M.K.: Resources: M.K.: Supervision.

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Data availability The datasets generated during and/or analysed during the study have been presented in the article.

Code availability NA.

Declarations

Competing interests The authors declare no competing interests.

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