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Effect of Biochar Amendments on the Co-Composting of Food Waste and Livestock Manure

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Abstract: The global increase in population will result in increased global food production which can, in turn, lead to excessive food waste. Although composting is widely adopted for the conversion of organic waste into value-added products, there are several limitations, such as its lower efficiency in composting food waste without co-composting, the loss of nutrients, and the emission of greenhouse gases. Due to its renowned characteristics, biochar amendments are used during composting to overcome these issues; each waste should be at an appropriate level to yield good quality compost with high nutrient levels. In this study, we co-composted food waste with chicken and swine manure with varying proportions in the presence and absence of biochar to identify the ideal proportion of each raw material and the biochar. Physicochemical parameters such as pH, EC, temperature, bulk density, porosity, C:N ratio, and gaseous emissions were analyzed. The results showed that the desired quality of compost was obtained in the treatment with 5% biochar with 40%, 20%, and 20% of food waste, chicken manure, and swine manure, respectively, and 15% sawdust.

Keywords: food waste; chicken manure; swine manure; biochar; nitrogen conservation; co-composting

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1. Introduction

The increasing global population has resulted in high demand for food and livestock production. It is predicted that the global demand for producing food [1], chicken meat, and pig meat will increase by 35%, 39%, and 32%, respectively, by 2030 [2]. According to Korean Statistical Information Service estimates, South Korea has 2786 poultry farms and 5951 pig farms with 11 million head of pigs and 171 million head of chicken [3]. This intensive livestock production has produced large amounts of manure containing considerable amounts of nutrients, heavy metals, and pathogens [4–6]. Recent studies have shown that food waste of about 1.3 billion tons is generated worldwide annually; this is expected to rise more in the next two decades [7,8]. The increasing population will lead to the depletion of resources, in addition to harmful impacts on the environment and health. The resource depletion can be minimized by a circular economy approach, where the material flow is continuous and ensures the material usage is at its optimal level of consumption [9,10]. The circular economy is a cost-effective approach and is preferable over other approaches such as landfills and incineration [11].

Composting is one of the most widely accepted circular economy approach for recycling organic waste and represents a cost-effective method for recycling nutrients. Although composting is considered to have a low environmental impact [12], it is inevitable that the composting of manure will release anthropogenic greenhouse gases and other gases such as ammonia, VOCs, etc. [13]. The release of carbon dioxide (CO_2) and methane (CH_4) causes a loss of carbon, while ammonia (NH_3) volatilization results in a loss of nitrogen, which reduces the nutritional content of the final compost. The composting efficiency of food

waste is also very low due to disadvantages such as its low porosity, high bulk density, poor C:N ratio, easy acidification, etc. [14–16]. The final product or the compost produced is used in agricultural lands for increasing crop yields by improving the quality of the soil [16]; the product produced should be of good quality, which increases the concentration and solubility of plant nutrients such as potassium and phosphorus with high water-retaining capacity and aeration. Hence, it is necessary to overcome the abovementioned difficulties. Several studies suggested that the co-composting of food waste in combination with manure that has high nitrogen and low moisture contents minimizes the potential environmental impacts [17–20]. Co-composting enables the aerobic degradation of organic waste mixtures, to obtain compost that can be used as fertilizer. Co-composting also reduces the time and effort associated with composting and can have economic benefits [21]. In order to minimize nutrient loss, the addition of carbonaceous material is highly preferred. Sawdust is a preferred amendment which is used to increase the carbon content and maintain the nitrogen from food waste and manure.

The usage of raw materials such as food waste and manures increases bulk density and decreases porosity. Hence, bulking agents must be used while co-composting food waste and manure to enhance the structure and oxygen diffusion [22]. Several studies have used biochar of different origin such as bamboo [23], rice-straw [24], willow woodchips [25], etc., and have suggested biochar as the best agent due to its high porosity and sorption capacity which enhance aeration during composting [26]. However, to achieve the best output, i.e., compost of high quality, the raw materials used for composting should be in appropriate proportions. Very limited research has focused on the proportions of raw materials to be used during the co-composting of food waste with one or more manure types. The present study concentrates on the effect of biochar amendment during the co-composting of food waste with chicken and swine manure, and attempts to identify the effect of different proportions of the raw material and amendments such as sawdust and biochar by exploring the changes in the physico-chemical parameters, gaseous emissions, and nutrient indicators during composting. This will help develop a clear understanding of the effect of biochar amendment and the relationship between the gaseous emissions and the quality of the obtained compost.

2. Materials and Methods

2.1. Feedstock Preparation and Experimental Design

The raw materials containing residential food waste was collected from the Suwon city food resource recycling facility; chicken and swine manure were collected from local farms. Sawdust was obtained from the local wood industry and was used for regulating the initial moisture content. The biochar of rice husk prepared by pyrolysis was obtained from a commercial company and was substituted with sawdust at different proportions. All the feedstock was mixed manually in different weight proportions to obtain a homogenous mixture. Nine different treatments were utilized, and their initial moisture contents were adjusted to 65%. Treatments without biochar served as controls. The physicochemical properties of the raw materials were reported in our previous findings [21,27]. The proportion details of the raw materials are tabulated in Table 1. The composting experiment was carried out for 50 days in a reactor at a temperature of 21 ± 2 °C, as described in [21]. Periodically, the raw materials were thoroughly mixed to distribute evenly.

2.2. Physicochemical Analysis

The pH, electrical conductivity, bulk density, and porosity of the composting mixtures were measured on the first day and the last day of the experiment. The pH and EC were determined as described in [21] by mixing the sample in distilled water at a 1:10 ratio (w/v). The bulk density and porosity were measured according to [28]. The C:N ratio was measured on days 1, 7, 14, 21, 28, 35, 42, and 50 of the composting process. The C:N ratio was estimated by determining total carbon and nitrogen contents according to [29] by Truspec CN carbon/nitrogen determination (LECO Corporation). The temperature,

ammonia, and carbon dioxide emissions were monitored daily. The NH_3 emissions (g/day) were measured using the detector tubes method [30] and the CO_2 (%) was evaluated using a biogas analyzer (GA5000, Geotech, UK).

Table 1. Weight proportions of feedstock.

Treatments	FW	CM	SM	Sawdust	Biochar
T1	20% (1.6 kg)	30% (2.4 kg)	30% (2.4 kg)	20% (1.6 kg)	Control
T2	40% (3.2 kg)	20% (1.6 kg)	20% (1.6 kg)	20% (1.6 kg)	Control
T3	60% (4.8 kg)	10% (0.8 kg)	10% (0.8 Kg)	20% (1.6 kg)	Control
T4	20% (1.6 kg)	30% (2.4 kg)	30% (2.4 kg)	17% (1.36 kg)	3% (0.24 kg)
T5	40% (3.2 kg)	20% (1.6 kg)	20% (1.6 kg)	17% (1.36 kg)	3% (0.24 kg)
T6	60% (4.8 kg)	10% (0.8 kg)	10% (0.8 Kg)	17% (1.36 kg)	3% (0.24 kg)
T7	20% (1.6 kg)	30% (2.4 kg)	30% (2.4 kg)	15% (1.2 kg)	5% (0.40 Kg)
T8	40% (3.2 kg)	20% (1.6 kg)	20% (1.6 kg)	15% (1.2 kg)	5% (0.40 Kg)
T9	60% (4.8 kg)	10% (0.8 kg)	10% (0.8 Kg)	15% (1.2 kg)	5% (0.40 Kg)

2.3. Statistical Analysis

The results obtained in the study on the changes in various parameters were subjected to two-way analysis of variance (two-way ANOVA) using SPSS computer software by fixing the significance level at $p < 0.05$. Here, the duration of composting (days) was considered as the dependent variable, while the treatment groups and parameters were considered as factors. All data are presented as the mean of three replicates ± standard deviation. For computing the values of pH, EC, bulk density, and porosity, initial and final values were compared with respective treatment's replicate values.

3. Results and Discussion

In this experiment, significant changes in the overall characteristics between the biochar-amended treatment and control treatment were observed, which indicated that the treatment had achieved maturity.

3.1. Changes in the Temperature, pH, and EC

One important characteristic that influences the successful maturity of compost is the temperature. The optimal temperature has to be maintained throughout the composting process to support microbial growth for the biodegradation of substrates followed by biogas production [31,32]. During the first week of composting, the temperature reached its maximum (between 40 and 60 °C) on the fifth day and gradually decreased, with some fluctuations until the third week. After the third week, the temperature continued to decrease until the final day of composting (Figure 1). The substrate mixtures were periodically turned to evenly distribute heat and aeration, which led to the observed fluctuations. Several studies have reported that biochar amendments increase the temperature; similarly, in our study, it can be observed that the temperature of the treatments in the absence of biochar (T1–T3) is comparatively low, especially in T3. The low temperature in T3 could be because of the high proportion (60%) of food waste used in the treatment mixture. Although food waste constitutes biodegradable materials that will produce heat during microbial degradation [33], high proportions will increase the moisture which will affect the temperature. The maintenance of optimal temperature was observed in the 5% biochar treatments (T8 and T7) and 3% biochar treatments (T5 and T4), but not in T9 and T6, which was also due to the high proportion of food waste in those treatments. The increased temperatures increase the rate of acidification, which will decrease microbial growth, ultimately affecting biodegradation. An ambient temperature supporting microbial growth and biodegradation is required. The temperatures achieved in our study were in accordance with the compost hygiene standard [34].

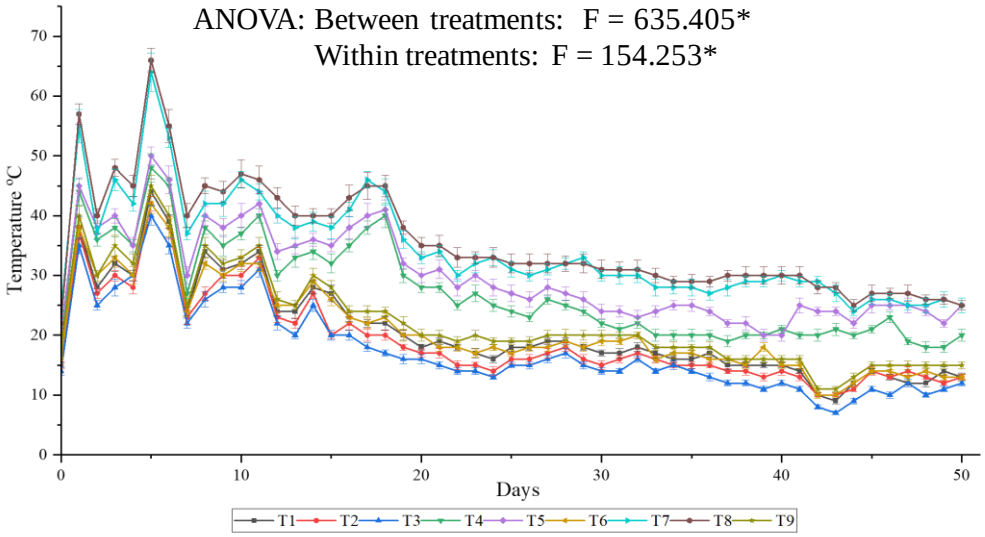


Figure 1. Dynamics of temperature among various composting treatment groups. '*' indicates a significant difference at $p < 0.05$ by ANOVA.

The initial pH of the treatment mixtures ranged between 5.70 and 7.18, and increased (ranging between 6.80 and 7.98) by the end of the composting process. The ammonization and volatilization reaction during the biodegradation followed by the emission of greenhouse gases led to this increased pH [25,35,36]. From Figure 2, it can be observed that in the treatments without biochar, the pH is slightly acidic, which is not favorable to the composting process and can result in poor-quality compost. The initial pH of the treatments without biochar is inversely proportional to the concentration of food waste and directly proportional to the concentration of manures. This could be because of the alkaline nature of the chicken manure and swine manure. However, the addition of biochar to the composting mixture increased the initial pH. This shows that biochar used as a bulking agent assisted in attaining an alkaline pH in the reaction at the initial stages itself. Previous studies have reported that a pH ranging from 7.0 to 8.5 with 12% biochar provides ideal conditions for biodegradation by microbes [24]. We attained favorable pH values with 5% biochar, which was likely due to the selection of feedstock proportions.

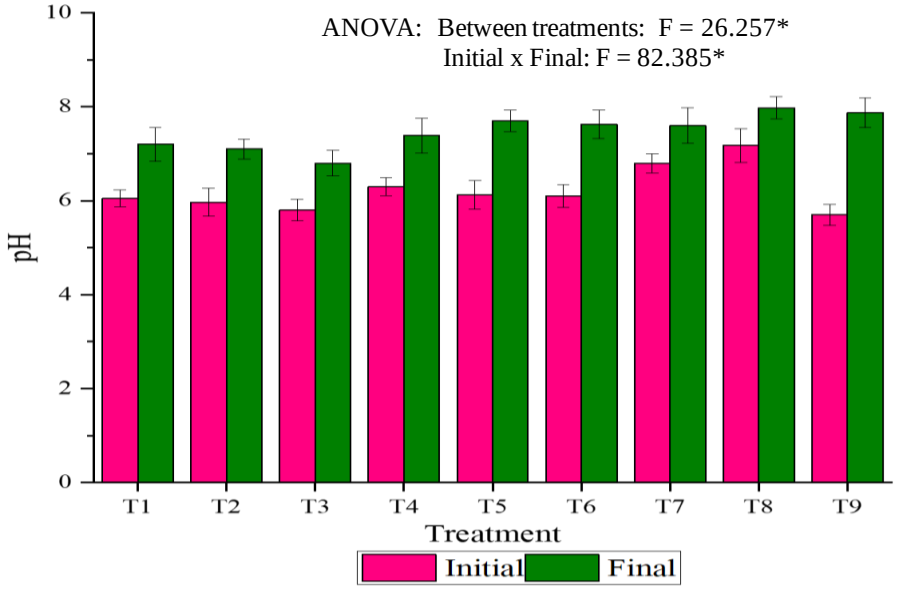


Figure 2. Dynamics of pH among various composting treatment groups. '*' indicates a significant difference at $p < 0.05$ by ANOVA.

The toxicity of salts and the suitability of compost for agricultural purposes can be evaluated by measuring the electrical conductivity (EC) [37–39]. In our study, the initial EC was found to be very high in treatments without biochar amendment, whereas the EC of the treatments with biochar was comparatively low (Figure 3). During the final stage of composting, the EC of all the treatments decreased and was in the range of 2.11–2.65. The decrease in the EC value was due to the precipitation and volatilization of salts and ammonia, respectively [40]. The EC observed in our results was in the permissible ranges of agricultural applications and in agreement with previous reports [30,41].

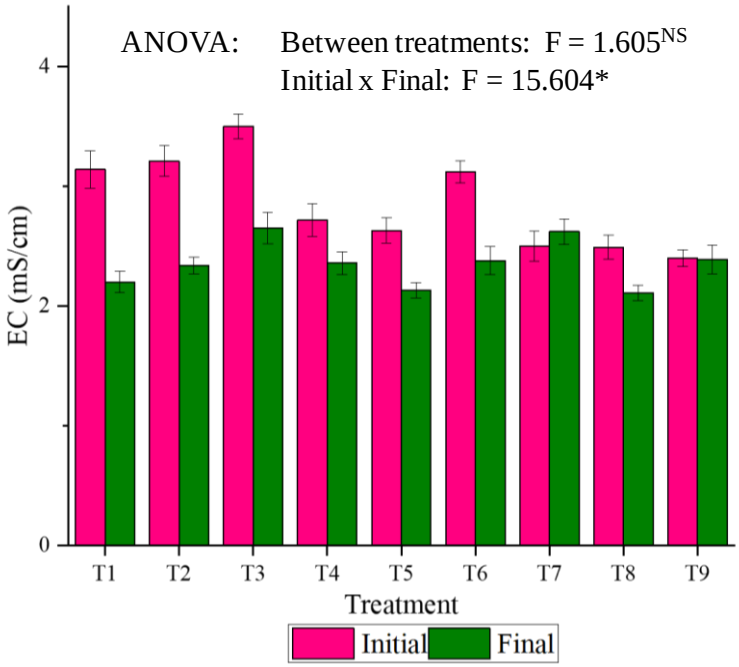


Figure 3. Dynamics of electrical conductivity among various composting treatment groups. '*' indicates significance of difference and 'NS' indicates 'non-significant difference' at $p < 0.05$ by ANOVA.

3.2. Changes in Bulk Density and Porosity

Previous studies have reported the importance of bulk density and total porosity in regulating the composting process [42]. Bulk density is an important parameter to be monitored in composting experiments; it should decrease over the period of composting as it reaches maturity [43]. In Figure 4, it can be observed that the initial bulk density of the treatments without biochar decreases with the increase in the proportion of food waste. In biochar-amended treatment groups, however, the initial bulk density was comparatively higher than those without biochar. At the final stage of composting, as the compost matured, in the treatments without biochar, the BD significantly increased $p < 0.05$, whereas the BD of the biochar-amended groups, T8, T7, T5, and T4, decreased significantly (53.05%, 39.25%, 21.71%, and 18.47%, respectively, data not shown) $p < 0.05$. In T9, where the composting mixture carried 5% biochar, the percentage reduction in BD was 4.68%, which was not observed in T6 (with 3% biochar amendment), indicating that the biochar percentage was not sufficient in T6. The final BDs of treatments with the biochar amendment were found to be 0.331, 0.321, 0.392, 0.274, 0.231 and 0.367 g/cm^3, which are within the optimal conditions of <0.4 g/cm^3. However, in the treatments without biochar (T1–T3), the BD was not in the optimal range indicating that the compost is not suitable. The increase in BD in treatments without biochar was because of the short thermophilic phase followed by a decline in the temperature (as observed in the temperature trends). Prior studies have mentioned that amendments such as the addition of bulking agents to the compost feedstock help to maintain the BD by augmenting the gaseous exchanges and aeration. This retains the

nutrients and enhances the quality of the compost [44,45]. The compost product with a low BD indicates high porosity, which is in agreement with our results of total porosity.

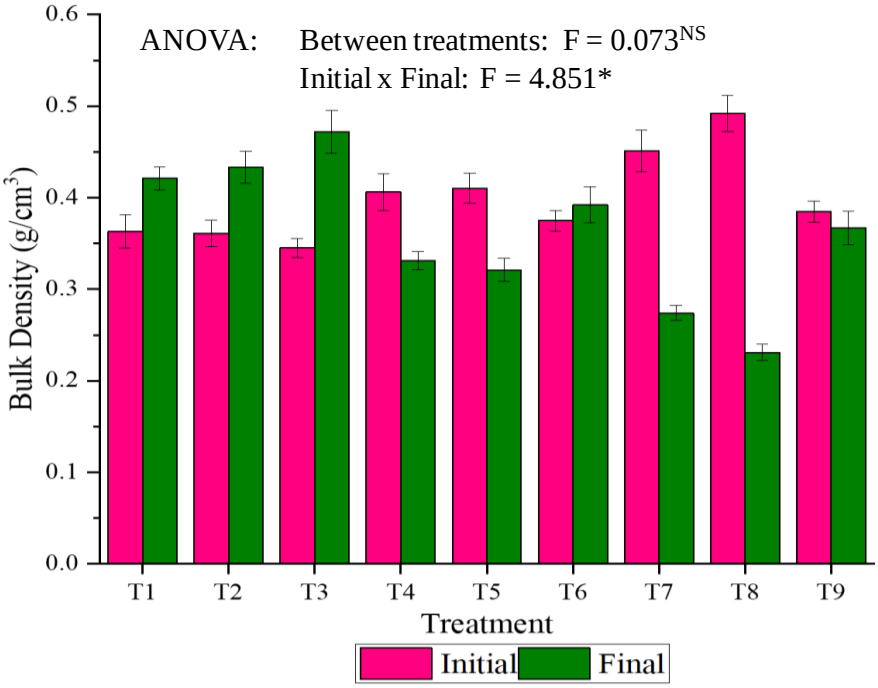


Figure 4. Profile of bulk density variations among different composting treatment groups. '*' indicates significance of difference and 'NS' indicates 'non-significant difference' at $p < 0.05$ by ANOVA.

The total porosity percentage of the composting mixtures was found to be inversely proportional to their BD. As observed in other parameters, the porosity was also affected by the concentration of food waste used in a composting mixture. Similarly, the biochar amendment influenced the composting process in a desirable way by increasing the final total porosity. The porosity percentages were 71.52%, 72.64%, 65.39%, 75.42%, 78.96%, and 67.36% for treatments T4–T9, respectively (Figure 5). The acceptable range of the porosity percentage was >70 [46], and it was achieved in the T4, T5, T7, and T8 treatments but not in T6 and T9. The porosity percentages of the T6 and T9 treatments were not in acceptable ranges, which was due to the high moisture content of the food waste which decreased the porosity [47,48]. This indicates that the moisture content was preserved [49], leachate loss was prevented [50], and the biodegradation of compost feedstock was promoted [51] in the treatments T4, T5, T7, and T8.

3.3. Changes in the C:N Ratio

The microbial degradation of OM requires macronutrients such as carbon, nitrogen, potassium, and phosphorus, of which carbon and nitrogen are most widely required for microbial growth [52]. This results in significant changes in the C:N ratio ($p < 0.05$). C:N ratio is the chief indicator of stability in the composting process and the maturity of the final product [53]. Figure 6 represents the C:N ratio of the treatment mixtures sampled at weekly intervals. At the initial stages, the C:N ratio was higher in biochar-amended treatments than in the treatments without biochar. Biochar amendments in organic feedstock increased the carbon content, which is the underlying reason for the increased C:N ratio [49,54]. As the composting process progressed, the C:N ratio eventually decreased in all the treatments, irrespective of the biochar amendments, with the maximum decrease in T8 (where the C:N ratio is 16.52). During the biodegradation of OM, a portion of the carbon is released, especially in the form of CO_2, and another portion along with nitrogen serves as a source of energy for microbes. This will decrease the carbon content while the nitrogen is simultaneously recycled by the microorganisms, leading to a decrease

in the C:N ratio, as observed in our study. The maximum C:N ratio decrease observed in our biochar-amended treatments is an indication of OM biodegradation [55]. A C:N ratio < 20 indicates the maturation of the compost, which was observed in all our treatments and is in agreement with reports in the literature [56–59]. However, the maximum reduction was observed in T8 with 16.52.

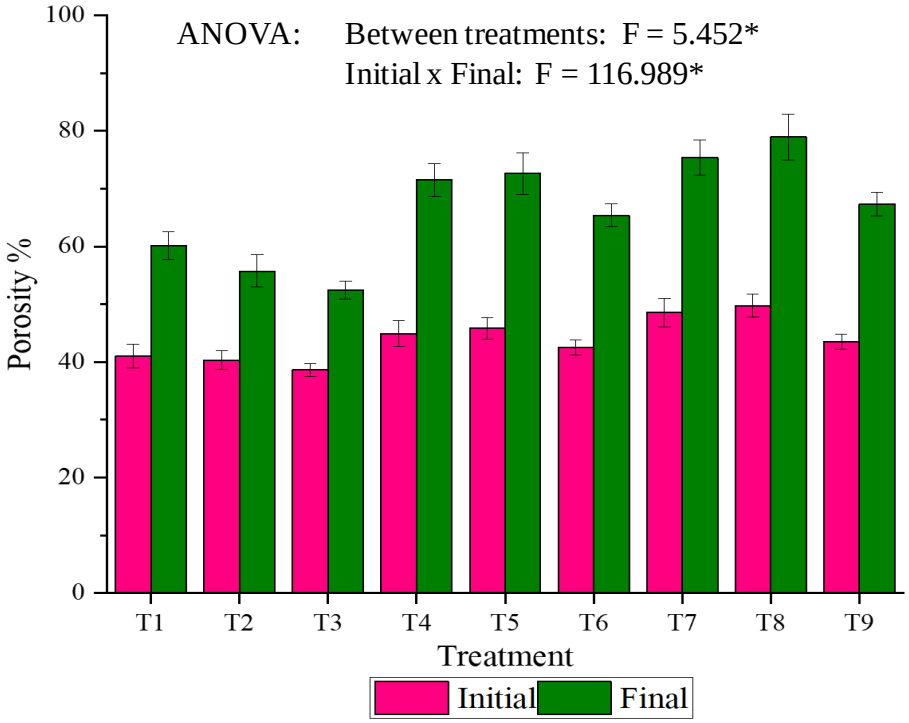


Figure 5. Profile of total porosity variations among different composting treatment groups. '*' indicates a significant difference at $p < 0.05$ by ANOVA.

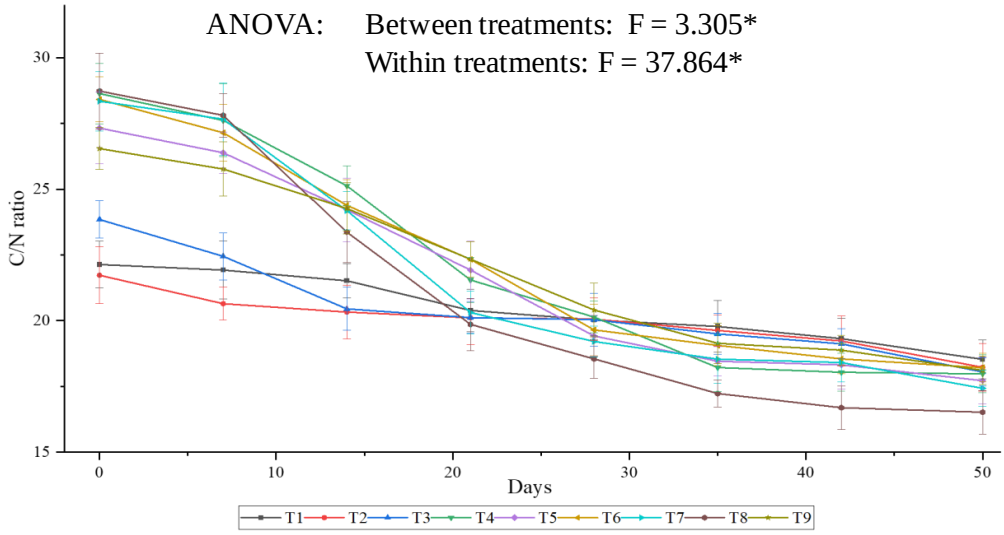


Figure 6. Profile of C/N ratio variations among different composting treatment groups. '*' indicates a significant difference at $p < 0.05$ by ANOVA.

3.4. Variations in CO_2 Emission

The reflection of microbial growth and mineralization of OM can be observed through CO_2 emissions. During the composting process, as the microbes degrade the OM, the CO_2 emissions reach it maximum, and as the treatment attains maturity, microbial activity,

in addition to the decreased CO_2 emission [60]. Similarly, in our study, CO_2 emissions were high during the initial stages and reached the maximum peaks between the 5th and 10th days of composting, after which CO_2 emissions gradually decreased with slight fluctuations and completely stopped by the end of the experiment (Figure 7). However, the increase in CO_2 emissions followed by its decrease was comparatively high in the treatments with biochar amendments than in the treatments without biochar. This indicates the accelerated biodegradation due to the carbon-rich biochar [61]. The trendline of CO_2 emissions corresponds with the trendline of temperature, where the CO_2 emissions decrease after the end of the thermophilic phase where the microbial activity also decreases. In our study, due to the large surface area ratio of biochar, the biochar amendment improved the aeration in the treatment mixtures, especially in T4, T5, T7, and T8, thereby supporting microbial growth and OM mineralization. Our results are in agreement with the previous reports of [62] and [63].

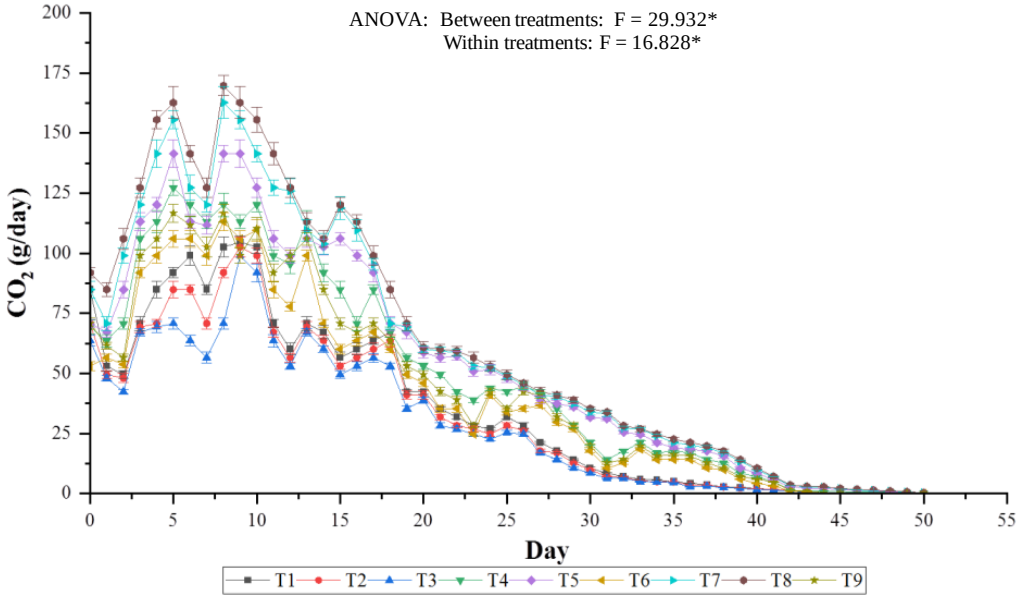


Figure 7. Profile of CO_2 emission (g/day) variations among different composting treatment groups. '*' indicates a significant difference at $p < 0.05$ by ANOVA.

3.5. Effect on Nitrogen Conservation

During the composting of OM such as livestock manure, nitrogen is lost at the thermophilic phase in the form of ammonia emissions, which decreases the quality of the final product [64]. Ammonia emissions not only reduce the nitrogen content in the final product; it is also an environmental pollutant which creates malodors. Biochar amendment is an effective strategy to address these issues. In our study, significant ($p < 0.05$) ammonia emissions were observed in all the treatment groups until the fourth week of composting, after which they continuously decreased (Figure 8). The ammonia emissions patterns observed in our study were in accordance with previous reports [65,66]. However, throughout the composting process, the ammonia emissions were kept low in the biochar-amended treatments. This clearly indicates that the biochar has reduced the volatilization and suppressed the ammonia emissions, preventing nitrogen loss and environmental degradation. Furthermore, the reason for the decrease in ammonia emission in the biochar amendment treatments is because the biochar provides a favorable environment to the nitrifying microbes and, to a certain extent, biochar itself acts as a habitat [67–69].

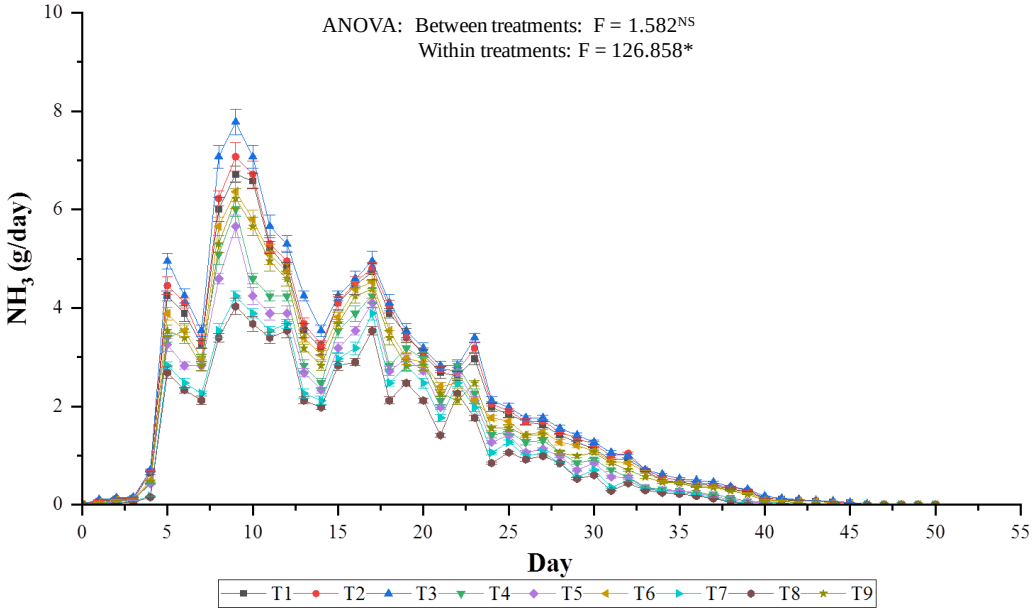


Figure 8. Profile of NH_3 emission (g/day) variations among different composting treatment groups. '*' indicates a significant difference, and 'NS' indicates a non-significant difference at $p < 0.05$ by ANOVA.

4. Conclusions

In this study, a novel approach for composting food waste along with chicken and swine manure in the presence of biochar was successfully carried out. Moreover, this study emphasizes the selection of a combination of raw materials and amendments in the correct proportions to obtain good-quality compost. Biochar amendments positively influenced the co-composting of food waste with manures, by maintaining optimum physico-chemical parameters such as temperature, pH, and EC to favor the microbial degradation of organic matter. Furthermore, biochar amendments reduced the bulk density caused by the addition of food waste and increased the porosity to provide aeration in the feedstock mixture. These changes maintained the C:N ratio at the desired levels and preserved the nutritional value of the final compost product by reducing nitrogen loss through ammonia emission. Thus, all the parameters of the final product were in alignment with the regulations, thereby providing assurances on the quality of the compost, favoring its acceptability in agricultural purposes and also inflating the local circular economy.

Author Contributions: Conceptualization, methodology, and investigation—W.C., J.S. and B.R.; data curation—W.C. and B.R.; writing—original draft; writing—review and editing—W.C., J.S., S.W.C. and B.R. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflict of interest .

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