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Co-Composting of Municipal Solid Waste with Activated Biochar: A Promising Approach to Improve the Quality of Compost

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ABSTRACT

Biochar reduces composting problems and improves compost quality. However, Activated Biochar (AB) and its size are often overlooked. This research aimed to evaluate the impact of co-composting of Municipal Solid Waste (MSW) with different-sized biochar and AB on the quality of the resulting co-compost. The MSW were mixed thoroughly with different-sized ($B_{2\text{-}4mm}$, $B_{1\text{-}2mm}$ and $B_{0.5\text{-}1mm}$) and activated biochars (H_2SO_4-$AB_{0.5\text{-}1mm}$ and NaOH-$AB_{0.5\text{-}1mm}$) and co-composted for 90 days until compost maturity. The results revealed that the activation of biochar with NaOH and H_2SO_4 caused the appearance of a mesh structure on the biochar surface, leading to improved stability and maturity, enhanced biodegradation and humification indices. Specifically, NaOH-AB (5%, w/w) showed the highest temperature (71.5°C), germination index (130.9%), and total nitrogen content (1.37%) and the longest thermophilic period (7 days). The highest Organic Matter content (OM) (37.9%) and the lowest electrical conductivity (7.4 dS m^{-1}) were recorded in $B_{1\text{-}2mm}$ (10%, w/w). Furthermore, the lowest nitrate concentration (254.4 mg kg^{-1}) and the highest C/N ratio (18.1) were in H_2SO_4-AB (10%). Principal Component Analysis (PCA) highlighted the critical role of the C/N ratio and OM content during the composting. The study recommends the addition of biochar to MSW to achieve an appropriate C/N ratio and prevent nitrogen loss. Overall, incorporating NaOH- and H_2SO_4-activated biochars was found to be a valuable strategy for the composting of municipal solid wastes. Our findings provide valuable insights into the potential of biochar in optimizing the composting process.

Keywords: Biochar activation, C/N ratio, Composting process, Humification.

INTRODUCTION

The management of Municipal Solid Waste (MSW) is a global concern. According to the United Nations Environment Program, the global MSW generation will reach 3.8 billion tons by 2050 (UNEP, 2024). In the Middle East, nearly 65% of MSW consists of organic waste, which is higher than the global average and more than 70% of this MSW is primarily disposed of in unsanitary landfills (UNEP, 2024). Consequently, effective management of MSW has emerged as a pivotal 21st-century challenge, which requires innovative technologies to recover resources and facilitate the transition to a sustainable bio-economy, particularly in developing countries. From both economic and environmental perspectives, composting offers a promising solution for managing the organic fraction of MSW, while also reducing waste disposal costs (Bhattacharjee *et al.*, 2023). Composting involves various stages where diverse microbial communities (bacteria, fungi, and actinomycetes) operate at different temperatures, generating heat as they decompose organic matter. The resulting compost is a nutrient-rich organic fertilizer that improves the physicochemical,

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and biological properties of soil, enhances soil fertility and reduces the reliance on chemical fertilizers (Babu *et al*., 2021). Additionally, composting can be associated with challenges such as greenhouse gas emissions, nitrogen loss, and the contamination of soil and water resources (Barthod *et al*., 2018; Nguyen *et al*., 2022). To address these challenges, "co-composting", which involves the use of additives at the beginning of the composting, has emerged as a promising approach (Barthod *et al*., 2018).

Recently, biochar has been recognized as a valuable additive and a key component to reduce the adverse effects of MSW composting and improve the quality of the final compost (Feng *et al*., 2024). Biochar possesses a range of beneficial characteristics, including a porous structure, high specific surface area, high ion exchange capacity, active oxygen functional groups, and resistance to decomposition. These properties enhance aeration and accelerate the decomposition of toxic substances through co-metabolism, reducing heavy metal bioavailability, nitrogen loss, greenhouse gas emissions, and composting time (Nguyen *et al*., 2022). In addition, the physicochemical properties of biochar, including particle size and activation, can affect its efficiency in improving compost quality. The particle size affects aeration, moisture, porosity, turning efficiency, and the uniformity of the compost pile (He *et al*., 2019). However, previous studies have provided limited insights into the effects of biochar particle size on the co-composting process.

The main purpose of the activation process is to enhance the oxygen-containing functional groups, surface area, pore volume and diameter, and increase the porosity of the Activated Biochar (AB) (Panwar and Pawar, 2020). Chemical activation (includes acid and alkaline activation) is the most widely adopted process for activation, with several advantages over physical methods. Among various chemical activators, NaOH and H_2SO_4 are considered more suitable due to their cost-effectiveness and lower environmental impact (Panwar and Pawar, 2020). Ye *et al*. (2019) reported that chemical-activated biochar increased available habitats for microorganisms, thereby improving the intensity of microbial respiration. Given the limited studies on AB composting, further investigation is warranted.

The objective of this study was to evaluate the impact of co-composting of MSW with different-sized biochar and AB on the quality of the resulting co-compost. The compost quality characteristics were evaluated, including maturity and stability, enzyme activity, and humification indices.

MATERIALS AND METHODS

Preparation and Activation of Biochars

MSW was collected from the Municipal Waste Management Organization, Tabriz, Iran. The waste biomass for the production of biochar, was prepared by mixing the pruning branches of plum and pomegranate trees. Biochar was produced by slow pyrolysis at 400 °C with a heating rate of 10°C per minute and a one-hour holding time at the target temperature. The biochar was separated using 0.5-1 mm ($B_{0.5\text{-}1\ mm}$), 1-2 mm ($B_{1\text{-}2\ mm}$), and 2-4 mm ($B_{2\text{-}4\ mm}$) sieves. For biochar activation, the biochar ($B_{0.5\text{-}1mm}$) was mixed with solutions of 2M NaOH and/or H_2SO_4 at a solid-to-solution ratio of 1:2 (w/v) with gentle stirring for 2 hours under the hood. Then, the suspension was filtered, and the residual solid was washed several times with distilled water until the pH was fixed at approximately 7.0. Finally, the washed biochar was dried in an oven at 65°C for 12 hours (Fan *et al*., 2010).

Chemical Analysis of Biochars and MSW

For the chemical analysis, the pH and EC were determined in a 1:10 (w/v) compost to water ratio (Singh *et al*., 2017). The contents of carbon, hydrogen, nitrogen, and sulfur was measured by CHNS analysis (Vario ELIII Elementary Analyzer, Germany). The biochar Cation Exchange Capacity (CEC) was determined by the method of Wang *et al*. (2013). The ash content was obtained by the Singh *et al*. (2017) method. The total concentrations of P, K, Na, Fe, Mn, Zn, Cu, Pb, and Ni were determined by ash digestion with a 3:1 mixture of two acids (HNO$_3$:HCl, 1:3, v/v) (Jones Jr. and Case, 1990). The available P concentration was determined by the Olsen method (Kuo, 1996), and the NH$_4^+$ concentration was determined by the indophenol blue method (Li *et al*., 2015). Water soluble K and Na concentrations were determined at 1:10 ratio (w/v). The concentration of heavy metals was measured by an atomic absorption spectrometer (Shimadzu, AA-6300). Biochar functional groups were determined by the FTIR technique as a general characterization technique (Bruker Tensor 27 FTIR spectrometer). Furthermore, the biochar surface morphology was evaluated by SEM (Tuscan FEG-SEM, MIRA3). The characteristics of the produced biochars and the MSW used in this study are presented in Table 1.

Composting System and Experimental Design

The experiment was carried out with two factors of biochar type at eleven levels, and time at eight levels of biochar, with two repetitions for three months. For this purpose, biochars of 2-4 mm, 1-2 mm, and

Table 1. Basic characteristics of the MSW and biochars.[a]

Properties	MSW	B*$_{(0.5\text{-}1mm)}$	B*$_{(1\text{-}2mm)}$	B*$_{(2\text{-}4mm)}$	NaOH-AB**	H$_2$SO$_4$-AB**
Ash (g 100 g^{-1})	72.05±3.04	25.57+0.58	19.75±0.35	19.02±0.31	18.80±0.14	17.95±0.35
C (g 100 g^{-1})	16.03±1.00	54.47±5.67	54.47±5.67	54.47±5.67	63.61±4.28	50.67±2.86
H (g 100 g^{-1})	0.75±0.01	1.60±0.04	1.60±0.04	1.60±0.04	1.69±0.07	1.54±0.06
N (g 100 g^{-1})	1.28±0.02	1.01±0.00	0.88±0.00	0.85±0.00	1.22±0.00	0.95±0.00
S (g 100 g^{-1})	0.74±0.00	0.36±0.01	0.36±0.01	0.36±0.01	0.27±0.00	1.81±0.00
O (g 100 g^{-1})	8.88±1.59	16.99±6.29	22.94±5.35	23.7±5.4	14.41±4.06	27.08±2.44
O/C	0.42±0.05	0.23±0.15	0.32±0.14	0.44±0.15	0.17±0.08	0.40±0.08
H/C	0.56±0.01	0.35±0.00	0.35±0.00	0.35±0.00	0.32±0.00	0.36±0.00
C/N	12.52±0.98	53.93±6.58	61.9±6.68	64.08±6.6	52.14±4.73	53.34±3.26
CEC (Cmolc kg^{-1})	-	25.04±1.47	14.74±2.88	11.76±1.7	28.34±2.7	25.57±0.74
EC (dS m^{-1})	8.2±0.31	0.55±0.00	0.34±0.00	0.28±0.01	0.47±0.01	1.76±0.01
Total K (g kg^{-1})	10.66±0.20	5.03±0.01	5.03±0.01	5.13±0.01	2.67±0.00	2.47±0.01
Total P (g kg^{-1})	1.41±0.08	1.16±0.01	1.13±0.01	1.12±0.03	0.94±0.01	0.72±0.01
Total Na (g kg^{-1})	2.64±0.06	0.86±0.00	0.78±0.01	0.79±0.01	2.04±0.01	0.35±0.00
Total Fe (g kg^{-1})	1.28±0.33	1.18±0.01	1.07±0.01	0.83±0.03	1.1±0.00	1.01±0.01
Total Mn (mg kg^{-1})	143.34±14.11	110.78±2.86	68.73±2.86	61.20±2.97	98.87±2.85	84.04±1.46
Total Zn (mg kg^{-1})	49.47±1.56	30.1±0.21	28.3±1.41	25.4±0.57	163.71±4.26	138.21±2.86
Total Cu (mg kg^{-1})	58.01±5.67	20.67±0.44	13.85±0.57	14.18±0.45	24.24±0.74	16.77±1.81
Total Pb (mg kg^{-1})	180.52±28.34	161.13±7.11	163.90±4.53	163.9±14.27	172.21±2.98	166.67+11.46
Total Ni (mg kg^{-1})	81.91±12.76	73.12±4.38	71.66±7.79	70.19±14.3	81.18±1.5	74.59±5.69
pH	Min: 7.53 Max: 7.61	Min: 8.58 Max: 8.74	Min: 8.92 Max: 9.20	Min: 9.15 Max: 9.21	Min: 9.06 Max: 9.34	Min: 7.63 Max: 7.77

[a] Values indicate the mean±standard deviation based on determination with two replications.
*B= Biochar **AB= Activated biochar

0.5-1 mm Activated Biochar (AB) with H_2SO_4 and NaOH (H_2SO_4-$AB_{0.5\text{-}1mm}$ and NaOH-$AB_{0.5\text{-}1mm}$) were thoroughly mixed with MSW, each at two levels of 5 and 10% (w/w). One treatment with no addition of biochar was considered the control. The substrates were accommodated in 100-L plastic barrels (44 cm diameter and 76 cm height) with an approximate weight of 70 kg. In each barrel, one kg of cow manure was added to increase the microbial activity, and 30 holes were drilled for better ventilation. The temperature of the composting mixture was monitored daily. Once a week, the compost materials were turned and thoroughly mixed. The moisture of the materials was kept in the range of 50-60% by weight until the end of the experiment. Sampling was performed on days 1, 7, 14, 28, 42, 56, 70, and 90, and each time at least five subsamples (approximately 500 g) were taken from different depths of the barrel and mixed thoroughly, and a composite sample was taken (Vandecasteele *et al*., 2016). The composite sample was divided into two subsamples (air-dry and moist). The air-dried samples were used to measure the basic physicochemical properties and elemental concentrations, and the moist samples were used to measure the biological indicators and concentrations of NO_3^- and NH_4^+. Both samples were stored in the refrigerator at 4°C prior to analysis.

Compost Analysis

The pH and EC were measured in 1 to 5 (w/v) compost to water ratio (Awasthi *et al*., 2017a). The Organic Matter (OM) content was determined by ashing at 550 °C for 6 hours (Haug, 1993). Total N (TN) was determined by the Kjeldahl method (Bremner, 1996). The NH_4^+ concentration was determined using the methods of indophenol blue (Li *et al*., 2015). The NO_3^- concentration was measured using the sulfosalicylic acid (Cataldo *et al*., 1975). The Germination Index (GI), as an indicator of phytotoxicity, was evaluated according to the method proposed by Zucconi *et al*. (1981). The activity of enzymes, including urease (Tabatabai, 1994), and dehydrogenase (Schinner *et al*., 2012) and microbial respiration (Anderson, 1983) were also determined in three composting periods of mesophilic, thermophilic, and maturing (1, 7, and 90 days, respectively). The humic acid was extracted and purified from compost according to the method described by Sánchez- Monedero *et al*. (2002). To determine the E_4/E_6 (absorbance ratio at 465 nm to 665 nm) and E_3/E_5 (absorbance ratio at 300 nm to 500 nm) ratios, the absorbance was measured using a spectrophotometer (SU-6100, Philler Scientific) at wavelengths of 465, 665, 300, and 500 nm (Chen et al., 1977).

Statistical Analysis

After the normality test, a repeated-measures ANOVA was performed to evaluate the main and interaction effects of treatments and time on some dynamic response characteristics. The mean comparisons were performed by the Duncan method ($P \leq 0.05$). Principal component analysis (PCA) and cluster analysis were also used to group similar individuals. All statistical analyses and drawing graphs were performed using SPSS 27.0 and Origin software**.**

RESULTS AND DISCUSSION

Effect of Chemical Activation on Biochar Properties

The chemical activation of biochar caused the appearance of a mesh structure with irregularly sized cavities and deep pores by modifying the biochar surface structure (Figures 1-a, -b, and -c). An *et al*. (2020) also reported that the chemical activation of biochar significantly changed the biochar

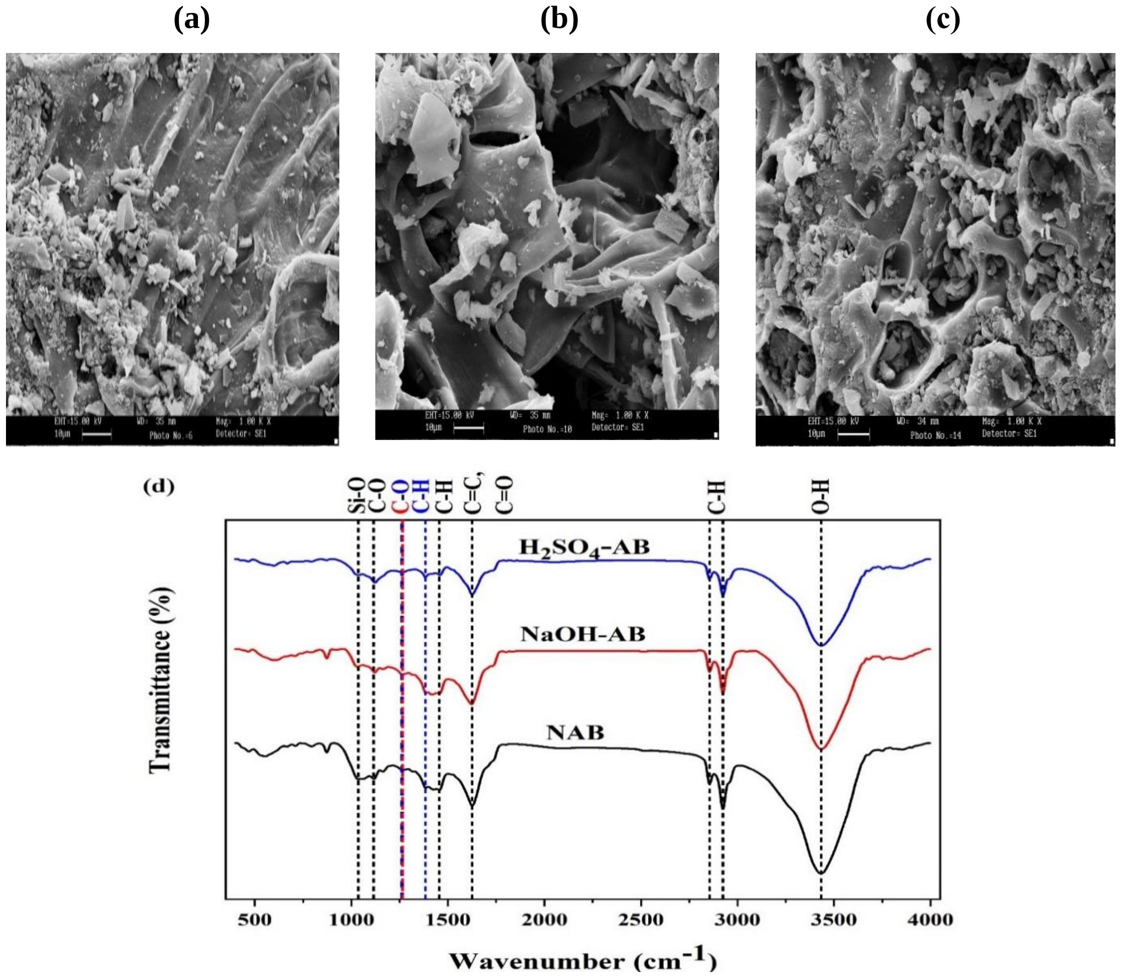


Figure 1. Scanning Electron Microscope (SEM) images of NAB (a), NaOH-AB (b), H_2SO_4-AB (c), and FTIR spectra of NAB and NaOH-AB and H_2SO_4-AB (d).

surface structure and increased its specific surface area.

Figure 1-d shows the FTIR spectra of the activated and Non-Activated Biochars (NAB). No distinct differences in the position of the relevant peaks were observed between the FTIR spectra of the non-activated and activated biochars. However, similar to the results of Dehkhoda *et al*. (2014), the chemical activation of biochar diminished the intensity of the peaks, indicating removal or reduction of some compounds. The activation of biochar each produced a peak of approximately 1,260 to 1,270 cm^{-1} related to the presence of C-O in aryl esters (aromatic structure). On the other hand, H_2SO_4-AB produced a peak of approximately 1384 cm^{-1} compared to NaOH-AB and NAB (related to the presence of C-H in CH_2 or CH_3 (aliphatic structure).

Impact of Biochar on Some Compost Maturity and Stability Indices

The addition of biochar increased the temperature in the thermophilic phase ($P< 0.05$), indicating the effect of biochar on microbial activity (Figure 2-a). Except for the control and H_2SO_4-AB (5%) treatment, in which the thermophilic period was five days, the rest of the biochar treatments had a longer thermophilic period (6 and 7 days). On the first day of the thermophilic period, the minimum temperature (54.5°C) was related to the control and the maximum (71.5°C) was associated with the longest thermophilic period (7 days) for the NaOH-AB (5%) treatment. Compared to the control, biochar treatments led to the early onset of the thermophilic phase, increasing the temperature and prolonging this phase, which agrees with the results of Manu *et al*. (2021).

The compost pH fluctuated between 7.4 and 7.9. As shown in Figure 2-b, at the initial phase of composting, the pH decreased, probably due to the release of organic acids, then, decomposition of proteins started and resulted in an increase in pH due to NH_3 production. On days 28 to 42, the pH increased again due to the continued decomposition of organic acids, which was consistent with Wang *et al.* (2023). Finally, pH of the compost pile stabilized at values between 7.49 and 7.74 and the compost produced in the NaOH-AB (10%) treatment had the highest pH (7.74) ($P< 0.05$), in response to NaOH solution used in the biochar activation process. There is confusing literature on biochar effects. Both increasing (Vandecasteele *et al*., 2016) and decreasing (Mao *et al*., 2018) effects of biochar addition on the final pH of the compost piles have been reported. However, some studies similar to our study, did not observe a significant difference in the pH of the final compost (Manu *et al*., 2021; Janczak *et al*., 2017). Much of the confusion has probably arisen from the different nature of feedstock as well as biochar and different conditions of co-composting processes.

According to Figure 2-c, the maximum and minimum values of final EC were recorded in the control (9.32 dS m^{-1}) and $B_{1\text{-}2mm}$ (10%) treatments (7.41 dS m^{-1}), respectively. The increase in EC was more intense in the thermophilic period and can be related to the increase in the activity of microorganisms and mineralization of OM. The most significant decrease was found in the treatments with 10% biochar, which indicated the dilution or absorption effect of added biochar. Qu *et al*. (2020) also reported the potential of biochar to reduce compost EC values through dilution and/or absorption.

The content of OM decreased over the time of composting process due to the consumption of carbon by microorganisms (Figure 2-d). After the thermophilic period, the decrease in OM content slowed. In the final compost, the highest and lowest OM contents were observed in the $B_{1\text{-}2mm}$ (10%) treatment (37.93%) and the control (27.1% based on dry weight), respectively ($P< 0.05$). In general, the level of OM in the 10% biochar treatments was almost higher than that in the 5% biochar treatments. Due to the chemical recalcitrance of biochar aromatic structure, it does not go through severe degradation during composting. This is consistent with the results of Manu *et al.* (2021). The reduction in OM content was the highest in the H_2SO_4-AB (10%) treatment (12.26%) and the lowest in the control (7.18%).

The NH_4^+ concentration increased at the beginning of the thermophilic period and then decreased (Figure 2-e). The initial increase could be due to ammonification reactions. In the final compost, the NaOH-AB (10%) treatment had the lowest NH_4^+ concentration (70 mg kg^{-1}), and the control had the highest NH_4^+ concentration (153 mg kg^{-1}), with significant differences from the rest of the treatments ($P< 0.05$), indicating the positive effect of biochar on the reduction in NH_4^+ concentration. The activated biochars, especially NaOH-AB (5%), had the highest impact on reducing NH_4^+ concentration, while the control had the lowest. This observation can be explained by combined roles of adsorption (the high absorption capacity of the activated biochars for NH_4^+) and microbial immobilization in reducing nitrogen loss. On the other hand, the carboxylic and phenolic functional groups attached to the surface of biochar had negative charges to adsorb NH_4^+, as a result of the aging process (Nguyen *et al*., 2017) or activation with NaOH.

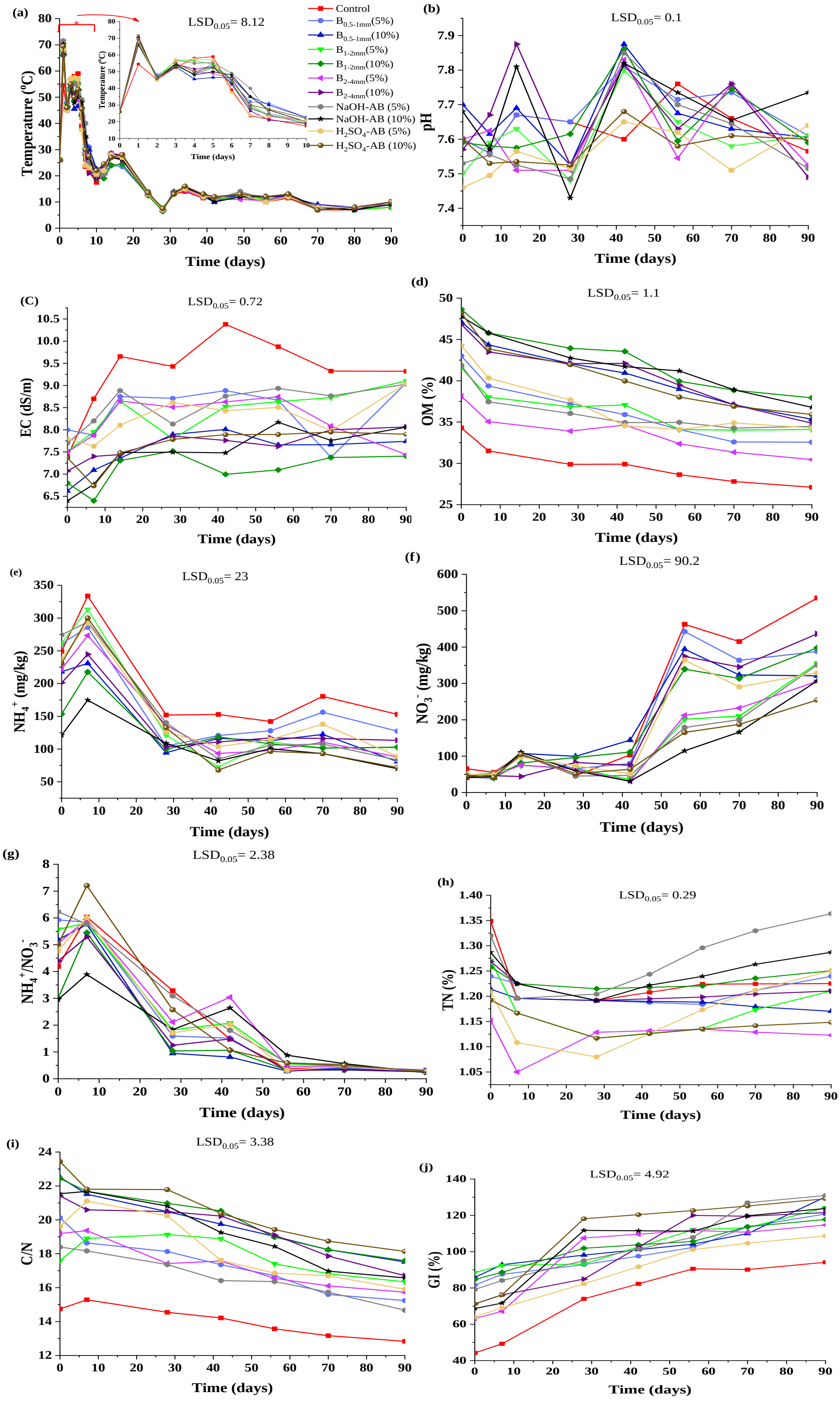


Figure 2. Changes in temperature (a), pH (b), EC (c), OM (d), NH_4^+ (g) and NO_3^- concentrations (h), NH_4^+/NO_3^- ratio (i), TN (j), C/N ratio (k), and GI% (l) during composting.

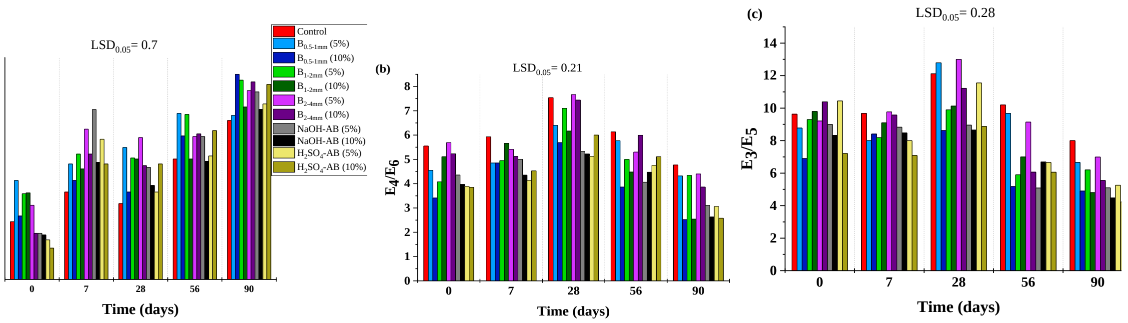
During composting, the concentration of NO_3^-, in contrast to NH_4^+, increased (Figure 2-f). In the first few weeks of the composting process, the NO_3^- concentration was low, and there were no significant changes in its concentration, because the temperature, pH, or NH_4^+ concentration was high enough to prevent the activity and growth of nitrate-producing bacteria (Ren *et al*., 2019; Wang *et al*., 2023). After 42 days, the NO_3^- concentration rapidly started to increase and, finally, reached a relatively constant level. The control and the H_2SO_4-AB (10%) treatment had the highest and lowest NO_3^- concentrations, respectively ($P< 0.05$). These results were consistent with the results of Manu *et al*. (2021). The higher concentration of NO_3^- in the control was due to its lower temperature, which favored the nitrification process.

The NH_4^+/NO_3^- ratio is used as a nitrification index to check the compost maturity and stability. Ratios less than 0.5 are considered fully mature compost. All the composts produced in this research were fully mature regarding the NH_4^+/NO_3^- ratio (Figure 2-g). The highest and lowest ratios in the final compost were detected in the control (0.33) and the NaOH-AB (10%) treatment (0.23), respectively. It was observed that the treatments with 10% biochar had lower NH_4^+/NO_3^- molar ratios and reached the mature phase earlier. Furthermore, in the NaOH-AB treatments, the NH_4^+/NO_3^- ratio decreased with decreasing biochar particle size ($B_{0.5\text{-}1mm}< B_{1\text{-}2mm}< B_{2\text{-}4mm}$).

In this study, the TN content first decreased sharply and then gradually increased during the composting process ($P> 0.05$) (Figure 2-h). The most significant decrease in TN content coincided with a sharp increase in NH_4^+ concentration. These results were consistent with the reports of Wang *et al*. (2023). The reason for the reduction in TN content in the thermophilic phase can be associated with de-nitrification and/or ammonia volatilization. The TN content decreased in all treatments from the first to the seventh day (thermophilic period). However, the highest initial TN content (1.35%) and the maximum of its subsequent decrease from the first day to the seventh day (11.35%) were both observed in the control ($P< 0.05$). This sharp decrease was accompanied by a significant increase in NH_4^+ concentration (Figure 2-e). Manu *et al*. (2021), reported that N losses during the composting averaged 31.4% TN, 17.2% NH_3, and 1.4% N_2O.

The decline in the C/N ratio in the control was less than that in the biochar-amended treatments (Figure 2-i). The lowest C/N ratio at both the beginning and end of the composting process was detected in the control (14.74 and 12.83, respectively), which indicated the loss of nitrogen through ammonia volatilization and/or NO_3^- leaching from the compost pile. At low C/N ratios, carbon is consumed before nitrogen fixation, and an unpleasant smell is generated due to ammonia volatilization. In the conditions of this research, the decline in the C/N ratio in the composts that received biochar was 28-46% higher than the decline in the C/N ratio in the control. The average C/N ratio in the composts receiving 10% biochar was higher than those receiving 5% biochar. Wang *et al*. (2023) recommended the use of biochar to decrease the C/N ratio of the final compost, likely due to enhanced nitrogen conservation and OM degradation in the compost pile. However, other researchers, such as Vandecasteele *et al*. (2016), found the addition of biochar to be inappropriate, likely due to the high doses used. Some studies also reported no significant difference in the C/N ratio between composts with and without biochar incorporation (Malińska *et al*., 2014). One of the reasons for these conflicting results is the difference in the C/N ratio of the raw materials. Considering the carbon content in the biochar used in this research (51-64%), it is recommended to add biochar to MSW in order to increase the C/N ratio to the appropriate range of 20-30 and prevent nitrogen loss.

The most important tests to evaluate compost quality characteristics is the GI.



(a) (b) (c)

Figure 3. Time dependence of humification indices during the co-composing process: Humic acid yield (a), E_4/E_6 ratio (b), and E_3/E_5 ratio (c).

The standard value of the GI is reported to be ≥ 80% for compost maturity (Zucconi *et al*., 1981). The GI had an increasing trend during composting (Figure 2-j). However, in the final compost, the control had the lowest GI (94%), and the NaOH-AB (5%) treatment had the highest GI (131%) ($P < 0.05$). Similar to the results of this research, some researchers also reported that the GI in composts with biochar was higher than that in composts without biochar (Manu *et al*., 2021; Wang *et al*., 2023). The higher GI in the biochar treatments compared to the control in this study can be attributed to their higher temperature and longer thermophilic period, which helped remove pathogenic bacteria and improve compost quality.

Humic Acid Yield, E_4/E_6 and E_3/E_5 Ratios

The HA yield increased during composting, mainly in the thermophilic phase (Figure 3-a). The highest and lowest HA% were related to the $B_{0.5\text{-}1mm}$ (10%) treatment (8.9%) and the control (6.9%), respectively. By adding 0 to 10% biochar to the compost, the HA% of the final compost increased, on average, from 0 to 22.54%, which is consistent with the results of Jindo *et al*. (2016). The enhanced humic acid production induced by biochar addition during composting may be due to the release of aromatic precursors from biochar or the adsorption of soluble organic compounds on the active surfaces of biochar (Jindo *et al*., 2016).

The E_4/E_6 ratio is inversely related to the degree of aromatic condensation of the humic substances (Ren *et al*., 2019). The E_3/E_5 ratio also denotes a more or less similar concept. In this research, the trends of both the E_4/E_6 and E_3/E_5 ratios over time increased first and then decreased (Figures 3-b, and -c). For composts with low degrees of humification due to the presence of proteins and carbohydrates, the ratios of E_4/E_6 and E_3/E_5 were high (Chen *et al*., 1977). As the degree of humification increased, large molecules were formed, and the E_4/E_6 and E_3/E_5 ratios decreased. The E_4/E_6 ratios of the extracted HA varied between 2 and 10. The ratios near 2 are considered to be mature compost. In this research, the control had the highest E_4/E_6 and E_3/E_5 ratios (4.77 and 8, respectively), and the $B_{0.5\text{-}1mm}$ (10%), $B_{1\text{-}2mm}$ (10%), NaOH-AB (10%), and H_2SO_4-AB (10%) treatments had the lowest ratios of E_4/E_6 (2.52 to 2.63) and E_3/E_5 (4.23 to 4.9) ($P < 0.05$). Wang *et al*. (2023) also reported E_4/E_6 ratios of 2.84 to 3.47 for biochar-treated composts. The control in the compost production process decreases in the E_4/E_6 and E_3/E_5 ratios, indicating the lower production of humic substances without biochar application. These results were consistent with those of Wang *et al*. (2023) and Manu *et al*. (2021).

Microbial Respiration, Activity of Urease, and Dehydrogenase

The biochar treatments, compared to the control, caused a significant increase in microbial respiration for the thermophilic period only ($P< 0.05$). Microbial respiration increased in the thermophilic period due to the presence of easily degradable compounds, whereas it decreased in the final days of composting (Figure 4-a). In the thermophilic period, the control and the AB treatments had the lowest and highest microbial respiration, respectively. Biochars with smaller sizes ($B_{0.5\text{-}1mm}$ and $B_{1\text{-}2mm}$) had greater rates of microbial respiration than biochars with larger sizes ($B_{2\text{-}4mm}$). This is probably because of their higher specific surface area supporting a large proportion of the total microbial community in the compost pile. The biochar treatments had higher levels of microbial respiration (17.5%, on average) than the control. This finding is consistent with the results of Steiner *et al*. (2011).

Urease is an enzyme whose activity is determined by measuring the concentration of NH_4^+ produced. In the final compost, the highest and lowest urease activities were observed in the control and the H_2SO_4-AB (10%) treatment, respectively. Similar results were obtained for the NH_4^+ concentration. As expected, urease activity increased from the beginning of composting to the thermophilic phase and then decreased toward the maturing phase (Figure 4-b).

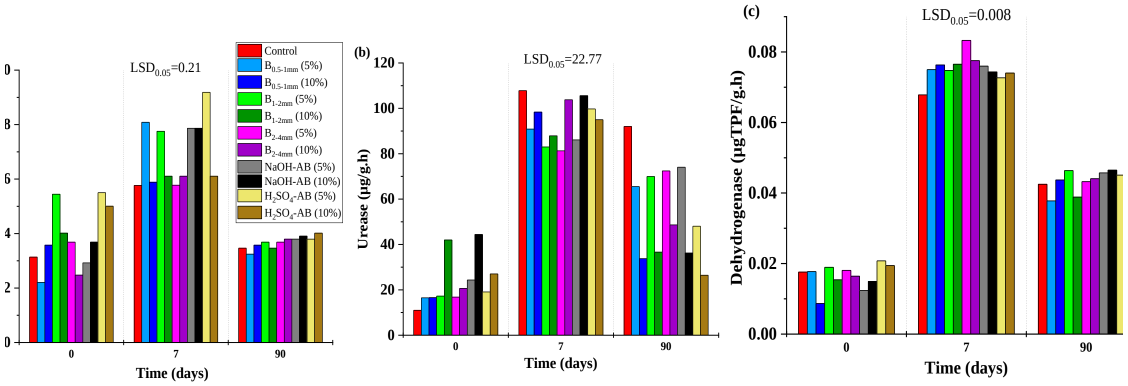


Figure 4. Changes in biological indices during composting: Respiration (a), urease (b), and dehydrogenase (c).

The activity of dehydrogenases enzyme often matches the microbial activity. In this study, the changes in dehydrogenase activity were similar to those observed for microbial respiration and urease activity, with a maximum in the thermophilic period (Figure 4-c). Zhang and Sun (2014) also reported that the incorporation of biochar can increase the activity of dehydrogenase in the thermophilic phase. The possible reason for this is the supply of nutrients from the biochar.

Principal Component Analysis (PCA)

Based on the results obtained, 61% of the cumulative variance is explained by the first and second components (Figure 5). Among the quality parameters of the produced composts, those with the most impact on the first component were C/N> OM> Urease activity> Temperature> NO_3^-> EC> E_3/E_5 ratio> E_4/E_6 ratio> NH_4^+ concentration; and those with the most influence on the second component were HA> Dehydrogenase> GI. In addition, PCA enabled the grouping of different composts. As shown in Figure 5 (red points), there was a significant distance between the control and the biochar-treated

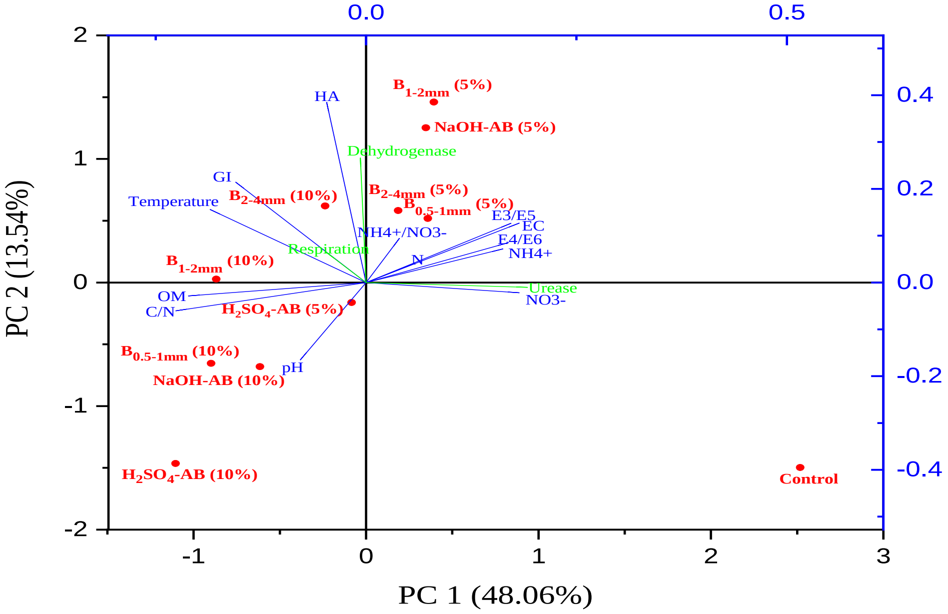


Figure 5. PCA biplot during composting.

composts, indicating the significance of biochar incorporation in the composting process. To elaborate on specific interactions between variables, it can be noted that the reduction in the C/N ratio was associated with an increase in OM, indicating improved decomposition of OM in the presence of AB. The NaOH/H_2SO_4-activated biochars enhanced microbial activity and surface interactions, which contributed to a faster reduction in the C/N ratio. Additionally, a positive correlation between OM content and temperature during the thermophilic phase highlighted biochar's role in enhancing microbial activity and enhancing compost quality. Similar to our findings, Awasthi *et al*. (2017a) reported that the PCA showed the strongest correlation with OM degradation and the C/N ratio.

CONCLUSIONS

The results indicated that, chemically, AB (NaOH-AB and H_2SO_4-AB) enhanced stability and maturity indices, promoted OM biodegradation, and improved humification indices, particularly with small-sized biochar (0.5-2 mm) and when incorporating 10% biochar compared to 5% (w/w). This presents an effective strategy for improving the quality of MSW co-compost. PCA further highlighted the critical role of the C/N ratio and OM content in the co-composting. We recommend that future studies compare various activation methods, optimize biochar activation conditions to maximize composting efficiency, and conduct cost-benefit and carbon footprint analyses.

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کمپوست سازی همزمان زباله‌های جامد شهری با بیوچار فعال: رویکردی امیدوارکننده برای بهبود کیفیت کمپوست

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چکیده

بیوچار مشکلات کمپوست‌سازی را کاهش داده و کیفیت کمپوست را بهبود می‌بخشد. با این حال، بیوچار فعال (AB) و اندازه ذرات آن اغلب نادیده گرفته می‌شوند. این تحقیق با هدف ارزیابی تأثیر کمپوست‌سازی مشترک پسماند جامد شهری (MSW) با بیوچار و بیوچار فعال با اندازه‌های مختلف بر کیفیت کمپوست حاصل انجام شد. MSW به طور کامل با بیوچارهای با اندازه‌های مختلف ($B_{0.5-1mm}$, B_{1-2mm}, B_{2-4mm}) و همچنین بیوچارهای فعال‌شده با (H_2SO_4- $AB_{0.5-1mm}$, NaOH- $AB_{0.5-1mm}$) مخلوط شد و به مدت 90 روز تا زمان بلوغ کمپوست، فرایند کمپوست‌سازی مشترک انجام گرفت. نتایج نشان داد که فعال‌سازی بیوچار با NaOH باعث ایجاد ساختار مشبک روی سطح بیوچار شده و منجر به بهبود شاخص‌های پایداری و رسیدگی کمپوست، افزایش شاخص‌های تجزیه‌زیستی و هوموسی‌شدن می‌شود. به‌طور خاص، NaOH-AB (5% w/w) بالاترین دما (71/5 درجه سانتی‌گراد)، شاخص جوانه‌زنی (130/9%) و محتوای نیتروژن کل (1/37%) و طولانی‌ترین دوره گرمادوستی (۷روز) را نشان داد. بالاترین میزان ماده آلی (37/9%) (OM) و کمترین میزان قابلیت هدایت الکتریکی (7/4 دسی‌زیمنس بر متر) در B_{1-2mm} (10% w/w) ثبت شد. علاوه بر این، کمترین غلظت نیترات (254/4 میلی‌گرم بر کیلوگرم) و بالاترین نسبت C/N (18/1) در H_2SO_4-AB (10%) به‌دست آمد. تجزیه و تحلیل مؤلفه‌های اصلی (PCA) نقش حیاتی نسبت C/N و میزان OM را در طول کمپوست‌سازی برجسته کرد. این مطالعه افزودن بیوچار به MSW را برای دستیابی به نسبت C/N مناسب و جلوگیری از هدررفت نیتروژن توصیه می‌کند. به‌طور کلی، ترکیب بیوچارهای فعال شده با NaOH و H_2SO_4 به عنوان یک استراتژی ارزشمند برای کمپوست‌سازی پسماند جامد شهری شناخته شد و یافته‌ها بینش‌های ارزشمندی در مورد پتانسیل بیوچار در بهینه‌سازی فرایند کمپوست‌سازی ارائه می‌دهند.