

Research article

Untapped potential of zeolites in optimization of food waste composting

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ABSTRACT

This study aims to examine the effect of zeolites in optimizing the process of food waste composting. A novel method of sequential hydrothermal was introduced to modify the natural zeolite and apply to in-vessel compost bioreactors. Raw and modified natural zeolites were applied at 10 and 15% (w/w) of the total waste and compared with un-amended control trial. Both raw and modified zeolites affected the composting process, but the notable results were observed for modified natural zeolite. The results for compost stability parameters were prominent at 15% modified natural zeolite concentration. The rapid and long-term thermophilic temperature and moisture content reduction to the optimum range was observed for modified natural zeolite. Furthermore, the total ammonium (NH_4^+) and nitrate (NO_3^-) concentration in modified natural zeolite were increased by 11.1 and 21.5% respectively as compared to raw zeolite. Compost stability against moisture contents (MC), electrical conductivity (EC), organic matters (OM), total carbon (TC), mineral nitrogen, nitrification index (NI) and germination index (GI) was achieved after 60 days of composting that was in accordance with the international compost quality standards. The findings of this study suggested the suitability of modified natural zeolite addition at 15% to the total waste as the optimum ratio for the composting of food waste in order to achieve a stable nutrient-rich compost.

1. Introduction

Today the sustainable management of food waste is a stern issue in most of the developing countries including the Kingdom of Saudi Arabia (KSA) where around 8 million tons of food waste is generated every year (Chan et al., 2016; Waqas et al., 2018a). Most of this food waste is disposed to open landfills as being the easiest way. Such practice is causing several environmental issues such as emissions of greenhouse gases (GHG), odors and leachate production (Anjum et al., 2016). The key constituents of this food waste are carbohydrates (60%), proteins (20%), and lipids (10%), which make them suitable to process into a stable and nutrient-rich organic fertilizer and other value-added chemicals like enzymes (Awasthi et al., 2017). Therefore, in KSA, food waste composting has emerged as a sustainable, economical and eco-friendly approach to produce organic fertilizer while reducing the food

waste problems (Waqas et al., 2017).

The composting process is an aerobic degradation of complex organic matters (OM) into simpler components and finally into a mature organic compost by the action of different microbes including bacteria and fungi (Sadeef et al., 2016). However, the poor chemical and physical structure of food waste pose several challenges during the composting process (Wang et al., 2016). During the early stages of composting, the rapid degradation of readily available OM initiates a sequence of events that result in intensive acidification and slowing down of composting process (Waqas et al., 2018a). Several research studies convincingly demonstrated the addition of various additives and bulking agents to overcome these limitations and modify the physical structure of the composting matrix (Wang et al., 2016). Several organic materials such as biochar, wood barks, and leaves, and inorganic materials like zeolites, lime and minerals were added as bulking agents to the composting

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process with the ambition to optimize and provide an appropriate biological, chemical and physical properties to the composting matrix (Dias et al., 2010).

The critical function of adding bulking agents is for drying and structural amendment that provide air voids for better aeration of the pile and structural support to hinder the physical compaction of the pile (Dias et al., 2010; Waqas et al., 2017). Among the applied bulking agents to the composting matrix, the use of natural zeolite is getting significant attention in recent years due to its unique physiochemical characteristics (Awasthi et al., 2016). Zeolites are naturally occurring hydrated aluminosilicate minerals of a porous structure with important physiochemical properties such as cation exchange capacity, sorption, bulking agent and molecular sieving (Nizami et al., 2016; Chan et al., 2016). The microporous structure makes zeolite capable of absorbing excess moisture, therefore provides aerobic conditions to microbes (Jiwan et al., 2013). In addition, zeolite alters the compost pH, as pH is a critical parameter that reflects the degradation process and influences the microbial activities and GHGs emission during the composting process (Awasthi et al., 2016). During the initial stages, the formation of organic acids decreases the pH of the compost mixture that is responsible for inhibiting microbial activities and degradation process (Waqas et al., 2018a). The addition of zeolite increases the pH of the compost mixture due to its porous nature and provides aerobic conditions to the microbes for their activities and degradation process (Waqas et al., 2018b). Moreover, the high cation exchange capacity ($100 \text{ cmol}_c \text{ kg}^{-1}$) of zeolite allows the adsorption of ammonium and nitrate ions on its surface and thus inhibits its conversion to free ammonia that ultimately controls nitrogen losses and odors problems in the composting process (Omar et al., 2015).

The use of modified natural zeolite for improving the process of food waste composting is seldom reported in the literature. The most common modification methods used for the structural and physiochemical properties of zeolite are acid and thermal treatments (Ajemba, 2012). Thermal treatment is a physical activation and modification process that involves calcination at elevated temperatures. The main advantage of thermal activation is the improvement in surface chemistry by removing any impurities or moisture attached to the framework (Al-Asheh et al., 2003; Ajemba, 2012). During thermal treatment, the high temperature leads to the destruction of vicinal micropores walls and increases the mesopore content (Aivalioti et al., 2010). Moreover, Ajemba (2012) reported that in comparison to a raw sample, the adsorptive capacity and surface area of the modified sample were increased three times using thermal treatment.

The present study was designed to introduce a novel method of sequential hydrothermal modification of natural zeolite and its application to in-vessel food waste composting. The natural zeolite sample was heated at high temperature followed by steam treatment, as zeolites are hydrated aluminosilicate minerals that contain water molecule in its structure (Nizami et al., 2016). High-temperature treatment may change its chemical structure, therefore the samples were steamed to rehydrate its structure. The overall aim of the study was to examine the effect of both natural zeolite and modified natural zeolite in optimizing the process of food waste composting.

2. Material and methods

2.1. Feedstock preparation

Food waste was regularly collected, to get a homogenous mixture of feedstock, for one week from the central canteen of King Abdulaziz University (KAU), Jeddah, KSA. Every day about 1500 individuals enters the canteen for breakfast, whereas during lunchtime the number exceeds 3000. The moisture content (MC) of the collected food waste sample was 87.9%, which was unfavorable for the composting as high MC can cause anaerobic and waterlogged conditions that lead to poor composting process (Brinton, 2000). The sample was sun-dried for 24 h

Table 1

Physiochemical characteristics of food waste.

Parameters	Unit	Mean	Standard Deviation
Moisture content (MC)	%	77.5	3.08
Total solid	%	22.5	3.71
pH		6.7	0.51
Electrical conductivity (EC)	mS cm^{-1}	0.9	0.21
Organic matter (OM)	%	86.1	2.97
Ash content	%	13.8	3.01
Carbon	%	51.3	1.61
Ammonium Nitrogen (NH_4)	mg kg^{-1}	83.2	7.55
Nitrate Nitrogen (NO_3)	mg kg^{-1}	20.3	2.34

The analysis was made on dry weight basis except for moisture, pH, and EC.

to achieve the desired MC ($\leq 70\%$) for the process (Brinton, 2000; EPA, 2014). According to the standard guidelines of environmental protection agency (EPA, 2014), fractional characterization of the food waste sample was carried out, and percent fraction of each component like rice, grain, vegetable, fruit, and bakery was estimated. Likewise, to accelerate the degradation rates of OM during the initial stage of composting, the sample was well mixed and ground into small particles with less than 5 cm. The lowered particle size of the sample was to provide a high surface area to the microbes for efficient degradation (Rawat et al., 2005). In addition, various physiochemical properties of the food waste were determined according to the standard methods (FCQAO, 1994) and their results were plotted in the given Table 1.

2.2. Experimental setup

A laboratory scale in-vessel compost bioreactor made of plastic was used. The height and diameter of the reactor was 63.5 and 68.6 cm respectively while the thickness of the vessel was 10 mm. The vessel was wrapped from outside with styrofoam and aluminum foil to

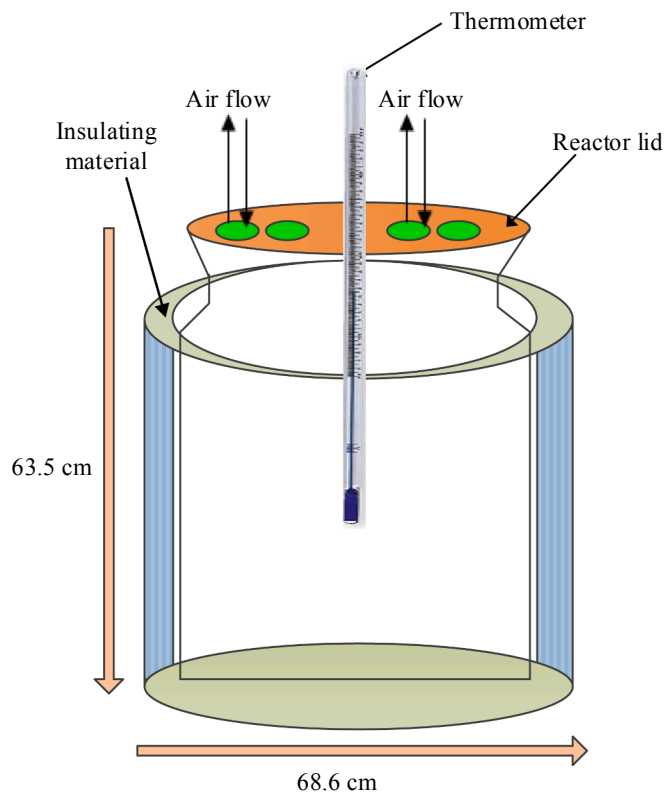


Fig. 1. Schematic diagram of in-vessel compost bioreactor.

Table 2
Comparison table for in-vessel composting experiments.

Study	Reactor type	Reactor volume	Feedstock materials	Sample size for analysis	Max. Temp. (°C)	Observations
Sadaka and El-Taweel (2003)	Compost-bin	10 kg	Household waste	10 g	60.1	<ul style="list-style-type: none"> Thermophilic temperature was achieved between the second to third week of composting MC was reduced at 0.003 m³/h/kg aeration, and this reduction was due to change in C:N ratio and high degradation
Al-Jabi et al. (2008)	In-vessel	5 L	Food waste	60 g	57	<ul style="list-style-type: none"> Zeolite addition reduced NH₃ losses by 41%
Makan et al. (2014)	In-vessel cylinder	15 L	MSW	20 g	52	<ul style="list-style-type: none"> The losses reduction was due to the high adsorption potential of zeolite Air pressure effect the in-vessel composting of MSW
Zhang et al. (2014)	In-vessel	12.5 L	Sludge	10 g	Maintained at 35	<ul style="list-style-type: none"> 0.6 bar pressure allowed elevated pile temperature Good quality and stable compost was produced at 0.4 and 0.8 bar pressure The Porous structure of biochar accelerate the OM degradation in sludge During aerobic degradation, the oxygen uptake rates of sewage sludge were increased due to biochar
Madrini et al. (2016)	In-vessel cylinder	10 L	Food-rice hull		64	<ul style="list-style-type: none"> The fulvic and humic-acid-like compounds were, increased by 26% and 30% respectively Zeolite addition from 31.5 to 47.2% significantly reduce NH₃ emission during food waste composting
Jia et al. (2016)	In-vessel	0.5 L	Chicken manure	5 g	53 °C	<ul style="list-style-type: none"> Biochar addition increase the pile temperature by 5.2% and CO₂ emission by a 148% 20% biochar addition reduced the MC and increased the pH of the compost CH₄ emission reduction and high degradation can be achieved by frequent turning (daily vs. every 3 or 7 days)
Zhang et al. (2016)	In-vessel	15 L	Pig manure		66.3	<ul style="list-style-type: none"> Biochar enhanced the OM degradation, and compost maturity was achieved after 42 days EC and the concentrations of water-soluble nutrients was increased that showed high-quality compost
Stamou and Antizar-Ladislao (2016)	In-vessel	2 L	Municipal solid waste		Maintained at 38	<ul style="list-style-type: none"> Nanoparticles did not inhibit microbial degradation Higher rates of nanoparticles application result in higher removal of inorganic carbon and lower humins formation
Chan et al. (2016)	In-vessel	20 L	Food waste	240 g	Around 65	<ul style="list-style-type: none"> 10% zeolite reduced nitrogen loss and increased OM degradation compost salinity was reduced by the combined addition of struvite and zeolite Zeolite lowered the EC to 2.82 mS cm⁻¹ and improved maturity of the compost

prevent heat losses during the process. Fig. 1 showed the schematic diagram of the in-vessel compost bioreactor. Up to 70%, the reactor was filled with the feedstock whereas the remaining 30% of the area was kept as a headspace (Waqas et al., 2017, 2018a). After the feedstock loading, the lid of bioreactor was closed. The pores located on the lid of the bioreactor acted as air ventilator. A thermometer was fixed in the middle of the bioreactor for monitoring the temperature variation during the process. For achieving uniform mixing and oxygen (O₂) supply throughout the experiment, the composting mixture was shredded mechanically through an agitator as recommended by An et al. (2012). The method adopted for aeration through mixing and turning of the compost materials was according to the procedure recommended by Singh and Kalamdhad (2014), Latifah et al. (2015) and Jindo et al. (2016). Furthermore, the current laboratory scale compost setup was in-line with the previously reported research works (Table 2).

2.3. Collection and characterization of natural zeolite

Natural zeolite was collected from Harrat Shamah, which is located on coordinate E39°40'18" at the distance of 100 km south to south-eastern Jeddah. The collected sample was washed with distilled water to remove impurities. After washing and drying in the oven, zeolite sample was crushed to a particle size of 3.0–3.5 mm for compost application, whereas for characterization like X-ray diffraction (XRD) the sample was further crushed to fine powder and sieved. The crushing was carried out using a stone crushing machine available in the laboratory of Earth Sciences Department at King Abdulaziz University, Jeddah, KSA. XRD was performed to determine the chemical and structural composition of the collected zeolite. PANalyticalX'Pert Pro instrument was operated with copper radiation (30 kV, 30 mA) as an X-ray source. Diffraction patterns and all the scans were recorded over the 2θ range of 5–80° using a step size of 0.01 with the scan speed of 10 s/step (Nizami et al., 2016). The XRD results of tested natural zeolite were presented in Table 3.

2.4. Zeolite modification

A novel method of sequential hydrothermal modification of natural zeolite was performed. The process was comprised of heating the sample at high temperature followed by steam sterilization in an autoclave under high pressure and temperature. For modification, the crushed samples were washed with distilled water and dried in an oven at 105 °C for 1 h. First, the sample was thermally treated at 750 °C in a furnace for 2 h (Aivalioti et al., 2010). Right after the thermal treatment, the sample was steamed at pressure 30 psi for 15 min at temperature 250 °C.

2.5. Experimental scheme

Different experimental trials on food waste composting were carried out to assess the effect of raw and modified natural zeolites using in-vessel compost bioreactor. Both raw and modified natural zeolites were applied to the compost bioreactors as an amendment at 10 and 15% of

the total weight of food waste. Likewise, for comparing the results, a controlled trial was also performed using food waste composting without any amendment. Prior proceeding to the composting experiments, all the bulking, seeding, and composting materials were well mixed and filled in the bioreactors.

The arrangement of performed experimental trials were as follow:

- Trial A = no amendments (food waste 100%)
- Trial B = raw natural zeolite (10%) + food waste (90%)
- Trial C = raw natural zeolite (15%) + food waste (85%)
- Trial D = modified natural zeolite (10%) + food waste (90%)
- Trial E = modified natural zeolite (15%) + food waste (85%)

After feedstock feeding, a small amount of cow manure was added at 1:0.1 (wet weight basis) as microbial inoculum to start the composting process because during the initial stage the microbes present in the mixture are not active enough to start the degradation process (Nakasaka et al., 2004; Woodford, 2009). Likewise, chopped dried waste leaves were also added at 1:0.2 (wet weight basis) as a source of initial bulking agent, according to the recommendations of An et al. (2012). The reason was that during the initial stage the mixture was rich in moisture ($\geq 70\%$), hence dried leaves as a bulking agent was added to avoid the anaerobic conditions and provide aerobic conditions to the degrading microbes. All the experimental trials were replicated three times to confirm the results and appropriate statistical analysis.

2.6. Analytical techniques

Each experimental trial lasted for 90 days. The temperature of the compost mixture was recorded every day. For evaluating the compost maturity, 20–25 g of the fresh compost sample was taken from each bioreactor with 10 days intervals throughout the experimental period, in-line with the previously published work on the composting (Table 2). The sample collection was carried out according to the procedure adopted by Turan and Ergun (2008) and An et al. (2012). The collected samples were subjected to various analysis including MC (%), pH, electrical conductivity (EC), OM (%), ash contents (%), total carbon (TC), ammonium (NH₄⁺), nitrate (NO₃⁻), nitrification index (NI) and germination index (GI). MC was determined by drying the fresh compost sample at 105 °C for 24 h in an oven (Model LDO-060E, Daihan Labtech, Korea). The net percent loss in weight was calculated as MC according to the following formula (Chan et al., 2016).

$$MC(\%) = \frac{\text{dry weight of sample}}{\text{initial weight of sample}} \times 100. \quad (1)$$

For pH and EC determination, the fresh compost sample was mixed with deionized water at 1:10 (w/v) and shaken for 2 h using an oscillating shaker (MSASW, 1970). pH was measured using the pH probe (HI 769828-1) of Hanna multi-parameter (Model HI 9828, Hanna Instrument, USA), whereas for EC (mS cm⁻¹) the EC probe (HI 769828-3) of Hanna multi-parameter (Model HI 9828, Hanna Instrument, USA) was used. The MC, pH, and EC were determined by using the fresh compost samples, whereas for other parameters the dried samples were used. The dried samples after MC determination were burnt for 3 h at 550 °C in a muffle furnace (Model 5300A30/F6010-TS, Thomas Scientific, Swedesboro, USA) to determine OM. The percent loss in weight (volatile components) was calculated as OM (FCQAO, 1994). The ash content (%) was calculated from the mass remaining after ignition at 550 °C according to the formula provided by McClements (2005). Likewise, the total carbon in the samples was determined using the following equation of Brake (1992).

$$FC(\%) = \frac{100 - (\text{Ash}\%)}{1.8}. \quad (2)$$

Mineral nitrogen contents like NH₄⁺ and NO₃⁻ (mg kg⁻¹) were analyzed by following the standard procedures of compost examination

Table 3
Chemical composition of the collected natural zeolite.

Mineral name	Chemical formula	2-θ value
Quartz alpha	SiO ₂	26.62
Natrolite	Na ₂ (Al ₂ Si ₃)O ₁₀ ·2H ₂ O	13.63
Potassium feldspar	(Na,Ca) ₂ (Al,Si) ₆ O ₁₀ ·8 H ₂ O	20.82
Anthrophyllite	(Mg,Fe) ₇ Si ₈ O ₂ (OH) ₂	23.56
Augite	(Ca ₂ Na)(Mg,Fe,Al)(Si,Al) ₂ O ₆	27.52
Manganite	MnO(OH)	27.79
Quartz low	SiO ₂	29.88
Chlorites	M ₅₋₆ (Al,Si) ₄ O ₁₀ (OH) ₈	39.52

(Thompson et al., 2002). For compost maturity, NI is an important indicator that is a ratio between NH_4^+ and NO_3^- . The NI value above 3 represents an immature compost while the value up to 3 shows mature compost and NI below 0.5 suggests fully mature compost (CCQC, 2001). Following formula is used to calculate the NI of the compost.

$$\text{NI} = \frac{\text{NH}_4^+}{\text{NO}_3^-} \quad (3)$$

Additionally, the seed germination test was conducted to assess compost maturity. The germination assay was conducted on compost-water extract (1:5, w/v). Water extract was prepared by mixing 1 g of compost with 5 mL of deionized water and shake 1 h at 180 rpm on an orbital shaker. After extraction, the sample was filtered through Whatman no. 2 filter paper. For comparison, a controlled trial on germination assay was performed by using distilled water. GI (%) was calculated according to the following formula, as suggested by Zucconi et al. (1981).

$$\text{GI} = \frac{\text{Seed germination} \times \text{Root length of the compost sample}}{\text{Seed germination} \times \text{Root length of the control}} \times 100. \quad (4)$$

The root length of the seedlings was measured through a graduated scale in centimeters (cm). All the collected data were subjected to analysis of variance (ANOVA) test whereas the Tukey's Honest Significant Test was applied for multiple comparisons among the trials. All analysis was carried out using SPSS 16 (SPSS Inc., Chicago, IL, USA) statistical software at 5% probability level for testing the significance among the trials.

3. Results and discussion

3.1. Temperature and moisture content (MC)

Thermophilic temperature phase for at least 1 week was critical for the efficient removal of pathogens and to produce hygienic compost (Chan et al., 2016). Strauch and Ballarini (1994) reported that when the temperature reached beyond 55°C , mostly all pathogens were destroyed. Furthermore, elevated temperature promoted degradation of the complex substrate to simpler components (He et al., 2013). Fig. 2a

depicted the temperature variation in experimental trials treated with raw natural zeolite, whereas Fig. 2b showed the compost bioreactor blended with modified natural zeolite. The temperature of all the experimental trials was increased rapidly within the first week, representing the rapid degradation of readily degradable OM that acted as a primary source of nutrients for the microbes (Wang et al., 2013). Statistical analysis of the data revealed that the types of zeolite, their different concentrations and time had a significant effect on temperature. In addition, the combined interaction of time with zeolite types and concentration also showed a significant effect on temperature (Table 4). Moreover, the Tukey's HSD test for multiple comparisons also depicted high significant results for raw and modified natural zeolites and their concentrations towards temperature variation (Table 4). The results showed that all the experimental trials were entered to thermophilic stage within the first week and after 10 days the maximum temperature (65.3 and 56.7°C) was recorded for the trials treated with 15% of the modified and raw natural zeolite respectively (Fig. 2a and b).

The thermophilic stage was maintained for more than three weeks, and afterward, it was progressively reduced to the mesophilic and cooling stage. It was observed that after 50 days no significant changes in temperature were recorded (Fig. 2a and b). Likewise, for the trials with 10% of zeolite concentration the maximum temperature (55.3°C) was recorded for modified natural zeolite. However, this value for temperature was statistically like the raw natural zeolite (52°C). Similarly, for trial A the temperature was dropped drastically after 10 days and reached 36.7°C after 30 days. The achieved thermophilic range was not enough to complete OM degradation and effective pathogens removal. The probable reason behind the lower temperature profile in trial A was the formation of organic acids during intensive degradation of easily available OM. In addition, there was no alkaline amendment to buffer the acidic environment thus resulted in a pH decrease and made the environment unfavorable for the microbial activities (Chan et al., 2016; Waqas et al., 2018b). The high-water retention capacity of zeolite, due to high porosity, enabled them to capture excess moisture and provided favorable aerobic conditions for faster O_2 uptake to the degrading microbes (Jiwan et al., 2013). These conditions resulted in higher microbial activities to degrade OM

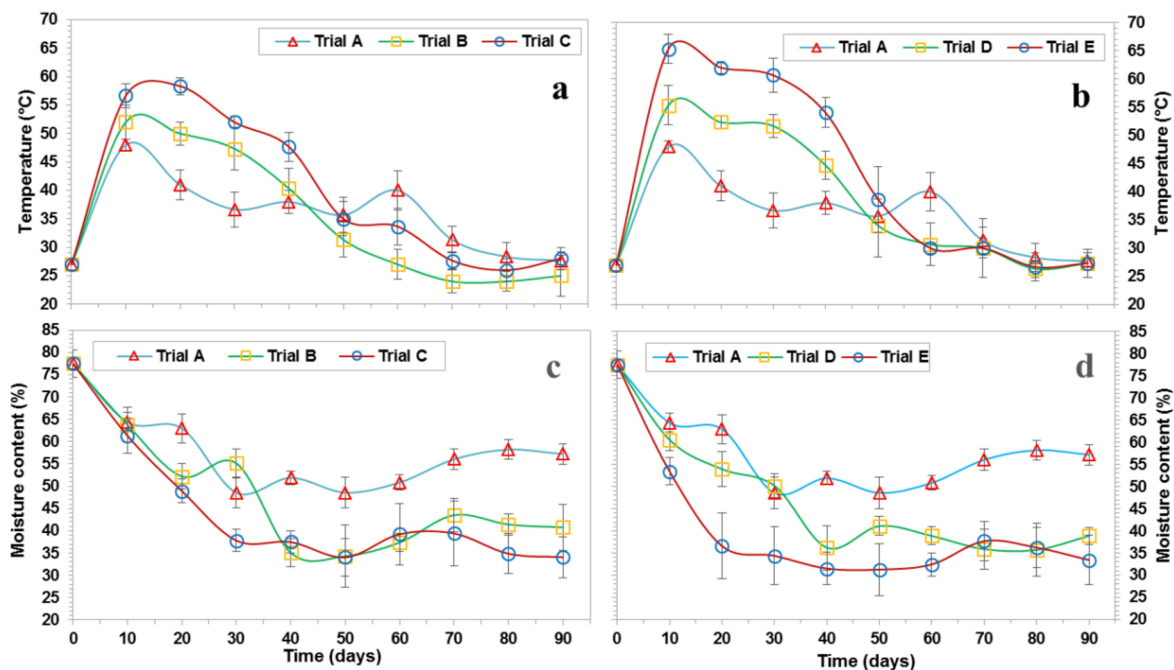


Fig. 2. Variation in temperature and moisture content during composting of food waste. Trial A: no zeolite amendment, Trial B: 10% raw natural zeolite, Trial C: 15% raw natural zeolite, Trial D: 10% modified natural zeolite, Trial E: 15% modified natural zeolite.

Table 4
Statistical analysis for compost parameters.

Source	SS	df	Temp	MC	pH
			F	F	F
Zeolites	279.07	1	43.82	15.37	.034
Concentrations	559.01	1	87.76	56.77	.000
Time	19263.83	9	336.05	195.1	.000
Zeolites * Conc.	.208	1	0.03	4.34	.039
Zeolites * Time	159.01	9	2.77	1.31	.235
Conc. * Time	293.74	9	5.12	5.70	.000
Z * C * T	99.54	9	1.73	2.75	.006
Error	828.00	130			
Corrected Total	23664.86	169			

Tukey's HSD Trials	Temp	MC	pH
	Mean Diff.	Mean Diff.	Mean Diff.
Conc.			
Control	-1.6333*	11.3220*	-2.303*
RZ	-4.6833*	13.9405*	-2.307*
MZ	-3.0500*	2.6185*	.0017
Concentrations			
0	-1.0000	10.1152*	-1.933*
10	-5.3167*	15.1473*	-2.671*
15	-4.3167*	5.0322*	-7383*

Source	pH	EC	OM	Ash	TC
	F	F	F	F	F
Zeolites	21.63	12.15	16.34	15.41	16.34
Concentrations	65.39	10.67	15.59	14.15	15.59
Time	25.50	136.5	257.9	251.4	257.9
Zeolites * Conc.	0.73	2.06	6.21	5.74	6.21
Zeolites * Time	0.71	1.78	1.27	1.27	1.27
Conc. * Time	4.10	1.33	7.46	7.04	7.46
Z * C * T	1.40	0.53	0.86	0.74	0.86
Error					
Corrected Total					

Tukey's HSD Trials	Temp	OM	Ash	TC
	Mean Diff.	Mean Diff.	Mean Diff.	Mean Diff.
Conc.				
Control	-9737*	4.8840*	4.1542*	2.7133*
RZ	-4.6833*	7.0107*	6.1574*	3.8947*
MZ	-3.0500*	2.1267*	2.0124*	1.1813*
Concentrations				
0	-1.0000	4.9088*	-4.9088*	2.7272*
10	-5.3167*	6.9858*	-6.9858*	3.8808*
15	-4.3167*	2.0770*	-2.0770*	1.1537*

Source	TC	NH ₄ -N	NO ₃ -N
	F	F	F
Zeolites	16.34	100.67	214.24
	.071	.000	.000

(continued on next page)

Table 4 (continued)

Source	TC			NH ₄ -N			NO ₃ -N		
	F	Sig.		F	Sig.		F	Sig.	
Concentrations	15.59	.011		73.21	.000		148.54	.000	
Time	257.9	.000		335.86	.000		641.36	.000	
Zeolites * Conc.	6.21	.014		1.36	.246		1.01	.316	
Zeolites * Time	1.27	.255		4.48	.004		11.06	.001	
Conc. * Time	7.46	.004		4.55	.000		10.15	.000	
Z *C *T	0.86	.557		1.22	.286		1.29	.246	
Error									
Corrected Total									
Tukey's HSD Trials			NH ₄ -N			NO ₃ -N			
Conc.	Conc.	Mean Diff.			Sig.		Mean Diff.	Sig.	
Control	RZ	-1.6333*			.000		-42.4424*	.002	
	MZ	-4.6833*			.000		-57.8860*	.000	
RZ	MZ	-3.0500*			.000		-15.4436*	.000	
Concentrations									
0	10	-1.0000			.000		-43.7345*	.000	
	15	-5.3167*			.000		-56.5939*	.005	
10	15	-4.3167*			.000		-12.8594*	.000	

RZ: Raw zeolite, MZ: Modified zeolite, Control: trial without zeolite addition.

*The mean difference is significant at the .05 level.

efficiently and ultimately achieved the thermophilic stage through rapid heat production (He et al., 2013). Likewise, other phenomena for the long-term thermophilic stage might be due to the higher OM content in initial feedstock that degraded with the production of heat (Awasthi et al., 2016; Chan et al., 2016). This phenomenon is highly reported that the long-term thermophilic stage during the composting process was due to the presence of complex OM and its slow decomposition to simpler molecules (Zeng et al., 2010; Suthar et al., 2012; Awasthi et al., 2016).

Fig. 2c and d showed variation in MC during the entire composting process. The ANOVA and Tukey's HSD test for multiple comparisons demonstrated that zeolite types, concentration and time showed a highly significant result towards MC variation (Table 4). At the start of the experiment, the MC was 77.5% that was changed during the process because of zeolite addition and their concentrations (Table 1). It was observed that the trials blended with 15% natural zeolite resulted in an apparent reduction in MC. The result showed that the MC was reduced with time where the lowest MC (31.3%) was recorded in trial E followed by trial C (34.1%) and trial B (34.3%) after 50 days of composting (Fig. 2c and d).

During the experimental period, fluctuation in MC was recorded for all trials. The reason was the release of water in the form of leachate during the degradation process, which was not removed and mixed again during turning of the composting mixture. Therefore, no extra water was added to the composting mixture. However, after 50 days of experimentation no significant changes in MC was recorded (Fig. 2c and d). The reason behind MC reduction in zeolite treated trials was the porous structure of zeolite that absorbed the moisture in their micro-porous cavities. It has been reported that zeolite has the water holding capacity up to 60% of their total weight due to high porosity and internal dehydrated cavities and channels (Turhan and Ergun, 2008; Omar et al., 2015). Similarly, the porosity can be further improved by removing the impurities from the internal cavities through high-temperature treatment (Ajemba, 2012). Moreover, it was observed that modified natural zeolite resulted in maximum MC reduction as compared to raw zeolite. Nizami et al. (2016) reported that zeolite has a high surface area up to $8.947 \text{ m}^2 \text{ g}^{-1}$ and high porosity that provides aerobic conditions and constitutes a suitable habitat for degrading microbial proliferation. MC at the end of the experiment was; trial A (57.2%), trial B (40.8%), trial C (34.1%), trial D (38.9%) and trial E (33.4%) (Table 5).

MC without zeolite amendment (trial A) was higher than the required limit (50%) in the final compost, as recommended by the compost standard guidelines (Rynk, 1994; OCQS, 2012). High MC hindered O₂ supply to aerobic microbes for their normal activities, led to anaerobic conditions, and resulted in the low-temperature rise (Waqas et al., 2018a). The thermophilic temperature and MC level in this study were according to the compost hygiene and standard guidelines recommended by various countries (Brinton, 2000; CCQC, 2001; EPA, 2014).

3.2. pH and electrical conductivity (EC)

In composting, pH is considered as one of the critical parameters that influence the microbial activities during the process (Awasthi et al., 2016). Changes in pH occur due to variations in the chemical composition of the substrate during composting (Lopez-Cano et al., 2016). In the initial stage, the pH was decreased due to the formation of organic acids, and with time it was raised to alkaline due to the bio-oxidation of the composting materials, formation of ammonia (NH₃), and acid consumption (He et al., 2013; Wei et al., 2014; Jindo et al., 2016). The pH of the food waste was 6.7 that was changed from neutral to acidic and then alkaline to neutral during the composting process. It was observed that the pH of the compost was considerably affected by the addition of zeolite (Fig. 3a and b). ANOVA results showed non-significant effects for both raw and modified natural zeolites that revealed

Table 5
Physiochemical characteristics of compost after 90 days.

Parameters	Trial A	Trial B	Trial C	Trial D	Trial E
Moisture content (%)	57.2 ± 2.31	40.8 ± 5.12	34.1 ± 4.58	38.9 ± 1.92	33.4 ± 5.58
pH	5.6 ± 0.93	7.5 ± 0.87	8 ± 0.49	7.7 ± 0.50	8.3 ± 0.21
EC (mS cm ⁻¹)	2.4 ± 0.05	3.4 ± 0.17	3.5 ± 0.03	3.5 ± 0.11	3.7 ± 0.08
OM (%)	63.7 ± 5.29	53.9 ± 2.82	55.3 ± 1.31	51.2 ± 2.14	53 ± 1.71
Ash content (%)	36.3 ± 5.14	46.1 ± 2.71	44.6 ± 0.98	48.7 ± 1.97	47 ± 2.47
Carbon (%)	35.3 ± 2.94	29.9 ± 1.57	30.7 ± 0.73	28.5 ± 1.19	29.4 ± 0.95
NH ₄ (mg kg ⁻¹)	121.1 ± 6.44	166.1 ± 5.55	168.3 ± 6.66	170.1 ± 5.60	187.4 ± 9.75
NO ₃ (mg kg ⁻¹)	38.8 ± 6.23	96.4 ± 7.12	131.7 ± 1.26	124.4 ± 4.73	143.4 ± 3.74
Nitrification Index	3.2 ± 0.52	1.7 ± 0.12	1.3 ± 0.05	1.4 ± 0.09	1.3 ± 0.09
Germination Index (%)	56.8 ± 1.48	92.8 ± 3.20	117.4 ± 1.83	98.3 ± 3.02	114.3 ± 1.93

Trial A: no zeolite amendment, Trial B: 10% raw zeolite, Trial C: 15% zeolite, Trial D: 10% modified zeolite, Trial E: 15% modified zeolite.

that both zeolites had a similar effect on pH (Table 4). However, a significant effect of concentration, time duration and the combined interaction for both time duration and concentration was observed for compost pH. Moreover, the Tukey's HSD test for the multiple comparisons also depicted non-significant results for zeolite types and highly significant result for zeolite concentration (Table 4). As shown in Fig. 3a and b, the pH of trial A was decreased from 6.7 to 4.9 and further shrunk to 4.4 after 20 days and then fluctuated between acidic range (4.4–5.6) until the end of the experiment, which was likely due to the accumulation of organic acids (Fig. 3).

Acidic pH was responsible for hindering the normal microbial activities and inhibited the degradation of the produced organic acids (Wang et al., 2013; Waqas et al., 2017). Whereas, the trials amended with zeolites showed a remarkable variation in pH during the composting process. During the first week the pH was lowered, and after 10 days it reached 5.6 for trial B, 5.9 for trial C, 6 for trial D and 6.2 for trial E. Afterward, pH was increased and reached the peak value of 9.5 in trial E followed by trial C (9.1) after 30 days. The high pH value for the trials with high zeolite concentration (15%) was due to the high zeolite quantity, which posed a dilution effect and affected the pH of the composting mixture (Chan et al., 2016). Likewise, for trial B and C, the peak pH after 30 days was 7.9 and 7.1 respectively (Fig. 3a and b). After achieving the peak values, the pH was reduced and reached the optimum value of 6.5–8.0 required for a stable compost (Awasthi et al., 2016). The final compost pH was 7.5 for trial B, 8.0 for trial C, 7.7 for

trial D and 8.3 for trial E that was in-line with the standard guidelines of America and Austria (Brinton, 2000). The findings of the current investigation were also in-line with those of Jiwan et al. (2013), which observed that the zeolite-amended trials had slightly higher pH in comparison to un-amended control trials.

Fig. 3c and d illustrated the variation in EC during the composting process. EC measured the total ions concentration and described changes in the levels of inorganic ions such as Na⁺, SO₄²⁻, K⁺, NO₃⁻, Cl⁻, and NH₄⁺ during the composting process (Zhang et al., 2014; Waqas et al., 2018b). High EC values represented excessive soluble salts and considered as detrimental to plant growth and development. During the composting process, the concentration of soluble salts was increased due to the degradation of complex OM. The statistical analysis revealed that the zeolite type had non-significant effects, whereas their concentration and time duration had a significant effect on the EC of the compost. However, the combined interactions of zeolite types with concentrations and time duration also showed non-significant effects towards EC (Table 5). Furthermore, Tukey's HSD test revealed high significant results for zeolite types and their concentration regarding control trials (Table 5). EC of the food waste was 0.9 mS cm⁻¹ that was changed gradually with time during the composting process (Table 1). In trial A, a fluctuation was recorded where EC was increased gradually to 2 mS cm⁻¹ after 20 days and then decreased to 1.5 mS cm⁻¹ after 30 days with least significant changes till 60 days (1.8 mS cm⁻¹). Afterward, the EC was again increased to 2.2 mS cm⁻¹.

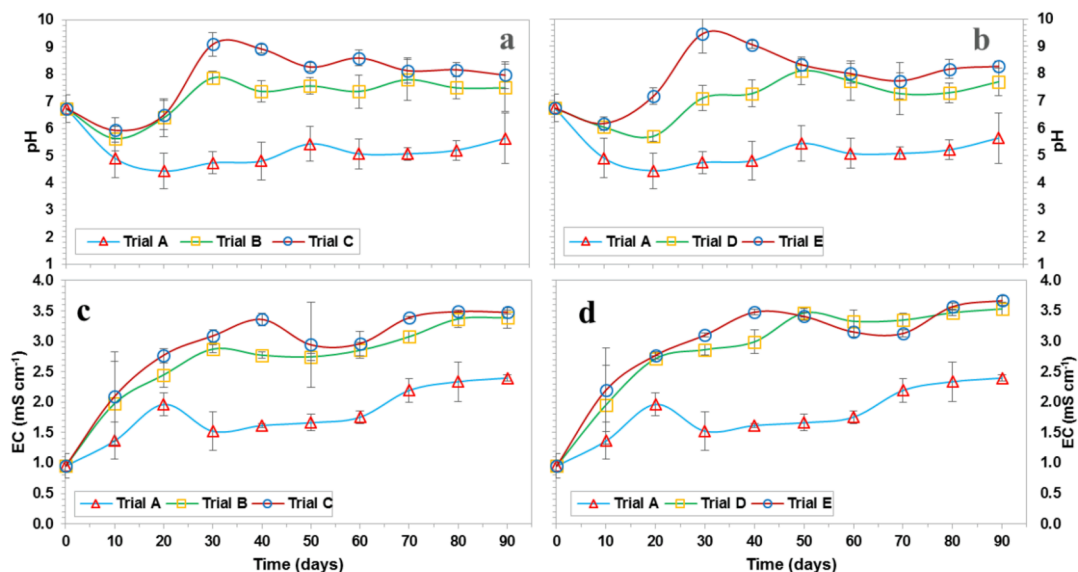


Fig. 3. Variation in pH and EC during composting of food waste. Trial A: no zeolite amendment, Trial B: 10% raw natural zeolite, Trial C: 15% raw natural zeolite, Trial D: 10% modified natural zeolite, Trial E: 15% modified natural zeolite.

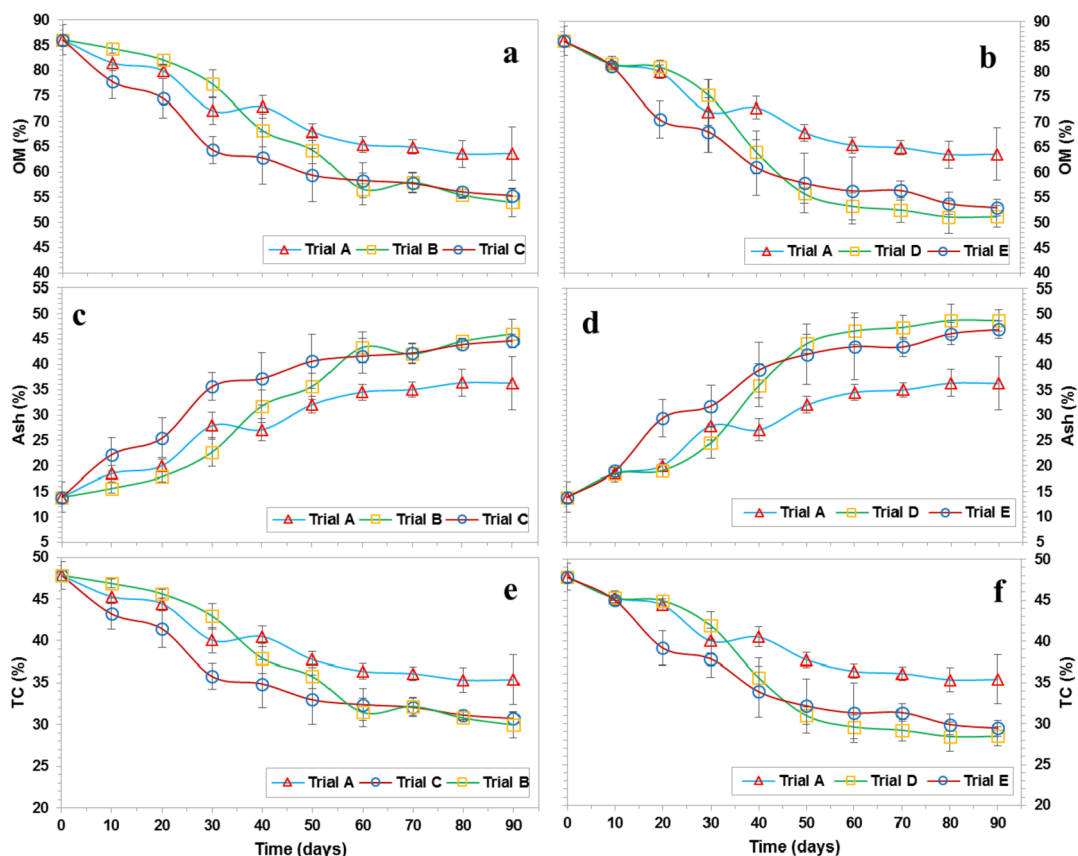


Fig. 4. Changes in OM, ash content and TC during composting of food waste. Trial A: no zeolite amendment, Trial B: 10% raw natural zeolite, Trial C: 15% raw natural zeolite, Trial D: 10% modified natural zeolite, Trial E: 15% modified natural zeolite.

and after 90 days of composting the EC, the value was reached to 2.4 mS cm^{-1} . However, this value of EC was much lower than a normal composting experiment due to the lower degradation. The other reason behind the lower EC in trial A was due to the unavailability of cation species to buffer the produced soluble anionic species in the aqueous phase (Wang et al., 2016). In contrast, the experimental trials blended with zeolite showed significant results for EC. EC value of the compost was increased gradually and reached a peak value of 3.5 and 3.4 in trial E and C respectively after 40 days. After that, the EC was slightly decreased to 70 days of composting and then again increased to 3.7 and 3.5 in trial E and C respectively (Fig. 3c and d).

In the initial stage of composting, higher EC values were due to a higher temperature that led to water loss by evaporation and release of mineral salts during OM degradation (Waqas et al., 2017). Whereas, the slight reduction in EC was due to NH_3 volatilization and precipitation of mineral salts. Moreover, other factors responsible for increasing the value of EC were the production of extractable nitrate, nitrite, ammonium, and ammonia (Villasenor et al., 2011; Wang et al., 2016). Hence, EC could be directly correlated with mineralization and OM degradation, where low EC values could be linked to lower degradation (Dias et al., 2010). EC of the final compost was; 3.4 for trial B, 3.5 for trial C, 3.5 for trial D and 3.7 for trial E (Table 5) that was below the standard limit (4 mS cm^{-1}) and considered to be tolerable for plants growth (Lasaridi et al., 2006).

3.3. Organic matter (OM) degradation and ash content accumulation

Fig. 4 showed the rate of OM degradation and ash content accumulation during the composting process. The degree of degradation of OM showed a direct indication of a successful composting process (Wang et al., 2016). The initial OM content was 86.1% that was

gradually changed during the composting process because of zeolite addition and their different concentrations (Table 1, Fig. 4). ANOVA and the Tukey's HSD test for the multiple comparisons showed that both raw and modified natural zeolites, their concentration (10 and 15%) and time duration had a significant effect on OM degradation and ash content (Table 4). Furthermore, the combined two-way interaction for zeolite types and concentration and concentration with time showed significant effects. Whereas the two-way interaction of zeolite types with time and the combined three-way interaction of zeolite types, concentration and time duration showed a non-significant effect for OM and ash content (Table 4). The OM content of all the trials was decreased significantly with time. The maximum reduction in OM was observed in trial C, and after 30 days the OM was 64.4% followed by trial E (68.1%). Likewise, for trial B and D, the OM content after 30 days was 77.3% and 75.4% respectively (Fig. 4a and b). The OM was further decreased with time, and after 60 days of composting, a non-significant change in OM was observed until the end of the experiment.

The OM content of the final compost was; trial A (63.7%), trial B (53.9%), trial C (55.3%), trial D (51.2%) and trial E (53%) (Table 5). Reduction in OM reflected the efficient degradation process (Waqas et al., 2017). The results showed that the reduction in OM was observed during the thermophilic stage (10–40 days) that indicated a drastic decomposition process (Figs. 2 and 4). This reduction could be directly related to higher microbial activities (Sun et al., 2016). The higher microbial activities and efficient degradation were due to the porous structure of zeolite that provided favorable conditions to the microbes (Jiwan et al., 2013). However, it was also observed that higher concentration (15%) of natural zeolite resulted in higher OM degradation. For raw and modified natural zeolites, a least significant effect was observed for the compost stability in all the trials as a result of zeolite addition after 50 days except trial B in which stability was achieved

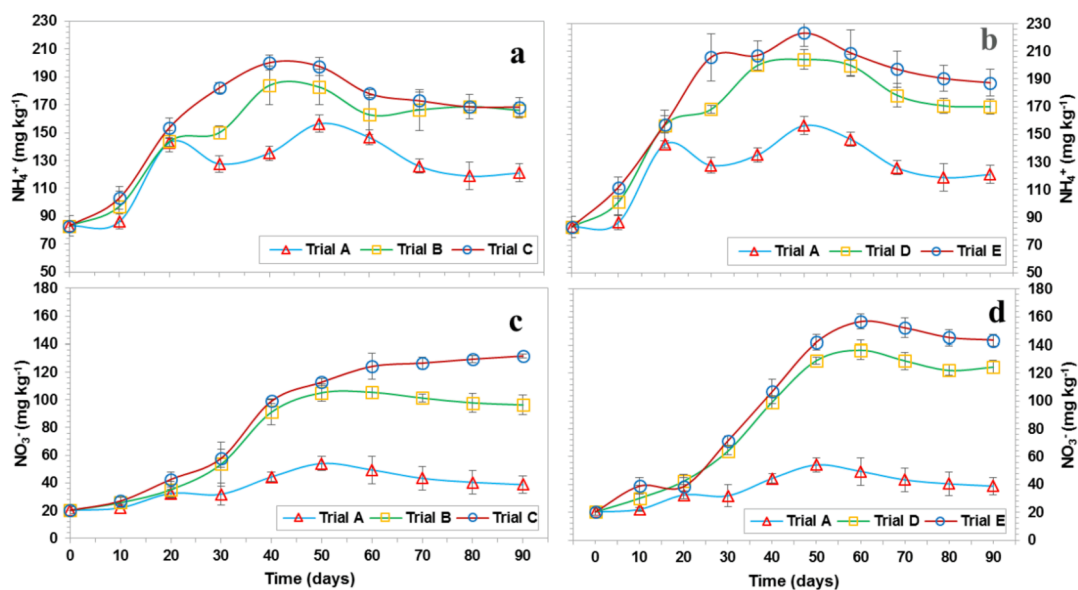


Fig. 5. Changes in NH_4^+ and NO_3^- during composting of food waste. Trial A: no zeolite amendment, Trial B: 10% raw natural zeolite, Trial C: 15% raw natural zeolite, Trial D: 10% modified natural zeolite, Trial E: 15% modified natural zeolite.

after 70 days (Fig. 4a and b). The high OM in trial A as compared to other trials depicted the lower OM degradation and a high percentage of unavailable OM. The lower OM degradation in trial A corresponded to lower pH, and high MC, which created anaerobic conditions that resulted in a poor composting process (Figs. 2 and 3).

Fig. 4 (c,d) illustrated the ash content accumulation during the composting process. Ash content was reciprocal to OM, where high OM showed low ash content. Ash represented the inorganic components that were mainly comprised of a variety of inorganic minerals (cations) such as iron, magnesium, sodium, calcium, and manganese along with some other trace metals (Venglovsky et al., 2005; Waqas et al., 2018a). These cations were in association with carbonates, nitrates, sulfates, and phosphates that were both produced as a result of degradation or available in the substrate mixture unaffected during the biological actions. Hence, the composting process remained unchanged (Venglovsky et al., 2005). The ash content in food waste was 13.8%, and with time it was linearly increased as a result of the reduction of OM. Results of this study showed a significant difference between trial A (control) and zeolite amended trials that represented the intensity of degradation (Fig. 4c and d).

The ash content was increased with time as after 40 days of composting the maximum ash content was recorded in trial E (39%) followed by trial C (37.2%). The notable difference between zeolite amended trials with trial A corresponded to the intensity of decomposition processes through temperature development (Fig. 2). However, after 60 days of composting no significant changes in ash content was recorded until the end of the experiment (Fig. 4c and d). The ash content of the final compost was 36.3% for trial A, 46.1% for trial B, 44.6% for trial C, 38.7 for trial D and 47% for trial E (Table 5). Ash content accumulation was considered as a good indicator of the decomposition process where high accumulation depicted a high degree of degradation. The reason behind high ash content in zeolite treated trials was the rapid decomposition of OM, O_2 consumption, and production of metabolic water, and carbon dioxide (CO_2) (Lopez-Cano et al., 2016). In addition, high inorganic content in the form of ash content was observed due to OM decomposition and accumulation of inorganic components in the composting matrix (Zhang and Sun, 2014).

3.4. Total carbon (TC)

During the composting process, TC content was decreased since the

microbes utilized organic carbon as their energy source (Wong and Fang, 2000). As illustrated in Fig. 4e,f, TC in all the trials was decreased along the composting process except trial A (control), which was due to the acidified environment that did not favor efficient microbial decomposition. Whereas, the zeolite amended trials showed a higher decomposition rate and TC reduction. As shown, a sharp decrease was observed in the composting mixture blended with a higher concentration of zeolite (Fig. 4). However, the statistical analysis of the data showed a non-significant effect for raw and modified natural zeolites on TC (Table 4). Similarly, the Tukey's HSD test for the multiple comparisons also revealed a significant impact between control (trial A) and zeolite trials and non-significant effects between zeolite types. Moreover, the multiple comparisons test demonstrated a significant result for various concentrations of zeolite (Table 4).

TC in initial food waste mixture was 47.8% and after 40 days of composting it reached to 33.9% in trial E, 34.9% in trial C, 35.8% in trial D, 37.9% in trial B and 40.5% in trial A (Fig. 4e and f). Afterward, a slight reduction in TC was observed, and after 60 days of composting no noteworthy changes were recorded that showed that all bio-transformable materials were converted to simpler components, and compost material became stable. TC of the final compost was 35.3% for trial A, 29.9% for trial B, 30.7% for trial C, 28.5% for trial D and 29.4% for trial E (Table 5). Carbon reduction was considered an essential indicator of compost maturity (Bernai et al., 1998). For trial A, the slow degradation as supported by the pH, EC and temperature, resulted in higher TC (Figs. 2 and 3).

3.5. Changes in ammonium (NH_4^+), nitrate (NO_3^-)

During the initial stage of food waste degradation, ammonium was produced due to the early breakdown of the nitrogenous compounds (Wong et al., 2009; Awasthi et al., 2017). Table 1 showed the initial NH_4^+ content in food waste whereas Fig. 5a and b depicted the changes in NH_4^+ during the composting process as a result of zeolite addition. The ANOVA results of the statistical analysis revealed that both raw and modified natural zeolites had significantly affected the NH_4^+ of the compost. Moreover, a significant effect for zeolite concentration, time duration, and multiple comparison tests was observed for NH_4^+ (Table 4). The NH_4^+ concentration was increased significantly at the beginning and after 50 days of composting the peak value (223.3 mg kg^{-1}) was recorded in trial E followed by trial D

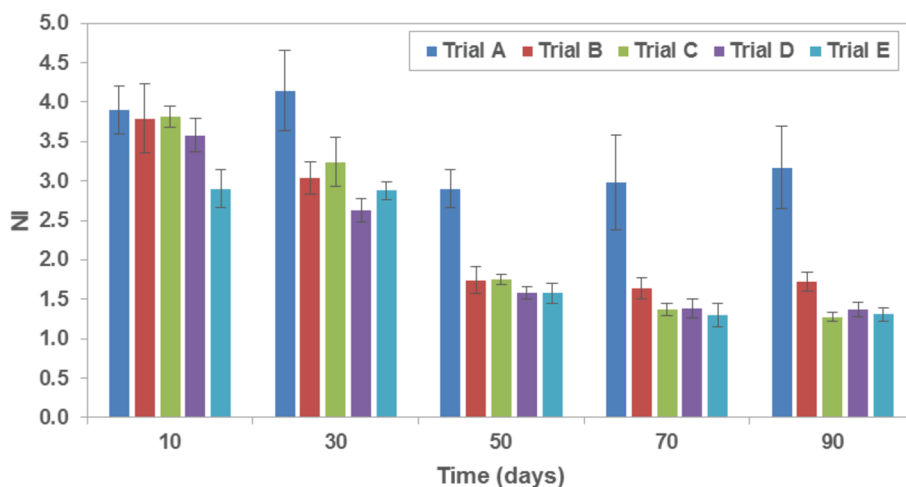


Fig. 6. Evolution in nitrification index (NI) during composting of food waste due to the addition of zeolite. Trial A: no zeolite amendment, Trial B: 10% raw natural zeolite, Trial C: 15% raw natural zeolite, Trial D: 10% modified natural zeolite, Trial E: 15% modified natural zeolite.

(204.2 mg kg⁻¹) (Fig. 5a and b). Likewise, the peak values for trial B and C were 183.9 and 200.1 mg kg⁻¹ respectively. The overall results showed that the maximum NH₄⁺ concentration was recorded for a higher concentration of zeolite addition (15%), whereas for zeolite types the maximum NH₄⁺ concentration was noticed for modified natural zeolite. Several mechanisms were responsible for higher NH₄⁺ concentration in modified natural zeolite such as high adsorption and cation exchange capacity, which attracted NH₄⁺ ions and inhibited its conversion to free ammonia (NH₃). The losses of NH₄⁺ in the form of NH₃ not only reduced the agronomic value of the end product but also contributed to environmental pollution (Wang and Zeng, 2017).

In the zeolite framework, aluminum ion occupies the center of the tetrahedron of four oxygen atoms. The overall zeolite lattice has a negative charge due to the isomorphous replacement of Si₄⁺ by Al₃⁺ (Chan et al., 2016). The net negative charge is balanced by exchangeable Ca₂⁺, K⁺, and Na⁺ and is commonly exchanged with cations such as NH₄⁺, Mn, A, Cd, and Pb (Turan and Ergun, 2008; Chan et al., 2016). From the last few years, research studies have been reported on the potential use of zeolites to enhance the degradation rate, adsorption of NH₄⁺ and reduction of NH₃ losses during the composting process (Jiwan et al., 2013; Chan et al., 2016). However, research studies showed that the adsorption and cation exchange potential of zeolite could be significantly improved through modification. The research findings of Mirzaei et al. (2017) demonstrated that the surface morphology and adsorption of zeolite was momentarily improved through modification.

The kinetics studies showed the maximum adsorption capacity of modified natural zeolite. Christidis et al. (2003) reported that thermal

and acid treatment significantly increased the cation exchange capacity of natural zeolite. Therefore, on the basis of previously reported research findings, it was suggested that modification improved the adsorption potential of natural zeolite that resulted in high NH₄⁺ in the compost of this study. On the basis of peak values after 50 days, the NH₄⁺ concentration in modified natural zeolite was increased by 11.1% as compared to raw zeolite. Likewise, another phenomenon for high NH₄⁺ was the active microbial degradation of OM during the thermophilic phase and high pH that favored the ammonification process (Figs. 2 and 3). However, it was also observed that after achieving the peak values the concentration was gradually decreased and after 70 days it reached to 197.1 mg kg⁻¹ in trial E, 178.3 mg kg⁻¹ in trial D, 172.8 mg kg⁻¹ in trial C and 166.3 mg kg⁻¹ in trial B with no-significant change till the end of experiment (Fig. 5a and b). After achieving the peak values, a slight decrease was observed that might be due to the nitrification process (Awasthi et al., 2016). It was also observed that the lowest NH₄⁺ (121.1 mg kg⁻¹) at the end of the experiment was recorded for trial A, which was due to the anaerobic conditions and acidic pH that hindered aerobic activities and the ammonification process (Turan and Ergun, 2008).

Fig. 5 (c,d) illustrated the changes in NO₃⁻ and showed that mineralization of food waste during the composting process increased the NO₃⁻ content in the end product. NO₃⁻ in the food waste was 20.3 mg kg⁻¹ that was increased with time in all experimental trials (Table 1 and Fig. 5). The trend observed in the current investigation was according to the general phenomenon that expects the ammonification process followed by the nitrification process. In the start of the experiment, the nitrification process was very slow, and it was observed

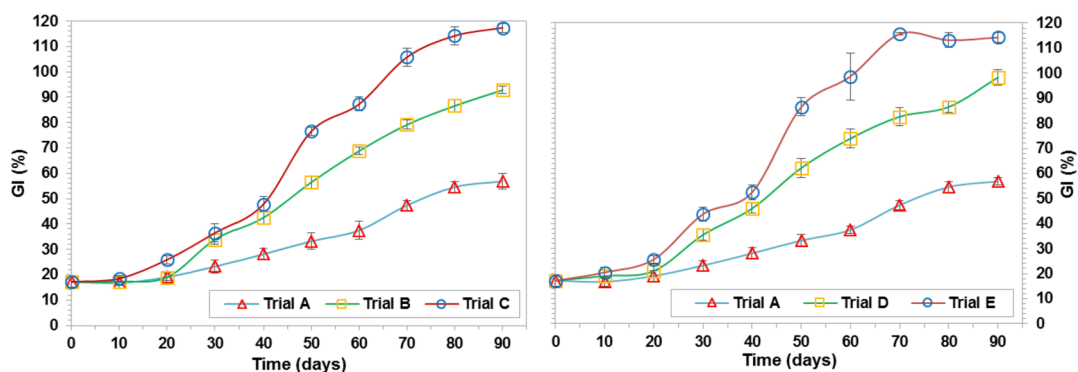


Fig. 7. Variation in germination index (GI) during composting of food waste because of zeolite addition. Trial A: no zeolite amendment, Trial B: 10% raw natural zeolite, Trial C: 15% raw natural zeolite, Trial D: 10% modified natural zeolite, Trial E: 15% modified natural zeolite.

that 20 days a non-significant change in the NO_3^- concentration was recorded for all experimental trials (Fig. 5c and d). The reason for low NO_3^- concentration in the initial stage was the fluctuation in pH that undergone from acidic to high alkaline (Fig. 3). However, after 30 days when the pH entered within the range of neutral value, the nitrification process was favored. As reported by Suthar et al. (2012) and Kumar et al. (2013) that the optimum pH (7–8) significantly enhanced the nitrification process and favored the formation of NO_3^- . Moreover, during the thermophilic stage, most of the nitrogenous compounds were disintegrated with the release of NH_4^+ , NO_3^- and NH_3 (Waqas et al., 2017).

The results showed that the peak values for NO_3^- were recorded after 60 days of composting. It was noticed that as like NH_4^+ , the maximum NO_3^- was also recorded for modified natural zeolite as compared to raw zeolite and control trials. The NO_3^- values for each trial after 60 days were; 156.6 mg kg^{-1} for trial E, 136.6 mg kg^{-1} for trial D, 124.2 mg kg^{-1} for trial C, 105.5 mg kg^{-1} for trial B and 49.5 mg kg^{-1} for trial A (Fig. 5c and d). However, after 60 days, a slight variation in NO_3^- concentration was observed until the end of the experiment. The NO_3^- concentration at the end of the experiment was 38.8 mg kg^{-1} for trial A, 96.4 mg kg^{-1} for trial B, 131.7 mg kg^{-1} for trial C, 124.4 mg kg^{-1} for trial D and 143.4 mg kg^{-1} for trial E (Table 5). For trial A, low NO_3^- content was due to low pH during the initial stage that did not allow the transformation of inorganic nitrogen to nitrates. Another possible reason for low NO_3^- content in trial A was the high MC that created anaerobic conditions. In an anaerobic environment, the nitrifying bacteria were unable to convert NH_3 to nitrates and therefore resulted in the nitrogen loss in the form of NH_3 (Turan and Ergun, 2008).

3.6. Nitrification index (NI) and germination index (GI)

There are various indices that indicate the maturity and stability of compost, including degree of degradation of OM, EC, nitrification and germination index (Zucconi et al., 1981; CCQC, 2001; Thompson et al., 2002; HKORC, 2005; Zhang et al., 2016; Chan et al., 2016). According to CCQC (2001), the NI below 0.5 suggests fully mature compost whereas the NI value up to 3 represents a mature compost and the value above 3 shows an immature compost for soil application. Hence, the value between 0.5 and 3 represent a mature compost. In the current composting experiment, a substantial variation in the values NI was noticed because of zeolite addition. It was observed that after 50 days stability in NI of all the zeolite-amended trials was achieved. NI of the compost at the end of the experiment was 1.3 for trial E, 1.4 for trial D, 1.3 for trial C, 1.7 for trial B, whereas for trial A the high fluctuations in NI value were due to the poor microbial activities that resulted in an uneven degradation (Fig. 6).

GI is also one of the critical parameters for the evaluation of compost toxicity level towards plant growth (Zucconi et al., 1981; Thompson et al., 2002). In the current study during the initial stage, the GI values were decreased in all trials that were due to the rapid OM degradation with the accumulation of organic acids and NH_4^+ , which inhibited the seed germination (Fig. 7). A value below 80% showed an immature compost while the value between 80 and 90% represented a mature compost and value above 90% depicted a highly mature and plant growth stimulator (CCQC, 2001; HKORC, 2005). The GI was increased with time, and after 50 days the GI of trial E was reached to 86.5%, whereas all other trials were entered to maturity after 60 days of composting (Fig. 7). The GI of the final compost was 114.3% for trial E, 98.3% for trial D, 117.4% for trial C, 92.8% for trial B and 56.8% for trial A (Table 5).

The short maturation time in the zeolite added trials was due to the establishment of a good buffering, physical structure, and NH_4^+ adsorption (Chan et al., 2016). Lin et al. (1998) reported that high rates of zeolite application to an acidic soil reduced the amount of leachable toxic substances and stabilized the soil to the good physical structure.

Thus, in composting zeolite provided a niche for the adsorption of the essential components that affected compost maturity and seed germination. Likewise, the acidic pH, low OM degradation, and high organic acids in the compost from trial A required more extended time and was not mature even after 90 days. The findings of this study were in line with previously reported work that suggested that addition of zeolite to composting not only reduced the nitrogen loss, but it also diminished phytotoxic compounds during the composting process (Villasenor et al., 2011; Chan et al., 2016; Awasthi et al., 2016).

3.7. Practical implications of this work

In KSA, the largest waste stream of municipal solid waste (MSW) is food waste and most of it is disposed to landfills that consume massive workforce and resources. In addition, the landfill disposal of food waste is causing several public health and environment-related issues. Composting is an easy way to handle the food waste by converting to compost (organic fertilizer), as being a promising alternative. For optimization of food waste composting, natural zeolite could be successfully used as a bulking agent and adsorbent material for improving the compost quality. In KSA, massive reservoirs of natural zeolites are available in the areas of Jabal and Harrat Shamah, near to Jeddah city. The identified different types of natural zeolites found in these areas are thomsonite, clinoptilolite/heulandite, analcime, mordenite, chabazite, stilbite, wairakite, and natrolite (SGS, 2015). So far, minimal research has been carried out on utilizing these natural zeolites. Therefore, using natural zeolites for food waste composting would not only provide sustainable management to MSW but also fulfill fertilizer demand for KSA, which is about 500 thousand tons per year. From an economic point of view, composting saves waste disposal cost. It was estimated that after compensating the operating cost total net savings to the country economy from the compost facility could be around US \$70.72 million per year (Waqas et al., 2017).

4. Conclusions

Natural zeolite was modified through a novel method of sequential hydrothermal modification and applied at 10 and 15% (w/w) to the total waste. The effects of modified natural zeolite in the process of food waste composting were compared with raw natural zeolite. It was observed that in comparison to un-amendment control trial, the zeolite-amended trials significantly affected all the tested compost maturity parameters. Zeolite addition significantly buffered the acidic pH, increased the EC and OM degradation of the substrate in the initial stage of compost. However, as compared to raw natural zeolite, the modified natural zeolite positively affected the compost parameters. The highest thermophilic temperature and moisture reduction to an optimum range were achieved in modified natural zeolite with 15% concentration. Moreover, the peak values of the total ammonium (NH_4^+) (223.3 and 204.2 mg kg^{-1}) and nitrate (NO_3^-) (197.5 and 182.6 mg kg^{-1}) concentration was recorded for modified natural zeolite that was increased by 11.1 and 21.5% respectively in comparison to raw zeolite. Likewise, for zeolite application rate, noteworthy results in term of all the studied compost parameters were recorded for 15% with respect to 10 and 0%. The maturity parameters such as moisture contents (MC), electrical conductivity (EC), organic matters (OM), total carbon (TC), mineral nitrogen, nitrification index (NI) and germination index (GI) showed that the stability was achieved after 60 days. The maturity and stability of the produced compost were in in-line with the international compost standards recommended by various countries. Therefore, it was concluded that the application of modified natural zeolite addition at 15% to the total waste could be the best formulation to the food waste composting for achieving a stable value-added compost in KSA.

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