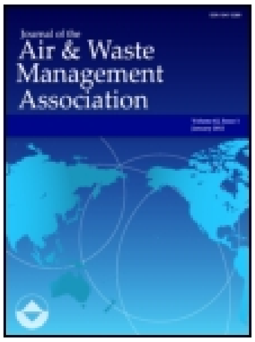

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TECHNICAL PAPER

Composting of wastewater treatment sludge with different bulking agents

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ABSTRACT
The main objectives of this study were to investigate the compostability of wastewater treatment sludge (WTS) containing different bulking agents (BAs) and to determine the most efficient BA. Four different compost trials consisting of mixtures of wheat straw (WS), plane leaf (PL), corncob (CC) and sunflower stalk (SS) with WTS were performed in laboratory reactors. In all experiments, a mixture of 60% WTS and 40% BA (wet basis) was used. The temperature, dry matter (DM), organic matter (OM), pH, electrical conductivity (EC) and C/N ratio were monitored during the composting process. Evaluation of the operational parameters showed that the highest organic matter degradation (i.e. 37.6%), loss of dry matter (i.e. 29.6%) and temperature (i.e. 64 °C) were achieved for the WTS-CC mixtures. Results also showed that the WTS-SS mixture was also successful in terms of these operational parameters. Use of bulking agents for the treatment of wastewater treatment sludge in composting process is an important issue with regards to process efficiency, economy and disposal of agricultural waste. Corncob and sunflower stalk that were previously not used for the composting of WTS from food industry were shown to be highly successful BA materials in this study.

Implications: The compostability of wastewater treatment sludge from the food industry with different bulking agents was studied. Wheat straw, plane leaf, corncob, and sunflower stalk were used as bulking agents. The required microbial stabilization and degree of mineralization were achieved with corncobs and sunflower stalks.

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Introduction

Wastewater treatment sludge (WTS) disposal is a major problem worldwide because increasing amounts are continuously being produced. Therefore, alternative disposal methods are currently being investigated worldwide. WTS may represent an alternative source of soil organic matter (Banegas et al., 2007). However, the use of WTS without previous stabilization represents an environmental risk because it may contain synthetic organic contaminants, heavy metals, or pathogenic substances (Topac et al., 2008; Uçaroğlu, 2014).

Composting is a biological process that uses naturally occurring microorganisms to convert biodegradable organic matter into a humus-like product and is a suitable method for recycling WTS. The composting process destroys pathogens, converts nitrogen from unstable ammonia to stable, organic forms of nitrogen, and reduces the volume of waste (Zhu, 2006). This process is controlled by environmental parameters (temperature, moisture content, pH, and aeration) and substrate properties (C/N ratio, particle size, and nutrient content) (Kulikowska and Gusiatin, 2015; Nikaeen et al., 2015).

Due to high moisture and low carbon contents, sludges must be mixed with dry materials for composting. The materials used as bulking agents (BAs) when composting waste treatment sludges include the organic fractions of municipal solid waste, sawdust, wood chips, and many other agricultural wastes (Doublet et al., 2010; Komilis et al., 2011). Wastes containing lignin, such as plant residues or hulls from agricultural production systems, are difficult to manage and dispose, because they are bulky and have a low commercial value (Conghos et al., 2003). These materials may be used as regulatory BAs to balance the moisture contents of the sludge and increase its porosity to permit airflow. In addition, these materials may be used to balance the C/N ratio and provide additional carbon for improve the microbial activity (Diaz et al., 1993; Haug, 1993; Iranzo et al., 2004; Tremier et al., 2005; Mohajer et al., 2009; Huet et al. 2012). Supplementation of bulking agents can also provide optimum free air space (FAS) and void dispersion in

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composting (Iqbal et al., 2010), which permit adequate water and gas exchange between gas and solid phases, and prevent excessive compaction of the composting materials (Kulcu and Yaldiz, 2007). The selection and use of appropriate BAs is important for obtaining quality WTS compost at a reasonable cost. Recent studies examined composting sludge with different bulking agents and determined their influences on the composting process efficiency. Shrub clippings (Margesin et al., 2006), sawdust (Banegas et al., 2007), green wastes and crushed wood pallets (Tremier et al., 2009; Ramdani et al., 2015), *Acacia dealbata* (Yañez et al., 2009), food processing waste (Grigatti et al., 2011), and paper wastes, food wastes, and tree branches (Komilis et al., 2011) have been used as bulking agents in sludge composting treatments.

In this study, WTS from the canned food industry was composted using four different BAs: wheat straw (WS), plane leaf (PL), corncob (CC), and sunflower stalk (SS). Food industry WTS is generated in considerable amounts (~115.000 ton year^{-1}) in Turkey and is mostly landfilled after dewatering (TURKSTAT, 2008). Physical and chemical changes such as temperature, dry matter (DM), organic matter (OM), pH, electrical conductivity (EC), total N, and C/N ratio in the compost mixtures were monitored following the composting process to compare the effects of the different bulking agents on composting efficiency. Although several studies have composted WTS with different BAs, few studies have investigated composting WTS from the food industry. Furthermore, no previous studies have used sunflower stalks or corncobs as BAs for WTS. In addition, the disposal of widely used agricultural wastes, such as WS, PL, CC, and SS, has been achieved because of their use in composting with WTS.

Materials and methods

Composting mixtures and process

Wastewater treatment sludge samples with four different BAs were composted in four different aerobic reactors. WTS was collected from the exit of the dewatering unit of the treatment plant of a canned food industry. The canned food industry processes fruits and vegetables and its wastewaters are treated with an activated sludge system. The flow rate of the wastewater entering the treatment plant is 5500 m^3 day^{-1}. WTS is dewatered by a filter press to a solid content of 22–28%. The amount of the WTS generated is 15 ton month^{-1}.

Wheat straw, PL, CC, and SS were used as BAs. WS and SS were obtained from an experimental farm at the Agricultural Faculty of Uludag University, the PL was obtained from parks at Uludag University, and the Cargill Bursa Factory provided the CC. These materials were ground to a particle size of 0.5–1 cm. The compositions of the WTS and BA in the aerobic composting reactors are provided in Table 1.

The composting systems consisted of four autothermal aerobic bioreactors that were operated in parallel. These systems had vertical cylinders with a volume of approximately 30 L (30 cm in diameter and 45 cm in height). Each composter was constructed of stainless steel and insulated with 50 mm of glass wool and an aluminum sheet (Figure 1). The compost material was retained on a perforated plate at the bottom of the reactor to effectively diffuse air into the mixture and to allow the leachate to drain from the bulk compost. A sampling port was placed on top of the composter, and a temperature sensor (thermocouples, TCR-M06-L180-K04.J) was placed at the center of the reactor. An additional temperature sensor was placed outside the reactor to monitor the ambient temperature, and air circulation was provided by aquarium pumps that had adjustable airflow (power: 15 W, pressure: >0.015 Mpa, maximum output: 16 L min^{-1}).

Methods

Experiments were conducted using mixtures of the WTS and bulking agents (WS, PL, CC, and SS) in four different compost reactors (R1, R2, R3, and R4). All of the composting experiments were conducted in batch processes over 21 days, which represented the active composting phase. All compost reactors contained a mixture of 60% WTS and 40% BA (wet basis). Each composting process was carried out in duplicate. The mixtures were manually introduced into the tops of the composters. The composting material was manually stirred three times each week to ensure proper mixing and aeration. Aeration was performed by applying air at a rate of 600–700 mL min^{-1} for 15 min each hour for each reactor using a solenoid valve that was connected to a time adjustment program. Compost samples were regularly collected from the top of the sampling hole at 0, 2, 7, 14, and 21 days for chemical analyses. Changes in the compost mass were measured at the beginning and end of the composting process. Additionally, the composting reactors were weighed before each sampling (2, 7, and 14 days) to determine the losses of DM and OM. A structured control system with supervisory control and data acquisition (SCADA) software was used to automate the pilot composting plant and for data (temperature and airflow data) acquisition. Three temperature and airflow data were recorded every minute.

Table 1. General properties of the raw materials.

Parameters[a]	WTS[b]	WS[b]	PL[b]	CC[b]	SS[b]
pH (1:10, solid–water)	8.45 ± 0.01	6.67 ± 0.04	6.45 ± 0.01	5.16 ± 0.00	6.69 ± 0.01
EC, mS cm^{-1} (1:10, solid–water)	2.62 ± 0.06	1.98 ± 0.02	1.54 ± 0.07	3.08 ± 0.01	0.20 ± 0.00
Moisture, %	84.4 ± 4.0	9.97 ± 0.15	21.2 ± 1.03	12.2 ± 0.24	10.3 ± 0.12
OM, %	67.6 ± 0.49	87.2 ± 2.8	80.0 ± 6.3	82.9 ± 3.6	91.6 ± 2.4
OC, %	17.5 ± 0.39	38.4 ± 2.44	41.6 ± 3.0	36.7 ± 2.4	47.0 ± 0.94
NH_4-N (mg kg^{-1})	70.0 ± 0.02	189 ± 9.90	0.00 ± 0.00	70.0 ± 10.10	0.00 ± 0.00
NO_3-N (mg kg^{-1})	70.0 ± 0.02	16.0 ± 2.83	0.00 ± 0.00	17.5 ± 0.00	0.00 ± 0.00
TKN, %	2.47 ± 0.20	0.37 ± 0.01	0.87 ± 0.02	0.50 ± 0.02	0.485 ± 0.10
C/N ratio	7.1	104	47.8	73.4	96.9
Cellulose, %	—	34.2[c]	—	38.8[d] ± 2.5	41.6[e]
Hemicellulose, %	—	23.7[c]	—	44.4[d] ± 5.2	20.0[e]
Lignin, %	—	13.9[c]	—	11.9[d] ± 2.3	25.3[e]

Notes: [a]On dry-weight basis
[b]Mean value ± standard deviations.
[c]Adapa et al, 2009
[d]Pointner et al., 2014
[e]Conghos et al., 2010

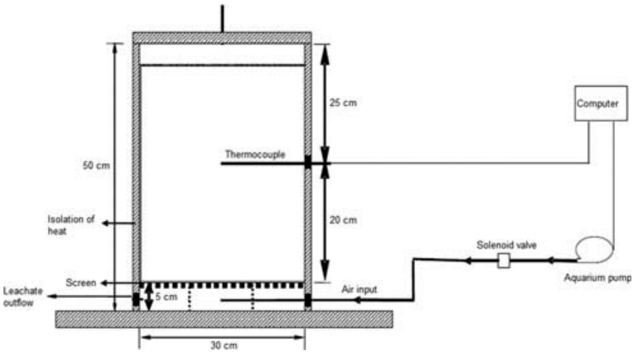

Figure 1. The diagram of composting system.

Analytical methods

pH and EC of the samples were measured in sample extracts obtained by shaking the material with distilled water at 1:10 (w/v) sample:water ratio using a pH meter and conductivity meter, respectively (Rhoades, 1982; Mc Lean, 1982). The total organic carbon (OC) for raw materials and total N for all samples were determined according to the method of Nelson and Sommers (1982) and the Kjeldahl procedure (Bremmer and Mulvaney, 1982), respectively. The nitrate (NO_3^{-}N) and ammonium (NH_4^{+}-N) nitrogen were measured using 2 *M* potassium chloride (KCl) in the method by Keeney and Nelson (1982). The moisture content was measured by drying the material in an oven at 105°C, and the ash content was determined after drying the sample at 105°C and calcination at 550°C for 5 hr (American Public Health Association [APHA], American Water Works Association [AWWA], and Water Pollution Control Federation [WPCF], 1998). The OM contents of all of the samples and the OC contents of the compost samples were estimated as follows: OM (%) = 100 – ash (%) and OC (%) = OM (%)/1.8 (Okalebo et al., 1993; Barrington et al., 2002; Diaz et al., 2007; Khalil et al., 2011). Finally, FAS was determined using the methodology proposed by Madejon et al. (2002). For all compost samples, the initial WTS and BA were analyzed in triplicate.

Results and discussion

Characterization of the raw material and initial compost mixtures

The BA used in the WTS composting process had organic matter contents of between 80.0% and 91.6%, while the percentage of organic matter in the WTS was 67.6% (Table 1). Similarly, the OC contents of the BA were between 36.7% and 47.0%, whereas the WTS contained 17.5% of OC (which was lower than in the other materials). The WTS had higher moisture content (84.4%) and a lower C/N ratio (7.1). Therefore, it was important to use the BA to regulate the moisture content and C/N ratios of the WTS for a successful composting process.

The initial characteristics of the mixtures in the composting reactors are given in Table 2. The initial pH values of the mixtures were nearly neutral (between 6.80 and 7.50), and the addition of BAs to the WTS in each of the composting reactors resulted in significantly greater organic matter and carbon contents and lower moisture contents. The moisture levels in the reactors were between 45.9% and 56.7%.

Temperature

The temperature variations within the composting reactors and the ambient air are illustrated in Figure 2. The temperature variations during co-composting provide the first index of the degree of composting success. The temperatures in the compost reactors were found to

Table 2. Initial properties of the compost mixtures in the reactors (mean value ± standard deviation).

Parameters	R1 (WTS + WS)	R2 (WTS + PL)	R3 (WTS + CC)	R4 (WTS + SS)
pH (1:10, solid–water)	6.94 ± 0.03	6.91 ± 0.00	6.83 ± 0.03	7.53 ± 0.02
EC, mS cm^{-1} (1:10, solid–water)	2.35 ± 0.06	2.55 ± 0.01	3.30 ± 0.2	3.19 ± 0.09
Moisture, %	45.9 ± 2.6	56.7 ± 0.98	50.8 ± 2.6	50.4 ± 3.8
OM, %	80.5 ± 2.4	72.8 ± 0.47	77.0 ± 3.2	81.0 ± 3.9
Total N, %	1.05 ± 0.04	1.38 ± 0.04	1.20 ± 0.04	0.99 ± 0.04
C/N	42.4	29.2	35.7	45.6
FAS, %	37.1	29.9	27.6	35.7

increase, implying the existence of sufficient amount of composting substrate and biodegradation of the organic compounds in the compost mixtures by microorganisms. Several authors reported that such a temperature increase may significantly sanitize the compost in terms of pathogens (Haug, 1993; MetCalf & Eddy, 2003; El Fels et al., 2014). In this study, the maximum temperatures reached in the R1, R2, R3, and R4 reactors were 46, 49, 64, and 57°C, respectively. The available organic substrates for microbial growth enhanced the biological activities and the production of heat and CO_2 (Nakasaki and Ohtaki, 2002; Jolanun and Towprayoon, 2010). To significantly reduce pathogens, waste should be kept at 40°C for a minimum of 5 days. In addition, the temperature should be increased to more than 55°C for at least 4 hr (USEPA, 1993). The temperature in R1 remained above 40°C for 18 hr, and the temperature in R2 remained above 40°C for 2 days and 10 hr. However, the temperatures in these reactors never reached 55°C and did not provide pathogens control. By contrast, the temperature in R3 remained above 40°C for 8 days and 18 hr, during which temperatures of more than 55°C were maintained for 2 days and 10 hr. Similarly, the temperature of R4 remained above 40°C for 5 days and 11 hr, and a temperature of more than 55°C was achieved for 22 hr. These results show that the temperatures necessary for microbial stabilization were reached only in reactors R3 and R4. In a previous study, Ucaroglu (2014) reported that the thermophilic phase (55°C) was reached when composting sewage sludge with sunflower stalks. In composting processes that are operating correctly, the temperature should reach 50–65°C due to microbial activity (Abouelwafa et al., 2008). The main mechanism controlling the temperature variations in all

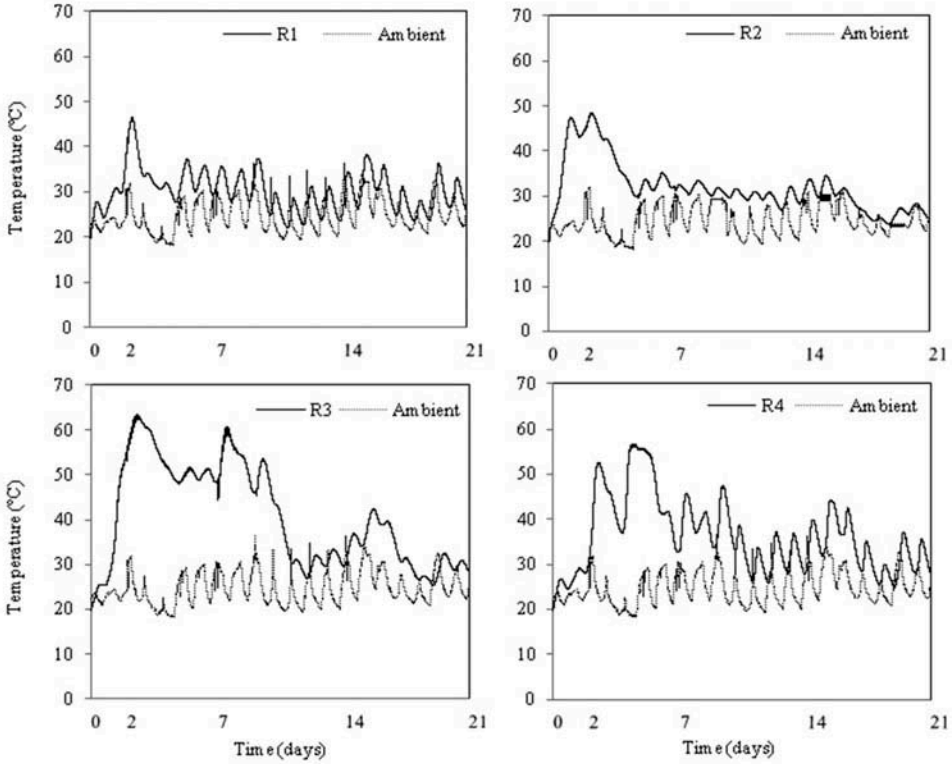

Figure 2. Reactor and ambient temperatures during composting.

reactors was assumed to result from the amount of easily biodegradable organic matter. It has been considered that CC and SS were more easily biodegradable organic matter than WS and PL.

Effects of bulking agents on the physical and chemical parameters of the compost

Figure 3a shows the pH evolution during the composting process. The pH values varied between 6.7 and 6.9 in R1, between 6.9 and 7.2 in R2, between 6.3 and 6.8 in R3, and between 6.6 and 7.5 in R4. Within the first week, the pH values in reactors R1, R3, and R4 slightly decreased, while the pH in reactor R2 remained constant. As shown in Figure 3a, the pH values of reactors R1, R3, and R4 decreased from 6.9 to 6.7, from 6.8 to 6.3, and from 7.5 to 6.6, respectively. The results of pH are in agreement with other studies, which stated that initially, the pH was acidic as a result of degradation of organic matter by the acid-forming bacteria. Afterward it became alkaline due to ammonia formation, and finally it dropped back to near neutral as a result of humus formation with its pH-buffering capacity (Epstein, 1997; Ouatmane et al., 2000; Himanen and Hänninen, 2011; El Fels et al., 2014). Larger amounts of organic acid were thought to be produced in R3 and R4 since pH decreases in these reactors were greater. Toward the end of biodegradation, the pH became near neutral in all of the reactors except R3. Low pH during composting in R3 could be possibly explained by the acidic nature and high buffering capacity of corncob, which may have prevented increase of pH. In a study conducted by Amir et al. (2005), similar values were observed for the final compost in composting studies that used wastewater treatment sludge.

The EC can be used as an indirect method to evaluate the degree of salinity in the composting mixture, which indicates its possible phytotoxic/phytoinhibitory effects on plant growth after application to the soil (Lin, 2008). The EC values varied between 2.0 and 4.3 mS cm^{-1} in all of the reactors (Figure 3b). For reactors R1 and R2, the EC values fluctuated without any major changes between 2.0 and 2.9 mS cm^{-1} throughout the process. Due to the formation of organic acids and the release of mineral salts (such as phosphates and ammonium ions) through the decomposition of organic substances in reactors R3 and R4, the EC values increased during the first week before decreasing to approximately 3.5 mS cm^{-1} at the end of the process (Gómez-Brandón et al., 2008). As the composting process progressed, the volatilization of ammonia and the precipitation of mineral salts potentially resulted in lower EC values during the later composting phase (Gao et al, 2010; Wang et al., 2013).

Table 3 presents the decreases in the DM and OM values that were calculated for all composting reactors. Decreasing DM and OM contents during the composting process have been widely reported and result from the mineralization of the OM by microorganisms (Banegas et al., 2007; Rihani et al., 2010; Tognetti et al., 2006). The DM and OM contents decreased in all composting reactors in this study. An evaluation of Table 3 indicated that the DM loss was lower in reactors R1 and R2 than in R3 and R4. The highest DM loss was observed in R3 (29.6%), followed by reactor R4 (26%). Organic matter decomposition is directly related to microbial degradation and results in the loss of organic matter (Paredes et al., 2002). Biodegradable organic matter losses during composting are expected to be between 30% and 60% (Diaz et al., 2007). Table 3 shows that organic matter losses were relatively lower in R1 and R2 and were 37.6% and 33.0% in R3 and R4, which were operated with corncob and sunflower stalk additives, respectively.

The changes in the total N contents during the composting process are shown in Figure 4. Figure 4 shows that the total N level did not significantly change in

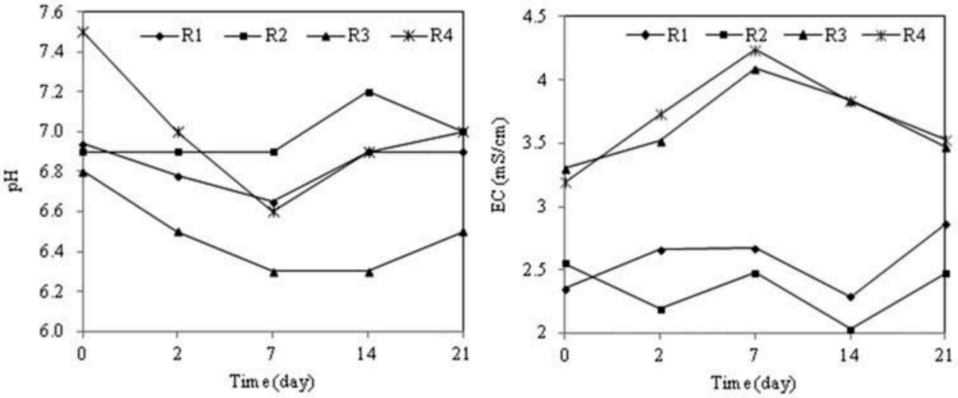

Figure 3. Changes of pH (a) and electrical conductivity (b) during composting.

Table 3. Dry matter (DM) and organic matter (OM) losses from the composting reactors.

	R1 (WTS + WS)	R2 (WTS + PL)	R3 (WTS + CC)	R4 (WTS + SS)
DM loss (%)	14.5	10.3	29.6	26.0
OM loss (%)	14.7	14.5	37.6	33.0

reactor R1 and increased in the other three reactors. In reactors R3 and R4, where the total N levels increased more, the total N values increased from 1.20% to 1.50% and from 0.99% to 1.73%, respectively. This increase in total N can be explained by the loss of DM and the biodegradation of carbon based compounds in the reactors (El Fels et al., 2014; Ucaroglu 2014).

The initial C/N values for R1, R2, R3 and R4 (Table 2) decreased to values of 41, 22, 25, and 23, respectively, which represented decreases of 5%, 24%, 31%, and 49%. These results showed that the carbon reductions in R3 and R4 were significantly greater than those in R1 and R2. Thus, the organic materials were potentially more biodegradable in R3 and R4, which contained corncobs and sunflower stalks (Diaz et al., 2002; Garcia et al., 1992).

During composting, the FAS level is important for determining the amount and flow of air and to increase the oxygen distribution in the compost mass (Huet et al., 2012; Jolanun and Towprayoon, 2010; Lu et al., 2001; Kulcu and Yaldiz, 2007). Haug (1993) stated that the minimum FAS value to supply enough oxygen should be between 20% and 30%, regardless of the type of waste or the technology used. The results were evaluated by considering the relationships between the FAS values and the temperatures that were reached in the reactors. The FAS values were 37.1%, 29.9%, 27.6%, and 35.7% and the temperatures were 46, 49, 64, and 57°C in R1, R2, R3, and R4, respectively. Although the FAS values applied in the present study were not far from the optimal range (20–30%), the results indicated that when different BA are used, FAS values may not indicate a successful composting process, in contrast with previously reported results (Jolanun and Towprayoon, 2010; Kulcu and Yaldiz, 2007). Temperature variations in our study was assumed to result from the existence of the sufficient amount of easily biodegradable organic matter.

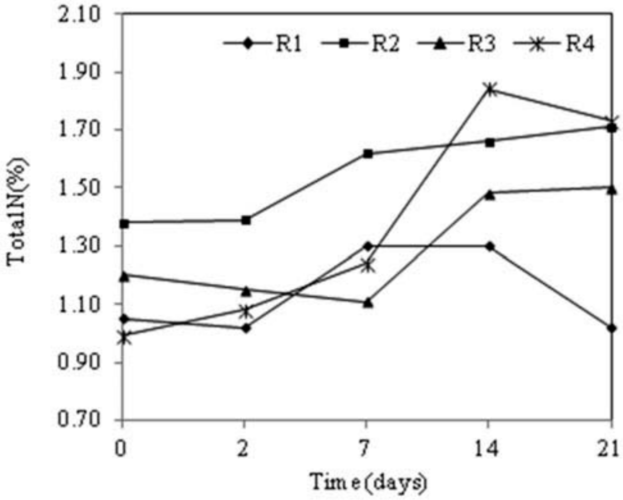

Figure 4. Changes of total N levels during composting in all reactors.

Conclusions

The results of this study indicated that the reactors that were run with corncobs (R3) and sunflower stalks (R4) reached the highest temperatures (64°C and 57°C) and resulted in significant microbial stabilization. Similarly, losses of dry matter (29.6% and 26.0%) and organic matter (37.6% and 33.0%) and decreases of C/N ratio (31% and 49%) were higher in these reactors. The FAS values and maximum temperatures reached in the reactors were not correlated. The main mechanism controlling the temperature variations in our study was assumed to result from the amount of easily biodegradable organic matter. The highest volume reduction and highest microbial stabilization were reached in R3 and R4. Composting with corncobs and sunflower stalks, which were not previously used as bulking agents with treatment sludge, successfully yielded a stabilized compost product that could be used in agriculture as a soil additive and nutrient source. In addition, the use of wheat straw and plane leaf as bulking agents in the composting process was not efficient when considering the temperature increase and the amount of mineralization.

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