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Sewage sludge composting: quality assessment for agricultural application

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Abstract In order to use sewage sludge (SS) composts in agriculture, it is extremely important to estimate the quality of compost products. The aim of this study was to investigate the quality of composted SS as a fertilizer and soil amendment especially in semi-arid areas. To determine the quality and agronomic value of the SS compost products, analyses on pH, electrical conductivity, organic matter content, C/N ratio, phytotoxicity, microbial load, and heavy metal content of composted anaerobically digested SS, with different proportions (1:1, 1:2, and 1:3 *v*/*v*) of green and dry plant waste, as bulking agents, were performed. The 1:2 and 1:3 mixtures of SS and green/dry plant waste were the most beneficial for composting, with final composts attaining high organic matter degradation and exhibiting low amounts of heavy metals, a relatively high germination index, and significant reduction of pathogens, suggesting the agricultural relevance of composted SS and green/dry plant waste at 1:2 and 1:3 (*v*/*v*) proportions. pH and electrical conductivity were also within the permissible limits. With respect to international standards, it appears that composted SS and green/dry plant waste at 1:2 and 1:3 proportions pose no threat to soil or plant quality if used in agriculture or land restoration.

Keywords Compost · Soil amendment · Semi-arid area · Heavy metals · Pathogens

Introduction

In recent years, considerable attention has been directed toward recycling of organic waste as an alternative to chemical fertilizers and to promote environmentally sound waste disposal. Sewage sludge (SS), or biosolid, is a by-product of wastewater treatment plants that remains after municipal wastewater treatment (Kalderis et al. 2010). Considering that SS contains organic matters, it is a good candidate for composting and can be used in agriculture as fertilizer or soil amendment (Banegas et al. 2007). The production of compost from SS to obtain organic additives for use in agricultural lands has been widely reported (Ayuso et al. 1996; Banegas et al. 2007; Grigatti et al. 2004). Composting, when followed by land application, combines material recycling with sludge disposal simultaneously and is therefore considered as one of the most efficient ways for the sustainable treatment and final disposal of SS (Cai et al. 2007a). SS composting also returns useful resources to the environment and has a number of beneficial effects, such as accelerating plant growth,

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improving moisture retention, increasing organic matter in the soil, and improving erosion control (Zbytniewski and Buszewski 2005; Kulikowska and Klimiuk 2011; Chazirakis et al. 2011). Composting is a biological, aerobic process, in which microorganisms utilize organic matter for metabolism and reduce the biodegradable fraction of the wastes to stable humic components (Grigatti et al. 2004; Kalderis et al. 2010). Composting proceeds through three phases, which include the mesophilic phase, the thermophilic or stabilization phase, and, finally, cooling or maturation phase. In this process, pathogens can be killed by the heat generated in the thermophilic phase.

The applicability of SS compost for agricultural use may be restricted by heavy metal content (Yañez et al. 2009). Heavy or toxic metals present naturally in the environment and could enter in wastewater from groundwater infiltration. Other sources of metals in wastewater include residential, commercial, and industrial discharges which subsequently transfer to SS through wastewater treatment processes (Tchobanoglous et al. 2003). Furthermore, application of SS compost without a good stabilization and maturation process may induce plant and soil toxicity and could have negative effects on the metabolism of soil microorganisms because of the presence of phytotoxic or pathogenic substances that may be contained (Ayuso et al. 1996). Consequently, prior to land application of composted SS, a complete quality monitoring of composted materials is required to ensure that such compost application does not lead to environmental or human health problems via pathogens, heavy metals, or organic contaminants (Cai et al. 2007b; Hernandez-Apaolaza and Guerrero 2008; Cooke et al. 2001). To prevent and minimize the potential environmental and health risks from land application of composted SS, a number of standards for the quality of compost have been proposed. The US Environmental Protection Agency (USEPA) has developed the most widely used standards for the chemical and microbial quality of compost, with main parameters being pH, electrical conductivity (EC), heavy metal content, pathogens, and germination index (GI).

The present study was designed to investigate the agronomic quality of final products from co-composting of anaerobically digested SS with fresh green and dry pruning waste, as bulking agents, through measurement of various physicochemical and microbiological parameters.

Materials and methods

SS and bulking agents

Dewatered, anaerobically digested SS was collected from Isfahan wastewater treatment plant (WWTP) (Isfahan, Iran), which treats mainly domestic wastewater. Green plant waste (GW), a mixture of fresh turf grass, hedge clippings, tree leaves, foliage, and small twigs, was collected from parks and gardens. Dry leaves and pruning waste (PW) were obtained from deciduous and coniferous trees in the WWTP area. These wastes were used as cost-effective and readily available bulking agents at the area. The characteristics of these materials are presented in Table 1.

Experiment establishment and sampling

Two composting trials were carried out at the WWTP between May and December 2013: trial A was conducted throughout the spring–summer season and trial B in wintertime. For trial A, SS was used with green waste, and for trial B, SS, dry leaves, and PW were used for composting. SS was thoroughly mixed with GW and PW using a front-end loader at three different volumetric ratios to obtain SS/GW and SS/PW ratios of 1:1 (A1, B1), 1:2 (A2, B2), and 1:3 (A3, B3) and submitted to a windrow process for 12 and 15 weeks in the A and B trials, respectively. The approximate dimensions of the trapezoid piles were as follows: width, 2.5 m; height, 1.5 m; and length, 3–4 m. Using the front-end loader, mixtures were turned and mixed every 5–7 days to provide oxygen for the piles.

At the end of each composting trial, composite samples were collected from the finished compost piles, dried at room temperature, and tested for heavy metals (Cd, Cr, Cu, Ni, Zn, and Pb), GI, pH, and EC. Determination of indicator and pathogenic microorganisms was also performed on moist composite samples. Each sample was collected from three different locations of each pile to ensure representative sampling.

Physicochemical analyses

The moisture content was determined by oven-drying of compost sample at 70±5 °C for 24 h (Thompson et al. 2001). The organic matter content (measured as volatile solids) was determined at 550 °C for 2 h in a muffle furnace. Heavy metal content, pH, and EC were all

Table 1 The characteristics of bulking agents and sewage sludge (SS)

Parameter	SS	Green waste (GW)	Pruning waste (PW)
Moisture content (%)	77.8 (3.1)[a]	51.5 (5.2)	10.7 (2.6)
Organic matter (%DW)	43.5 (5.4)	85.3 (15.4)	92.4 (13.2)
Total nitrogen (%DW)	2.4 (0.3)	0.5 (0.1)	0.4 (0.1)
C/N	11.7 (0.6)	94.8 (8.5)	122.1 (5.1)
pH	7.8 (0.6)	5.8 (0.5)	6.0 (0.2)
EC at 25 °C (mS/cm)	8.2 (1.3)	0.74 (0.08)	0.21 (0.09)
Heavy metals (mg/kg DW)			
Cd	4.1	NA	NA
Cr	213	NA	NA
Cu	330	NA	NA
Ni	110	NA	NA
Pb	169	NA	NA
Zn	1908	NA	NA
Total coliforms (MPN/g DW)	6.56×10^{8}	NA	NA
Fecal coliforms (MPN/g DW)	7.19×10^{7}	NA	NA
Fecal streptococci (MPN/g DW)	9.33×10^{5}	NA	NA
Salmonella (MPN/4gDW)	7.2×10^{2}	NA	NA

NA not analyzed, *DW* dry weight

[a] Standard deviations are given in parentheses

determined using an integrated sample and following standard procedures (Thompson et al. 2001). EC and pH were determined in 1:5 (*w*/*v*) aqueous extracts of air-dried samples using a handheld digital EC meter and pH meter (Eutech Instruments, Singapore), respectively. In order to determine the available fraction of heavy metals in final composts, the water-soluble fraction of heavy metals was digested, and the extracts were analyzed by flame atomic absorption spectrophotometry (Varian SpectrAA220FS, Australia).

Bacterial indicator determination

The biological analyses evaluated the density of indicator and pathogenic microorganisms, including total coliforms (TC), fecal coliforms (FC), fecal streptococci (FS), and *Salmonella* in the feedstock and in the compost produced from each trial. For bacteriological determinations, fresh compost samples were suspended in a 0.8 % saline solution, allowing the bacteria to distribute themselves uniformly throughout the samples. The solution was then diluted tenfold, and the most probable number (MPN) method was used to estimate the number of bacteria on a dry mass basis according to the guidelines of *Test methods for the examination of composting and compost* and *Standard Methods* (Thompson et al. 2001; APHA 2012). The media and materials used included lactose broth, brilliant green lactose bile broth, and EC broth for TC and FC; azide dextrose broth and PSE agar for FS; and Selenite F and xylose lysine deoxycholate (XLD) agar for *Salmonella*. Suspected *Salmonella* colonies were confirmed with cultural and biochemical tests using triple sugar iron (TSI) agar, urea agar base, and SIM medium (APHA 2012).

Phytotoxicity test

The seed germination bioassay was carried out on filter paper in Petri dishes, according to Tiquia et al. (1996). Aqueous extracts of the final samples were prepared by adding two parts of deionized water per part of sample weight (on a dry matter basis). The phytotoxicity of these extracts was evaluated by the seed germination method. Water extracts of finished composts (filtered by 0.45 mm) were then used to germinate cress seeds, with distilled water used as control in other dishes. The control GI value was set to 100 %, and germination percentages relative to the control were determined after 5 days.

Results and discussion

General characteristics of final compost

The initial and final properties of the composting mixtures are shown in Table 2. The 1:1 piles (A1 and B1) were not further considered because even after several turnings, they were still inappropriate for composting (i.e., too wet, poor structure, and no temperature rise). Study of Nikaeen et al. (2015) showed that higher porosity of 1:3 mixtures (SS/PW) than 1:1 mixtures as a consequence of the higher proportion of bulking agents resulted in higher microbial activity and higher temperatures in these piles (Nikaeen et al. 2015). The final mature compost in 1:2 and 1:3 piles had a dark appearance (black), with good physicochemical characteristics and a sufficient amount of organic matter and nutrients (Table 2).

After the addition of GW and PW into the SS as bulking agents at 2:1 and 3:1 ratios, the structure and moisture of the initial material had improved. Haug (1993) reported that the most adequate moisture content for the mixture to be processed is around 60 % (Haug 1993), and in all mixtures, our initial moisture content was suitable for an optimum composting process startup (Table 2). The moisture content decreased during the process, reaching a level between 25 and 30 % in the final products; no intensive biological process can take place at such a low moisture level (Rihani et al. 2010).

The ratio of C/N is often used to assess the rate of decomposition of compost mixtures, as it may reflect compost maturity. Researchers have suggested various ideal C/N ratios from lower than 12 to lower than 25 (Rihani et al. 2010; Brewer and Sullivan 2003) for composted material, but the optimal value is often dependent on the initial feedstock. According to Chazirakis et al. (2011), compost may be considered mature when the C/N ratio is approximately 17 or less, unless lignocellulosic material remains (Chazirakis et al. 2011). According to this suggestion, the C/N ratio in final composts in the present study was satisfactory (less than 17), which qualifies as good-quality compost, applicable to agricultural land (Table 2).

For purposes of composting, it is useful to report the initial and the final organic matter (OM), as this gives an idea of the extent of biodegradation (Chazirakis et al. 2011). The initial OM content of the piles was higher than that obtained at the end of process as a result of microbial activity and OM biodegradation (Table 2) (Banegas et al. 2007). This decrease in OM content can to, a large extent, be attributed to the mineralization of sludge OM; since, bulking agents OM (especially PW) would be formed of a more structured fraction, which is less susceptible to microorganism attack (Banegas et al. 2007; Manios 2004).

The total reduction in OM content was 65, 61, 43, and 42 % for A2, A3, B2, and B3 piles, respectively. The biggest decrease of OM was found in A2 (65 % of the initial value), indicating that OM degradation was more intense in the SS/GW mixture. The 1:2 mixture of SS and GW was the best for composting because of its ability to achieve the highest OM degradation and a more active process in the pile. However, there is no ideal level of OM in terms of compost quality.

pH and EC

Electrical conductivity (EC) and pH are two key parameters that should be measured when a material is to be used as an organic amendment, since the physical–chemical and biological reactions taking part in the soil are affected by these (Banegas et al. 2007). At the end of composting process, the pH of compost stabilized, reaching values of 7.5 and 7.9 for the A and B piles, respectively (Table 2). pH values of the final products indicated good-quality compost from an agricultural point of view, being within the range of 6–8.5 that has been recommended in several studies (Chazirakis et al. 2011; Banegas et al. 2007; Rihani et al. 2010).

The compost EC value, which reflects the soluble salt content of the compost, has great importance in an agricultural approach, since it can be a preventive parameter for plant growth and seed germination if applied to soil (Banegas et al. 2007). In particular, the EC value may depend on the degree of decomposition of organic compounds, which leads to accumulation of different water-soluble salts (Manios 2004). Some researchers indicated that an EC higher than 8 mS/cm has a negative effect on soil microbial populations

Table 2 Characteristics of study mixtures at the start and final step of the sewage sludge (SS) composting process, in comparison with the USEPA and WHO guidelines for acceptable quality of compost

Parameter	A2 (SS/GW, 1:2)		A3 (SS/GW, 1:3)		B2 (SS/PW, 1:2)		B3 (SS/PW, 1:3)		Standard (USEPA)[a]	Standard (WHO)[a]
	First	Final	First	Final	First	Final	First	Final		
Moisture content (%)	63.5	25	55.2	26.3	57.7	29.8	50.1	28.1	–	–
Organic matter (%DW)	70.6	24.5	77.4	30.3	73.9	42.4	81.9	46.4	–	
C/N	28.0	12.2	41.3	10.5	31.6	10.9	48.8	15	15	–
pH	7.6	7.5	7.6	7.5	7.8	7.9	7.6	7.9	6–8.5	6–9
EC (mS/cm)	8.14	3.86	6.16	2.19	9.35	2.78	5.31	1.2	<8	–
Total coliforms (MPN/g DW)	6.77×10^7	3.6	5.67×10^7	ND	7.00×10^7	22	6.49×10^7	274	–	–
Fecal coliforms (MPN/g DW)	6.39×10^6	ND	3.83×10^6	ND	5.11×10^6	ND	3.31×10^6	ND	<1000	<1000
Fecal streptococci (MPN/g DW)	7.04×10^4	94	4.29×10^4	11	6.05×10^4	82	5.07×10^4	37	–	–
Salmonella (MPN/4g DW)	4.2×10^2	ND	3.3×10^2	ND	3.9×10^2	ND	3.48×10^2	ND	<3	<3
GI (%)	10	100	30	90	20	90	0	70	>80	–
Cd (mg/kg DW)	1.9	1.35	1.5	1.28	3.2	2.4	3	2.8	39	15–40
Cr (mg/kg DW)	167	32.1	113	31	98	25	67	26	1200	–
Cu (mg/kg DW)	250	104	149	89	283	117	236	103	1500	1000–1750
Ni (mg/kg DW)	127	81	72	33	65	37	59	40	420	300–400
Pb (mg/kg DW)	135	79	110	72	144	44	125	45	300	750–1200
Zn (mg/kg DW)	1674	470	1236	430	1857	410	1332	500	2800	2500–4000

DW dry weight, *ND* not detected

[a] Standard limits for agricultural use

and their activity (Garcia and Hernandez 1996; Banegas et al. 2007).

The initial EC value of trial A was 8.14 and 6.16 mS/cm, whereas EC decreased to 3.86 and 2.19 mS/cm by the end of composting process for A2 and A3 piles, respectively. Similarly, the initial EC value of trial B was 9.35 and 5.31 mS/cm, and it decreased to 2.78 and 2.53 mS/cm by the end of the composting process for B2 and B3 piles, respectively. The initial soluble salt content of the mixtures was very high (Table 2), and especially for 1:2 mixtures, they were above the value of 8 mS/cm recommended for safe and vigorous plant growth.

Bulking agents, such as fresh or dry PW, typically contain few soluble salts (Table 1), so the major contributor to the EC values was SS. Moreover, the 1:2 mixtures showed higher EC values, which is indicative of a high SS salt content. Therefore, a high proportion of bulking agent (as seen in the 1:3 mixtures) resulted in a decrease of the EC values. As expected, the EC decreased along the experiment for both green and dry PW mixtures. This parameter, correlating mainly with the concentration of nitrogen salts (Farrell 1993), should be regarded as one of the main reasons why all sludge composts present phytotoxic activity when used in large proportions.

Compost sanitization

As reported by other researches, one of the problems posed by the direct use of SS in agriculture not submitted to proper treatment processing, such as composting, is the possibility of pathogen contamination for the users and for the soil and the crops growing in it (Banegas et al. 2007; Manios 2004; Rihani et al. 2010). Fresh anaerobic digested SS contains a large amount of pathogenic microorganisms (Table 1), which highlights the need for efficient treatment before disposal. Therefore, a microbiological evaluation appears essential to ensuring the absence of pathogenic microorganisms in compost products. To estimate the reduction of pathogenic microorganisms, analyses have been performed to evaluate the density of TC, FC, FS, and *Salmonella* prior to and after composting as shown in Table 2.

Coliforms are indicators of the presence of pathogens. In this study, the mean fecal coliform counts in the initial mixtures were 6.39×10^6, 3.83×10^6, 5.11×10^6, and 3.31×10^6 MPN/g dry weight (DW) for A2, A3, B2 and B3 piles, respectively. Most coliforms are inactivated when they are exposed to a temperature of 55 °C for 1 h or 60 °C for 15–20 min (Banegas et al. 2007). A significant reduction in the number of coliforms was observed in all piles (Table 2), reaching a 6-log reduction in TC in all piles. Farrell (1993) recommended a density of FC of 1000 MPN/g DW to be safe for compost, because *Salmonella* is considered to be absent from all samples containing amounts of FC lower than that (Farrell 1993). Results showed that there was a significant decrease in the amount of *Salmonella* in composted SS. Table 2 shows that the final composts were sanitized, since *Salmonella* was not detected, and less than 1000 MPN/g DW of FC was found in all piles. However, FS are more resistant to unfavorable environmental conditions than coliforms and commonly considered as better indicators of fecal pollution (Khwairakpam and Bhargava 2009); these decreased to below standard limits (1000 MPN/g DW) in final products for both trials.

The regulations on compost quality proposed by USEPA for class A composted sludge state that a marketable, processed compost product must be free from *Salmonella*, with FC counts not exceeding 1000 MPN/g DW. The final compost from both trials complied with USEPA regulations, and the density of *Salmonella* and FC observed in all the final composts was below this limit (Table 2).

The levels of microorganisms detected at the end of the process were significantly lower than prior to processing. Similar results were observed by several researchers during composting of SS (Rihani et al. 2010; Lu et al. 2008; Farrell 1993). Microbial counts were always higher in 1:2 piles, and the best results were achieved when the volumetric ratio was 1:3. In all cases, the results comply with the guidelines for safe reuse of SS (World Health Organization 2006; USEPA 1995). The destruction or inactivation of pathogenic microorganisms in composts depends on the magnitude and duration of temperature elevation attained in a windrow and the number of times that the windrow is turned. The thermophilic duration depends on the chemical composition and biodegradability of the composting feedstock (Haug 1993). The active phase of windrow composting lasted for about 8–10 weeks, and the maturation period lasted for at least a further 4–5 weeks (data not shown). The thermophilic duration in different piles was long enough to meet the requirements of sanitary standards. Most pathogens were destroyed at the temperatures reached during composting process, rendering the end products harmless for agricultural utilization.

Phytotoxicity analysis

In order to evaluate the applicability of compost as plant growing promoter, a cress seed germination test was carried out to determine the effectiveness of the composting process in removing phytotoxic substances and to assess compost maturity. The results of the phytotoxicity analysis are presented in Table 2. The seed germination results showed that the cress seeds had not germinated exposed to the initial mixtures due to the phytotoxicity effect of the significant quantities of growth-inhibiting compounds such as ammonia in the SS (Chazirakis et al. 2011; Tiquia et al. 1996). In addition, toxic metals can inhibit plant growth and influence on germination time. Simantiraki et al. (2013) reported a high level of toxicity among samples of fresh municipal solid waste compost and concluded that the high toxicity mainly attributed to the presence of heavy metals (Simantiraki et al. 2013). However, the low concentration of toxic metals even in SS (Table 1) revealed no phytotoxicity effect. A GI of more than 80 % indicates phytotoxic-free and mature compost, and if the value is below 50 %, the compost presents a high level of phytotoxicity. Many SS compost studies have followed these limits (Zucconi et al. 1981; Tiquia et al. 1996; Roca-Pérez et al. 2009). In the present study, the results obtained after the composting process show that all of the obtained composts except B3 achieved GI above 80 %, revealing that phytotoxic substances had disappeared or lost their negative effect and indicating that the inhibitory effect on plant growth disappeared during composting. It should be highlighted that the percentages in trial A composts were higher than those obtained in trial B, indicating that GW is better for composting. The lower GI in trial B especially in 1:3 pile with higher content of bulking agent could be explained by the presence of toxic and phytotoxic compounds, such as resins, in PW. The results indicated that the GI is dependent on the initial composition of the mixture, which confirms the results by Yañez et al. (2009).

Heavy metals

Some heavy metals—in small amounts—are essential for plant growth; however, in higher concentrations, they are likely to have negative effects (Khwairakpam and Bhargava 2009). One of the major concerns in land application of SS compost is the presence of high concentrations of numerous heavy metals, which may have hazardous effects for soils and crops and which may pose an indirect risk to human health due to the bioaccumulation and biomagnification properties (Rihani et al. 2010). So, prior to application of compost to soils, there is a need to determine toxic metal concentrations in the final compost.

Composting may concentrate or dilute the metal content of SS, and toxic metal distribution and bioavailability in final compost depend on the metal itself, sludge characteristics, the composting process, and the physicochemical properties of the final compost, including the amount of organic carbon, humic matter content, and pH (Cai et al. 2007a; Wang et al. 2005). As described by several authors, the most important toxic metals present in SS include lead (Pb), zinc (Zn), cadmium (Cd), chromium (Cr), copper (Cu), and nickel (Ni) (Smith 2009; Wang et al. 2005). The limits (expressed as mg/kg DW) for these elements in biosolids applied to agricultural lands, forests, public contact sites, or reclamation sites have been stipulated by USEPA. The heavy metal concentrations of the SS used in our two composting trials are given in Table 1. The concentrations of the aforementioned metals in the initial mixtures and final products in the A and B composting trials were evaluated as shown in Table 2. These values were lower than the recommended standard values (World Health Organization 2006; USEPA 1995) for compost and soil pollution control. Comparing the total heavy metal concentrations of SS with the established limit values in the study of Alvarenga et al. (2015) showed that all heavy metals have low concentrations, allowing agricultural application of SS (Alvarenga et al. 2015). Zn and Cu represented the trace elements with the highest concentrations. This result is comparable with the result of Yañez et al. (2009) and Simantiraki et al. (2013) in which Cu and Zn were the metals with the highest percentages among the ones measured in composted materials.

The addition of bulking agents had a diluting effect on these metals, since the values for same types of metal were lower in the 1:3 mixture than in the 1:2 mixture. Yañez et al. (2009) also reported increments in heavy metal contents with the increase of SS portions to *Acacia dealbata* as bulking agent (Yañez et al. 2009).

Furthermore, by comparing toxic metal concentrations in the initial mixtures with those of the final products (Table 2), it appears that SS composting using GW and PW as bulking agents may decrease heavy metal bioavailability to levels sufficiently lower than those that can be tolerated for compost use in agriculture. Simantiraki et al. (2013) reported that composting of municipal solid waste reduced significantly heavy metal concentration. In other words, compost tends to retain heavy metals, thereby eliminating the environmental pollution (Simantiraki et al. 2013).

In addition, compost produced from both trials could be classified as class A compost based on the heavy metal quality standards for compost and stabilized SS (Table 2). Smith (2009) reported that aerobic composting processes increase the complexation of heavy metals in organic waste residuals (Smith 2009). In other words, metals are strongly bound to the compost matrix and OM, which limits their solubility and potential bioavailability in soil. The metal contents in the final compost were much lower than the standard borderline values for compost, and therefore, the compost products could be used safely as a soil fertilizer.

Conclusions

Our results indicated that the final products of 1:2 and 1:3 piles had a high level of stability. The relatively high GI especially in 1:2 piles and appropriate pH and EC indicated that the compost products can be used for agricultural purposes. Final compost products were well sanitized as a result of high temperatures achieved during the composting process. On the other hand, the concentrations of toxic metals after composting process were below the USEPA limits for biosolid land application. However, the volume ratio of 1:2 of SS to GW was the best, since these mixtures achieved the highest level of OM degradation and GI in the final compost products.

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