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Integrated windrow-based co-composting of domestic wastewater treatment plant sludge and solid waste for high-quality compost fertilizer production

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Abstract

Background: This study aimed to explore the feasibility of producing compost fertilizer through co-composting solid waste materials and dewatered sludge from the domestic wastewater treatment plant (WWTP) at Gole-Gohar Mining and Industrial Company, employing the windrow method with various treatments.

Methods: In this experimental study, three windrow piles were established, each with a volume of 0.3 m^3 and weight ratios of 1:2 (food waste:dewatered sludge) and 1:4 (garden waste:dewatered sludge), along with a control group without sewage sludge (SS) modification. The parameters influencing the compost production process, including temperature, moisture content, volatile solids, pH, electrical conductivity (EC), organic carbon, organic matter, C/N ratio, heavy metals, density, alkalinity, phosphorus content, microbial load, cations and anions were examined.

Results: The results showed that the concentrations of heavy metals and pH levels in all three compost piles fell within acceptable ranges. EC values fluctuated between 2 and 6 mS/cm across all piles. The C/N ratio decreased, with the pile containing sewage treatment plant sludge and food waste achieving the optimal range of 15-25. The germination index (GI) for lettuce, cress, and mung bean seeds was higher than the standard in all three piles. The produced compost was classified as Class A in terms of microbial load.

Conclusion: Overall, the physicochemical parameters of the produced composts met standard limits. According to the results, compost-containing food waste emerged as the most suitable for agricultural use.

Keywords: Sludge, Solid waste, Compost, Heavy metals, Soil

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Introduction

The term "Co-composting" refers to simultaneous composting, in which various types of waste, animal manure, sewage sludge (SS), and agricultural waste are simultaneously converted into compost (1). Sewage sludge is a semi-solid material that is produced in wastewater treatment plants (WWTPs) by biological activity or the separation of solids from chemical precipitation effluents, which is a crucial by-product of the wastewater treatment process (2,3). Since SS contains a high concentration of organic materials and some nutrients (e.g., nitrogen, phosphorous, potassium, and trace elements), it can be applied as a fertilizer or soil conditioner to boost the growth of crops (4). Given its high humidity and low C/N content, WWTPs sludge cannot be used for producing compost. In contrast, co-composting can be developed with recyclable components including dewatered municipal solid waste (MSW), livestock or crop residue, and industrial waste (5,6). The Code of Federal Regulations (CFR) and standards established by the United States Environmental Protection Agency (USEPA) for the utilization and disposal of SS have been compiled (7).

Sewage sludge is classified into two classes, A and B, depending on microbiological traits, according to the USEPA standards. Each class has been approved for a particular use in the soil. The traits of class A include intestinal virus density of less than 1 PFU/4g.DS^{-1}, parasite egg density of less than 1 Ova/4g.DS^{-1}, salmonella density of less than 3 MPN/4g.DS^{-1}, and fecal coliform density of less than 1000 MPN/g.DS^{-1}. Class B SS is exclusively intended for land restoration, while class A SS has no limitations on its reuse or disposal (8,9).

Unregulated dumping and inadequate control of solid waste result in unpleasant odors, fostering the proliferation of flies, mice, cockroaches and other insects, as well as the unchecked growth of stray cats and dogs (10). This underscores the crucial need for proper storage, correct collection methods, and appropriate disposal of these materials (11). To protect the environment, preserve public health, the economy, science, engineering, and aesthetics while also taking other environmental factors into account, waste management is a set of rules about the production, storage, collection, transportation, processing, and disposal of waste in conformity with existing laws (12).

One of the key techniques for waste management is composting (13). Urban development is hampered by the daily increase in the amount of SS and MSW in urban areas, which has turned into a major societal concern. Along with population and economic growth and the pressing need to safeguard the environment, the approach to managing solid organic waste has shifted from treatment and landfilling to employing environmentally friendly resources (13,14). The existence of strategies for the efficient reuse of this kind of solid waste and impact minimization is crucial (13,15).

In a rural area of Shanghai, China, Xu et al studied the changes in heavy metal concentrations during the simultaneous composting of rural organic solid waste (rural SS, kitchen waste, and plant stems). As a result, the concentrations of heavy metals Zn, Pb, Hg, Cu, and As increased, while those of heavy metals Ni and Cr decreased (16). In a pilot study, Dzulkurnain et al investigated the co-composting of landscaping waste and Indian city SS. They found that after 15 days, coliforms and *Escherichia coli* were eradicated during the thermophilic phase, indicating that the compost was safe for use in the natural environment (17). In the composting process of the dewatered sludge of the municipal sewage treatment plant in Rafsanjan county, Jafariniya Parizi et al employed dates and pistachio wastes for the first time. After 60 days, the quality of the date waste reactor was greater than that of the pistachio waste reactor. However, compared to the date reactor, the pistachio waste reactor was less harmful (18).

Currently, there are several environmental issues as a result of improper management of WWTP sludge disposal in developing nations, such as Iran. One of the best approaches in this situation is composting, which can increase the fertility of agricultural lands in the mining and industrial area of Gole-Gohar Mining and Industrial Company and prevent the overuse of chemical fertilizers in addition to preventing pollution of soil, air, and surface and ground water sources. The concept of a circular economy refers to the reuse and recycling of resources as much as possible. These types of initiatives help reduce costs and create new income streams through the sale of compost or other products derived from waste. It is one of the most well-known industrial mining centers in the Middle East, producing a lot of waste and effluent that has to be properly managed. Consequently, this research aimed for the first time to benefit the nation's large mines and industries by looking into the possibility of co-composting, or making compost fertilizer, out of solid waste and dewatered sludge from the Gole-Gohar Mining and Industrial Company domestic WWTP using a windrow method and various treatments. It is also suggested that natural catalytic materials such as eggshells, sawdust, and plant extracts be used, as they can affect the acceleration of the composting process and reduce the compost production period. This research can help promote and facilitate the acceptance of these ideas within the scientific and industrial communities.

Materials and Methods

The materials used in this experiment include xylose lysine deoxycholate (XLD), Lactose Broth (LB), and *E. coli* Broth (EC). It is from the German brand Merck, which was used for microbiological cultivation.

Pilot design

Located 55 km from the Sirjan-Neiriz road, the Gol-e Gohar iron ore mine hosted research facilities within Site No. 1's greenhouse. Here, three concrete chambers measuring 2 m in length, 1 m in width, and 0.8 m in height were established to facilitate experimentation (Figure 1). A compressed plastic substructure was employed to manage leachate production effectively. To conduct this study, sludge from the domestic WWTP of the Gole-Gohar Mining and Industrial Company was used as a sample. This selection was made due to the high capacity of this complex for sludge production, as well as the presence of organic materials and nutrients in this sludge. Treated sludge is one of the potential sources for compost production and soil quality improvement to initiate the research, windrows were constructed utilizing different waste materials. A food waste-sludge (FS) windrow was formed with a ratio of 1:2 (food waste to dewatered sludge), while a garden waste-sludge (GS) windrow was created at a ratio of 1:4 (green space waste to dewatered sludge). In contrast, the SS windrow remained unmodified. Each windrow reached a volume of 0.3 m^3 (Figure 2). To optimize the C/N ratio and serve as a bulking agent, wheat stubble straw was incorporated. Over 32 days, the constructed windrows underwent periodic covering to facilitate mixing and aeration, effectively reducing moisture levels. Additionally, manual cleaning of the windrows was conducted every week to ensure proper maintenance.

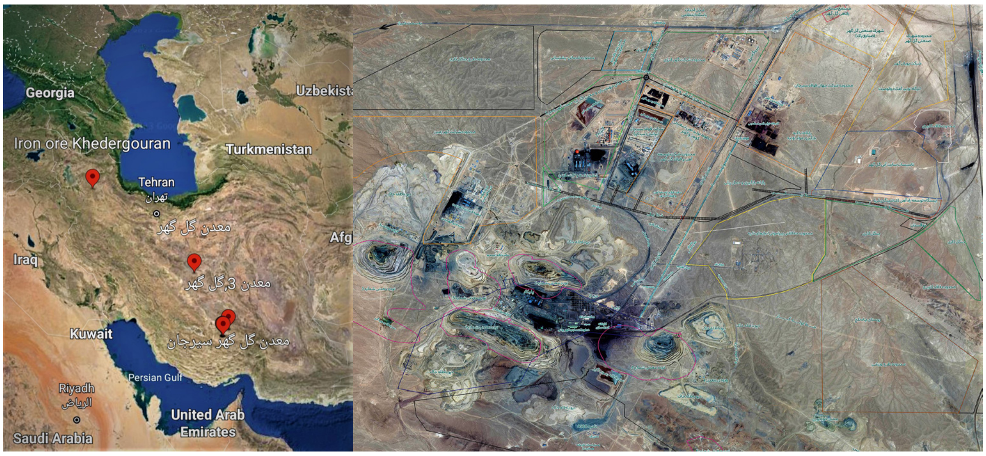

Figure 1. Map of the geographical location of Gole-Gohar Mining and Industrial Company

(A) (B) (C)

Figure 2. Experimental pilots used in the study, A: windrow containing food waste and sewage treatment plant sludge, B: windrow containing garden waste and sewage treatment plant sludge, and C: windrow containing sewage treatment plant sludge

Sampling

The required sludge was sourced from the sludge dryers at the sewage domestic WWTP of the industrial and mining complex, while additional inputs included food waste from local restaurants and garden waste comprising shredded tree leaves. During the fall of 2022, samples were systematically collected from depths of 0.1, 0.25, and 0.5 m of the piles, with a frequency of three days per week. These samples were then combined individually to create composite samples, each representing the desired quality. Subsequently, each composite sample was divided into two portions including one portion promptly frozen at 20 °C, while the other portion was air-dried, sieved through a 0.25 mm mesh, and stored for subsequent analysis (19).

This experimental study spanned 32 days during the fall season. Daily measurements of temperature, moisture content, pH, and electrical conductivity (EC) were accurately recorded throughout the study period. The temperature of all three piles was measured in the early hours of the day using a pen thermometer at three different points (20). To initiate the experimental procedure, 10 g of the sample were carefully weighed and placed into a beaker, and the volume was adjusted to 100 mL. Subsequently, the mixture was stirred vigorously for 3 min using a TAT-5003, Iran magnetic stirrer at high speed, followed by filtration through a strainer. pH and EC measurements were conducted using a portable multi-parameter device (model HQ30D, USA). For moisture content determination, another 10-g portion of the sample was subjected to drying at 105 °C for 24 hours (21,22). After cooling in a desiccator, the sample was re-weighed, and the difference in weight provided the moisture content. The total solids content of the compost was determined by daily drying of samples at a temperature range of 103 to 105 °C. Subsequently, the mineral and volatile solids were obtained by placing the dried compost samples in an oven set to 550°C after initial weighing. Furthermore, the density of the sample was determined using a density reading device (Pycnometer Accupyc 111340, Germany), contributing to a comprehensive characterization of the compost material (21).

Sterile containers were used for biological tests and to prevent the change of samples, they were kept at a temperature between 0 and 4°C until they were transferred to the laboratory. The biological parameters included fecal coliform, *salmonella*, and helminth ova. Microbial parameters were measured weekly by MPN standard method (9221 E) (21,23-25). Microbial culture was conducted using XLD culture medium, lactose broth, and EC Broth obtained from Merck, Germany. The results were quantified as the Most Probable Number (MPN) per g of dry matter (8,23,26,27). Weekly measurements of nitrogen, carbon, alkalinity, and organic matter were also performed. Nitrate and sulfate levels were determined using a spectrophotometer (UV/Vis-EU2200, Iran). Furthermore, heavy metal concentrations were determined after digestion, with readings obtained using an ICP-MASS device from Perkin Elmer, USA (21).

Germination and growth

To assess the quality of the produced fertilizer, the germination index (GI) of seeds from lettuce (*Lactuca Sativa*), cress (*Lepidium Sativum*), mung bean (*Vigna Radiata*), and radish (*Raphanus sativus*) was utilized. The GI was determined by preparing a suspension of compost extract dissolved in water (1 g of fresh sample in 20 mL of distilled water). Subsequently, 5 mL of the resulting solution was added to sterile plates fitted with a filter at the bottom, and 30 seeds of each plant species were planted in each plate. The plates were then kept in darkness at a temperature of 25 °C. After 24 hours, the number of sprouts and root growth were observed and recorded for 72 hours. This experiment was repeated three times for reliability. The GI was calculated using Eq. 1 (7,22,28,29):

$$\text{CHSg} = \left[(\%\text{Sg1} \times \text{RI})\ \text{compost} \div (\%\text{Sg2} \times \text{RSS})\ \text{water}\right] \times 100 \quad \text{(Eq. 1)}$$

CHSg = Germination index

where Sg_1 and Sg_2 are the number of seeds germinated in the compost extracts and distilled water, respectively. RI and RSS are the length of rootlets in compost and distilled water, respectively.

Results

The temperature dynamics within the compost piles yielded noteworthy insights (Figure 3). In the SS pile, temperatures exhibited an initial rise, peaking around the 13th day before gradually declining. Similarly, in the FS pile, an initial increase in temperature was observed, followed by a decrease after approximately 9 days. Conversely, in the GS pile, temperature initially ascended, then began to decline after 5 days.

The moisture percentage measurements depicted in Figure 4 reveal distinct trends among the compost piles. Initially, pile SS exhibited the highest moisture content, peaking at 69%, followed by pile FS at 55%, and pile GS at 51%.

The pH measurements, as illustrated in Figure 5, exhibit a consistent pattern across all three windrows. Initially, the windrow containing food waste and domestic WWTP sludge displayed acidity, gradually reaching standard pH levels by the 32nd day.

The results of EC measurements, as depicted in Figure 6, indicate a close similarity in values among all three piles, ranging between 2 and 5 mS/cm.

The findings from the assessment of physical and chemical parameters throughout the composting process are presented in Table 1.

The results of element measurements in the three compost piles at the beginning and end of the compost preparation process are provided in Table 2.

The results of the microbial load analysis are provided in Table 3.

The results of the measurement of the germination index are presented in Table 4.

Discussion

According to Figure 3, this observed temperature decrease during the composting process can be attributed to the enhanced porosity of the GS pile compared to the others, coupled with a reduction in moisture content due to moisture adsorption by the garden waste component. Conversely, the temperature increase witnessed in the SS and FS piles may be linked to higher levels of humidity. The presence of abundant food waste, along with the naturally higher moisture content of SS at the onset of the process, fosters heightened microbial activity, consequently elevating compost temperatures (4). The compost pile containing food waste treatment exhibited notably higher temperatures compared to the other piles. Within the first week, the temperature soared to 60 °C. Subsequently, the compost containing SS reached this temperature in the second week, while the compost treated with garden waste reached a slightly lower temperature of 55 °C during the same period. This discrepancy in temperature can be attributed to the higher porosity of the compost pile in the garden waste treatment pile. It is worth noting that achieving temperatures exceeding 55°C for at least 4 hours is crucial for ensuring adequate hygiene and the elimination of disease-causing pathogens in compost materials. Encouragingly, all three compost piles examined in this study successfully reached and maintained temperatures above this threshold, indicating the effective removal of dangerous pathogens from the produced composts (30).

According to Figure 4, the composting process, moisture content is important for the transfer of soluble nutrients required for the physiological and metabolic activities of microorganisms, and it depends on the specific physical and chemical properties as well as the biological characteristics of the materials being composted (25). The addition of bulking materials led to a reduction in moisture levels, with the decrease in moisture content being less pronounced in the pile containing food waste compared to the pile containing garden waste. This discrepancy can be attributed to the presence of vegetables

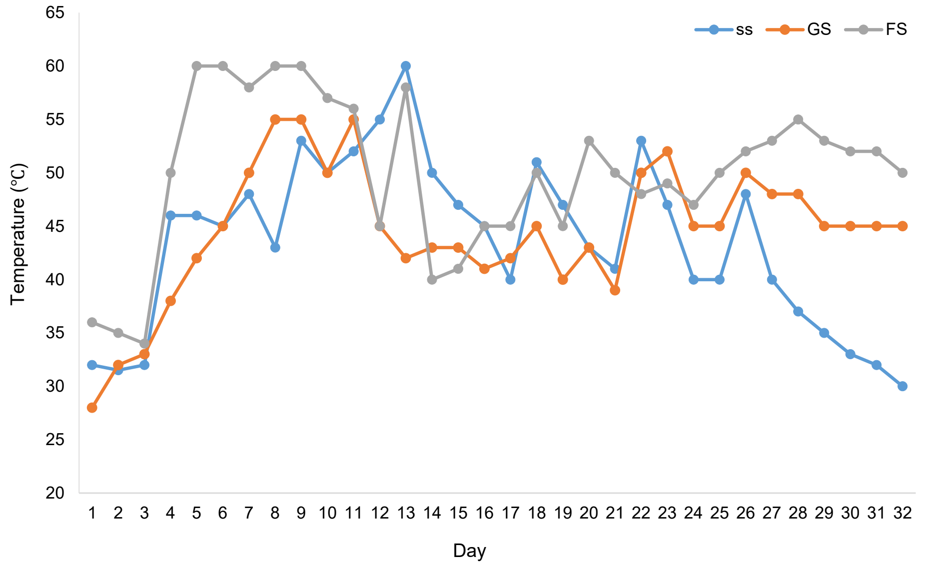

Figure 3. Temperature changes during the sewage sludge composting process with different treatments (SS: Sewage sludge, FS: Food waste and sewage sludge, GS: Garden waste and sewage sludge)

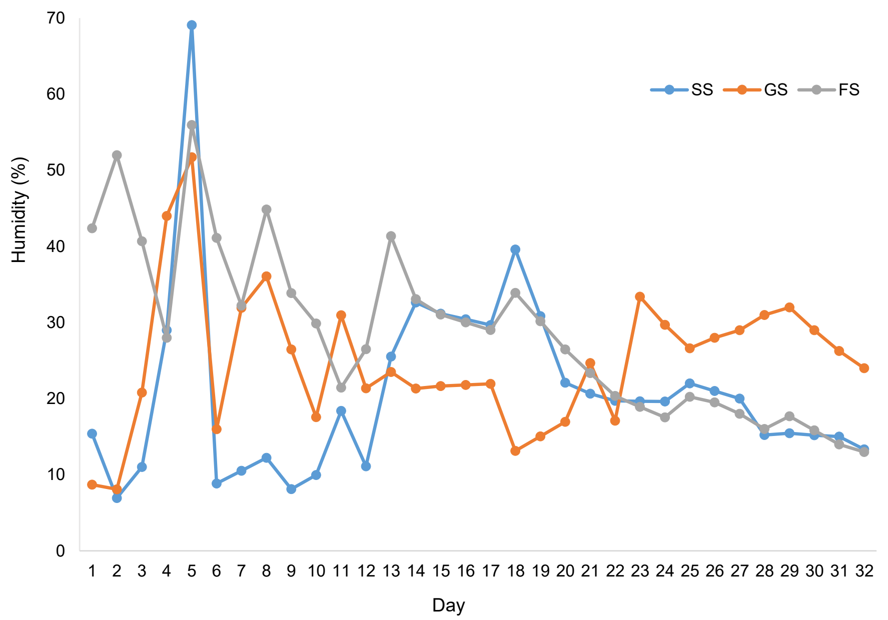

Figure 4. Humidity changes during the composting process of sewage sludge with different treatments (SS: Sewage sludge, FS: Food waste and sewage sludge, GS: Garden waste and sewage sludge)

and fruits in the food waste, which inherently possess higher moisture content. These findings align closely with the study conducted by Grgas et al, indicating a consistent trend in moisture changes across all compost mixtures. Specifically, an increasing trend in moisture content was observed during the first month, followed by a subsequent decrease in the following months (30).

The pH measurements, as illustrated in Figure 5, exhibit a consistent pattern across all three windrows. This transition can be attributed to the biological decomposition of acidic materials and the mineralization of organic nitrogen facilitated by microbial activities (4,31). Extreme pH levels, whether excessively high or low, pose significant risks to microbial survival. In this study, observations revealed that the compost containing sewage treatment plant sludge and food waste exhibited acidity during the initial stages of activity. This phenomenon can be attributed to the lack of oxygen in the deeper layers of the compost pile, coupled with high temperatures and rapid microbial activity, resulting in the production of organic acids and a subsequent decrease in pH levels. These findings closely mirror the trends observed in the study conducted by Okoh et al (32).

Numerous studies have highlighted an initial increase in EC levels during the early stages of the composting process. This elevation can be attributed to the microbial

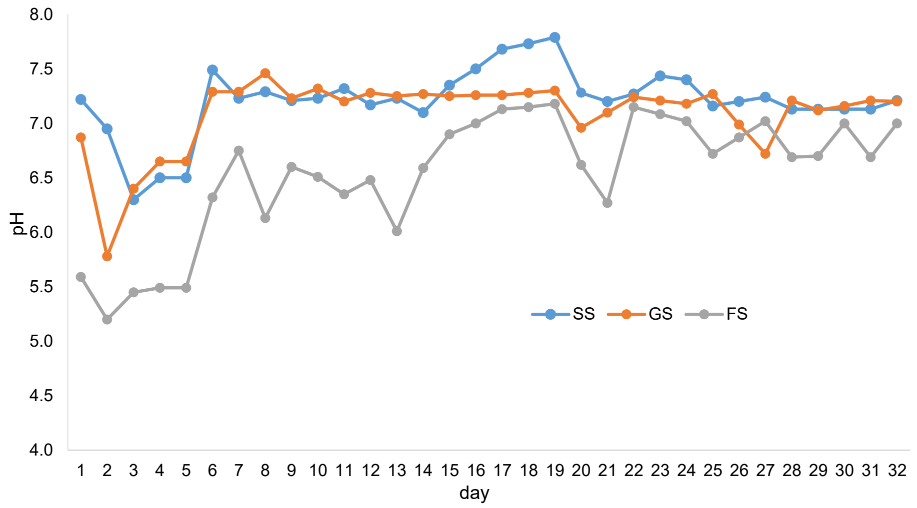

Figure 5. pH changes during the composting process of sewage sludge with different treatments (SS: Sewage sludge, FS: Food waste and sewage sludge, GS: Garden waste and sewage sludge)

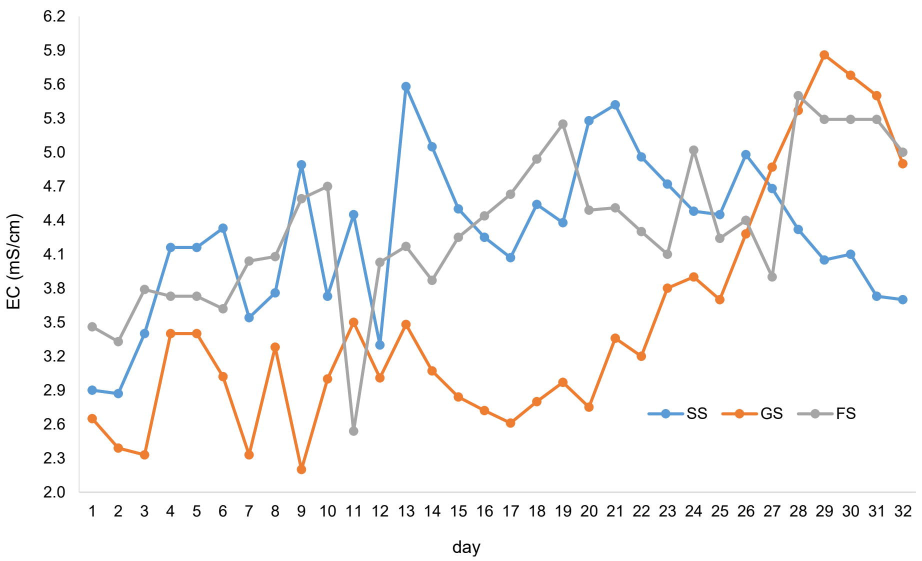

Figure 6. EC changes during the sewage sludge composting process with different treatments (SS: Sewage sludge, FS: Food waste and sewage sludge, GS: Garden waste and sewage sludge)

degradation of organic materials, leading to the release of mineral salts such as phosphates and ammonium ions. Conversely, instances of EC reduction may be linked to the evaporation of ammonia and the precipitation of mineral salts (4,33). Furthermore, the absence of EC observed in the pile GS compared to the other piles may indicate a lower moisture content (Figure 6). This aligns with the findings from the study conducted by Kebibeche et al, which also demonstrated a notable increase in EC levels until the 31st day for compost containing SS and wheat straw (4).

According to the findings presented in Table 1, the density levels for piles FS and GS exhibited a decrease in the fourth week, followed by an increase in 50 weeks. However, the density results for pile SS showed fluctuations throughout the observation period. Furthermore, the alkalinity levels decreased consistently across all three piles over the 32-day period, which may be attributed to the reduction in carbonates and bicarbonates (34).

The sodium content decreased in all three piles during the composting process. While the amounts of calcium and magnesium decreased in piles SS and FS, they increased in pile GS. Moreover, the sulfate and nitrate levels increased in all three piles over the 32-day duration. The increase in nitrate levels during composting can be attributed to the supply of oxygen during pile turning, which promotes nitrate formation through nitrification (33). The study by Şevik et al demonstrated that the concentration of nitrate-nitrogen increased in both the first and second groups of compost (35).

The C/N ratio is a critical parameter for assessing compost quality, which decreased over the 5-week observation period. Initially, the C/N ratio in the GS pile was 12.29, decreasing to 10.02, while in the FS pile, it

Table 1. Changes occurred in physicochemical parameters during the composting process

Parameter	Compost containing food waste and sewage sludge		Compost containing garden waste and sewage sludge		Compost containing sewage sludge		Standard value
	Day 1	Day32	Day 1	Day32	Day 1	Day 32	
Alkalinity	25.3	< 1	23	1.1	6.9	< 1	-
Na (mg/kg)	0.9	0.7	0.5	0.6	0.7	0.6	-
Mg (mg/kg)	1.5	1.3	0.9	1.6	1.9	1.7	-
Ca (mg/kg)	1.9	1.9	2.7	2.5	2.9	2.6	-
SO_4^{2-} (mg/kg)	192	358	35.5	125	153	192	-
NO_3^- (mg/kg)	127	1265	23	123	82.4	484	-
Volatile Solids (mg/L)	78	78	78	77.5	78	78	-
C/N	27.1	18	12.3	10	6.7	4.5	Class A: 15-20 Class B: 10-15
Nitrogen % (SD)	1.8 (0.45)	1.6 (0.14)	3.3 (0.66)	2.6 (0.46)	5.3 (0.18)	4 (0.75)	Class A: 1.25-1.66 Class B: 1.0-1.5
Carbon % (SD)	49.6 (0.95)	28.2 (1.47)	40.3 (2.2)	26.3 (0.54)	35.4 (1.2)	18.4 (0.4)	Class A: Min 25% Class B: Min 15%
Organic matter (%)	28.9	50.7	72.6	47.4	63.8	33.1	Class A: Min 35% Class B: Min 25%
P (mg/L)	0.6	0.5	0.3	0.6	0.9	0.7	Class A: 1-3.8 Class B: 0.3-3.8
Density (g/cm^3)	1.9	2	2	1.7	2.3	2.2	-

Standard value: Standard 10716 (acceptable limits for compost categories 1 and 2), the EPA standard.

decreased from 27.10 to 17.96, falling within the optimal range of 15-25 for compost C/N ratios. According to compost standards, the FS pile achieved the best C/N ratio and falls into the first class, followed by the GS pile, which falls into the second class. The decline in the C/N ratio signifies the transformation of unsaturated structures into saturated structures, thereby enhancing aromatic density and the degree of humidification (23,36). The study by Grgas et al similarly showed a decrease in the C/N ratio across all three piles comprising SS + GW + FW, SS + GW, and SS + FW (30). The nitrogen percentage in both GS and SS piles exhibited a declining trend over the five weeks. This increase in Total Kjeldahl Nitrogen (TKN) can be attributed to a concentration effect resulting from weight loss associated with the mineralization of organic nitrogenous compounds (4). The increase in nitrate levels in piles containing sludge from WWTPs and food waste can be attributed to the addition of kitchen food scraps to the sludge (37). Other reasons for the increase in nitrate during composting include the supply of oxygen during the turning of the piles, which leads to the formation of nitrate through nitrification (38). In the study by Wang et al, sheep manure was composted with three treatments involving mushroom litter, corn stalks, and garden litter for 49 days. The findings indicated that all additives led to reductions in total nitrogen and ammonium nitrogen levels. Significant losses of nitrogen may occur due to the evaporation and denitrification of ammonia (39). Moreover, the organic carbon percentage decreased in all three piles over 32 days. The gradual decrease in total carbon throughout decomposition indicates that the decomposed components are readily mineralized by existing microorganisms, which utilize these compounds as an energy source. As a result, the final product becomes enriched in stable compounds (34). Jafariniya Parizi et al also observed a decrease in the percentage of organic carbon in composts containing pistachio dehulling waste with urban sewage sludge (PW + SS) and date-palm straw with urban sewage sludge (PS + SS), which decreased from 69 to 15 and 78 to 48, respectively (18).

The organic matter in food waste reached 50% and showed an increase, which places it in Class A to Washington standards. However, it is greater than the minimum standard in Iran, which is 35%, the obtained values were consistent with the results of the study by Aghili et al (23). The total organic matter content in GS, SS piles decreased over 5 weeks, indicating the mineralization of biodegradable materials during composting (40). The results of the study by Zhang et al corroborate this trend, as they observed a continuous decrease in organic matter across all compost types in their study (31).

According to the findings presented in Table 2, the predominant heavy metals across all three compost piles were Zn, Sr, V, and Mn. Conversely, heavy metals such as Ag, Be, Bi, Cs, Dy, Er, Eu, Hg, Ho, In, Lu, Sb, Sc, Ta, Tb, Te, Tl, and Tm remained consistently below one for all three piles both at the beginning and end of the process, with no significant changes observed during composting. The fluctuations in heavy metal concentrations can be attributed to the concentration and mass reduction effects that occur during composting (41). Golbaz et al researched compost composed of SS, wood chips, and sawdust, revealing minimal levels of heavy metals such as cadmium (Cd), chromium (Cr), and lead (Pb) in the samples. These results indicate positive indicators for the composting process and the quality of the final product

Table 2. The elements concentration in three compost piles at the beginning and end of the composting process (mg/L)

Entry	Element	SS1	SS2	FS1	FS2	GS1	GS2	Standard value
1	Ag	< 1	< 1	< 1	< 1	< 1	< 1	-
2	Al	1.3	1.3	1	1	1.1	1.2	-
3	As	7	6.3	6.5	5	6.4	4.6	Max: 10
4	Ba	119.6	88	87.3	81.9	251	91.7	-
5	Be	< 1	< 1	< 1	< 1	< 1	< 1	-
6	Bi	1.1	< 1	20.7	< 1	< 1	< 1	-
7	Ca	2.9	2.6	1.9	1.9	< 1	2.4	-
8	Cd	4.9	< 1	3.9	< 1	< 1	< 1	Max: 10
9	Se	10.5	5.7	7.3	3.5	8.3	6.1	-
10	Co	25.9	14.4	35.1	14.6	15.5	12.6	Max: 25
11	Cr	60.9	67	51.4	50	33.8	60.8	Max: 150
12	Cs	< 1	< 1	< 1	< 1	< 1	< 1	-
13	Cu	93.5	108.5	76.4	74.4	52.6	97.1	Max: 650
14	Dy	< 1	< 1	< 1	< 1	< 1	< 1	-
15	Er	< 1	< 1	< 1	< 1	< 1	< 1	-
16	Eu	< 1	< 1	< 1	< 1	< 1	< 1	-
17	Fe	18.1	23.9	14.6	20.7	8.5	22.5	-
18	Ga	17.6	11.7	13.1	9.4	6.7	10.4	-
19	Gd	1.2	< 1	< 1	< 1	1.1	< 1	-
20	Hf	< 1	< 1	< 1	< 1	< 1	< 1	-
21	Hg	< 1	< 1	< 1	< 1	< 1	< 1	Max: 5
22	Ho	< 1	< 1	< 1	< 1	< 1	< 1	-
23	In	< 1	< 1	< 1	< 1	< 1	< 1	-
24	K	0.4	0.3	0.6	0.4	0.4	0.3	-
25	La	16.5	5.07	12.5	4.1	16.1	5.4	-
26	Li	6.1	< 1	4.7	< 1	4.7	< 1	-
27	Lu	< 1	< 1	< 1	< 1	< 1	< 1	-
28	Mg	1.9	1.7	1.5	1.3	0.88	1.63	-
29	Mn	254.9	215.9	188.4	167.1	200.4	199.2	-
30	Mo	6	4	4.9	2.8	3.2	4.6	Max: 5
31	Na	0.7	0.6	0.8	0.7	0.5	0.6	-
32	Nb	2.6	2.5	2.6	1.7	2.7	2	-
33	Nd	22.6	3.8	17.5	3.2	19.3	4	-
34	Ni	73.6	22	58	23.6	30.6	31.4	Max: 120
35	P	0.9	0.7	0.6	0.5	0.3	0.6	-
36	Pb	19.2	1	20.2	5	12.7	8.8	Max: 200
37	Pr	15.8	< 1	11.2	< 1	6.8	< 1	-
38	Rb	17.5	5.9	14	5.2	12	6	-
39	S	2.2	2.3	1.8	1.6	1.1	2.1	-
40	Sb	< 1	< 1	< 1	< 1	< 1	< 1	-
41	Sc	< 1	< 1	< 1	< 1	< 1	< 1	-
42	Sm	6.4	< 1	< 1	< 1	< 1	< 1	-
43	Sn	33.7	17.4	16.2	6.8	13	14.2	-
44	Sr	347	246	207	171.8	329	227.7	-
45	Ta	< 1	< 1	< 1	< 1	< 1	< 1	-
46	Tb	< 1	< 1	< 1	< 1	< 1	< 1	-
47	Te	< 1	< 1	< 1	< 1	< 1	< 1	-

Table 2. Continued.

Entry	Element	SS1	SS2	FS1	FS2	GS1	GS2	Standard value
48	Th	< 1	1.8	< 1	1.6	<	1.9	-
49	Ti	< 1	< 1	< 1	< 1	< 1	< 1	-
50	Tl	< 1	< 1	< 1	< 1	< 1	< 1	-
51	Tm	< 1	< 1	< 1	< 1	< 1	< 1	-
52	U	6.7	3	5.5	2.3	2.6	2.9	-
53	V	224.3	180.2	163.7	143.9	87.2	167.2	-
54	W	20.6	19.9	41.7	34.3	65.8	19.3	-
55	Y	4	4.1	3.3	3.1	3.4	3.8	-
56	Yb	3.3	4.3	2.4	3.4	1.4	4	-
57	Zn	440.3	369.8	354.5	254.4	200.6	341.6	Max: 1300
58	Zr	13.6	16.9	10.4	11.8	7.8	14.6	-

SS1, SS2: Windrow containing sewage sludge at the beginning and end of the composting process.
FS1, FS2: Windrow containing food waste and sewage sludge at the beginning and end of the composting process.
GS1, GS2: Windrow containing garden waste and sewage sludge at the beginning and end of the composting process.
Standard value: EPA standard 10716 specifies the acceptable limits for class A and B composts.

Table 3. Microbial load analysis results (MPN index)

Parameter	Compost containing food waste and sewage sludge		Compost containing garden waste and sewage sludge		Compost containing sewage sludge		Standard value
	Week 1	Week 5	Week 1	Week 5	Week 1	Week 5	
Total coliform	439	27.1	36.6	43.8	271.3	439	Class A: < 1000 Class B: < 2 × 10^6
Fecal coliform	383	31.2	31.2	31.2	383	136.3	Class A: < 1000 Class B: < 2 × 10^6
Salmonella	0	0	0	0	0	0	< 3 MPN
Parasite egg	-	-	-	-	-	1 <	Ova/4g.DS^{-1}

Standard value: EPA standard 10716 specifies the acceptable limits for class A and B composts.

Table 4. Germination index results*[%]

Treatment type	Lettuce	Cress	Mung bean	Radish	Standard value
Compost containing sewage sludge	156.62	37.23	174	29.61	Min: 70%
Compost containing garden waste and sewage sludge	295.18	138.66	289.5	120.5	Min: 70%
Compost containing food waste and sewage sludge	159.03	178.32	261.9	62.19	Min: 70%

(42). Similarly, Podgaiskyte and Vaitiekūnas evaluated cadmium levels in compost derived from municipal SS, and found that the concentration of cadmium in the final compost was 20 ± 3.6 mg/kg dry sludge, well below the maximum allowable concentration (39 mg/kg dry sludge) for compost sludge market use (43). The reuse predominantly affects the concentration of heavy metals in soil and agricultural products. Given that the consumption of vegetables is on the rise in societies today, it is essential to control the food materials consumed by humans (44).

The microbial load analysis results are presented in Table 3, detailing the measurements of total coliform, fecal coliform, and salmonella for all three compost piles. Throughout the 5-week sampling period, no evidence of Salmonella presence was observed in any of the samples containing sewage treatment plant sludge, whether combined with food waste or garden waste. Furthermore, the fecal coliform levels decreased across all piles after 32 days. While the total coliform levels decreased in the piles containing sewage treatment plant sludge combined with food waste and SS combined with garden waste over 32 days, an increase was noted in the SS pile. The elevated temperature (50 °C) experienced during composting expedites the process and contributes to partial pasteurization of the compost, facilitated by the vigorous activity of microorganisms. This elevated temperature effectively reduces the pathogenic load, resulting in the decline of many pathogens within the composting material (45). The formation of soil aggregates is primarily driven by microbial activities. Microbial communities significantly influence the dynamics of water and nutrients by creating microbial habitats (23,37).

The GI results are presented in Table 4, according to EPA standard 10716, the GI for Class B (minimum 70%) is considered. The seeds of mung bean and lettuce had the highest germination indices, while radish seeds had the lowest GI. According to the results, the GI for radish does not fall within either Class A or B; however, the highest GI for radish was obtained in the compost of the wastewater treatment sludge and food waste (FS) at a rate of 62.19%. Germination, being a pivotal stage in plant growth, involves a series of biochemical reactions facilitated by various enzymes. The diverse absorption and metabolic patterns, as well as the level of tolerance among different plant species, likely contribute to the observed disparities in seed germination responses to the compost extract treatments (46). Tiquia and Tam reported that a GI higher than 80% at the end of the experiment indicates the absence of phytotoxicity in the compost product (47).

Conclusion

According to the regulations set forth by the USEPA, SS is categorized into two classes, A and B, based on their microbial characteristics, with each class designated for specific ground use. The microbial analysis conducted in this study indicated that all three piles of sewage treatment plant sludge (SS), garden waste and sewage treatment plant sludge (GS), and food waste and sewage treatment plant sludge (FS), fell within the standard range and were classified as Class A. According to the guidelines outlined by the World Health Organization (WHO), EPA and the national standards of Iran, and based on the findings of this research, the produced composts met the standard limits for parameters such as heavy metals, pH, temperature, humidity, anions and cations, alkalinity, density, and microbial content. However, upon consideration of the C/N ratio and GI, compost containing food waste emerged as the superior compost in terms of physical and chemical quality, suitable for agricultural applications. After 32 days of composting, the compost derived from food waste and domestic WWTP sludge exhibited a brown color and lacked any unpleasant odor, indicating its readiness for use. It is worth noting that while compost containing garden waste also met the standard criteria both physically and chemically, it may require additional time to reach ideal conditions due to the presence of wood lignin, which undergoes a longer decomposition process. The results of this study demonstrate the high potential of the sewage treatment plant sludge from the Gole-Gohar Mining and Industrial Company as a valuable resource for compost production and soil quality improvement. The presence of organic materials and nutrients in this sludge is a suitable option for replacing chemical fertilizers. Utilizing treated sludge can not only aid in effective waste management but also improve environmental cycles and reduce soil pollution. Therefore, it is recommended that this process be considered as part of sustainable agriculture strategies and environmental protection efforts in industrial and mining areas. Thus, it can also serve as a practical guide for other industrial and mining complexes in the optimal use of treated sludge as a sustainable and environmentally friendly resource.

To achieve sustainable and environmentally friendly resources in the future, it is suggested to conduct studies on the following: investigating the environmental impacts and assessing the process of preparing compost fertilizer, creating space for large-scale compost fertilizer production for waste management, using produced compost to monitor plant growth, assessing the feasibility of using green waste for compost preparation, measuring the amount of lipase enzyme, and understanding the role of lipase in the joint composting process of food waste and WWTP sludge.

Overall, the physicochemical parameters of the produced composts met standard limits. However, considering the C/N ratio and GI, compost-containing food waste emerged as the most suitable for agricultural use.

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Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Ethics issues

This article is the result of an MSc thesis conducted at Kerman University of Medical Sciences (Project No: 401000415 and Ethical Code: IR.KMU.REC.1402.256).

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References

1. Mousavi SF, Gholami Borujeni F. Co-composting of wastewater treatment sludge and various types of organic wastes, a strategy to reduce pollution: a review study. J Res Environ Health. 2021;7(3):235-43. doi: 10.22038/jreh.2021.56103.1406.
2. Karimi H, Mohammadi F, Rajabi S, Mahvi AH, Ghanizadeh G. Biological 2,4,6-trinitrotoluene removal by extended aeration activated sludge: optimization using artificial neural network. Sci Rep. 2023;13(1):9053. doi: 10.1038/s41598-023-34657-z.
3. Mirhosseini G, Alavimoghaddam MR, Maknon R. Investigation of application of Tehran municipal WWTPs' dried sludge in agriculture. Environ Sci. 2007;4(4):47-56. [Persian].
4. Kebibeche H, Khelil O, Kacem M, Kaid Harche M. Addition of wood sawdust during the co-composting of sewage sludge and wheat straw influences seeds germination. Ecotoxicol Environ Saf. 2019;168:423-30. doi: 10.1016/j.ecoenv.2018.10.075.
5. Meng L, Li W, Zhang S, Wu C, Lv L. Feasibility of co-composting of sewage sludge, spent mushroom substrate and wheat straw. Bioresour Technol. 2017;226:39-45. doi: 10.1016/j.biortech.2016.11.054.
6. Vasudevan M, Karthika K, Gowthaman S, Karthick K, Balaganesh P, Suneeeth Kumar SM, et al. Aerobic in-vessel co-composting of dewatered sewage sludge with mixed municipal wastes under subhumid and semiarid atmospheric conditions. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects. 2021;43(24):3403-14. doi: 10.1080/15567036.2019.1624888.
7. Asadi Ardali H, Sadeghi M, Hassani AH, Javid AH, Hashemi H. Feasibility of using the dried sludge by municipal wastewater treatment with activated sludge process. J Health Syst Res. 2011;6(3):407-16. [Persian].
8. Yousefi Z, Batabi R, Ziaei Hezarjaribi H, Mousavi Nasab N. Survey on the quality of outlet biosolids and sludge heavy metals in the wastewater treatment plants of Mazandaran province. Environ Health Eng Manag. 2023;10(3):281. doi: 10.34172/ehem.2023.32.
9. United States Environmental Protection Agency, Office of Wastewater Management. A Plain English Guide to the EPA Part 503 Biosolids Rule. Washington, DC: US Environmental Protection Agency, Office of Wastewater Management; 1994. p. 183.
10. Hashemi H, Salehi N, Rajabi S, Isinkaralar K. Evaluation of acute phytotoxicity of raw leachate and landfill leachate using sorghum bicolor seeds. Environ Health Eng Manag. 2023;10(4):441. doi: 10.34172/ehem.2023.47.
11. Malakootian M, Yaghmaean K. Evaluation of the knowledge, attitude and paractice of residents of the city of Kerman to the municipal solid waste management. Journal of School of Public Health and Institute of Public Health Research. 2004;2(4):27-38. [Persian].
12. Adhikari RC. Investigation on solid waste management in developing countries. J Res Dev. 2022;5(1):42-52. doi: 10.3126/jrdn.v5i1.50095.
13. Lu Y, Wu X, Guo J. Characteristics of municipal solid waste and sewage sludge co-composting. Waste Manag. 2009;29(3):1152-7. doi: 10.1016/j.wasman.2008.06.030.
14. Zhang Z, Duan C, Liu Y, Li A, Hu X, Chen J, et al. Bacterial Community Links the Humification to Green Waste and Sewage Sludge Feeding Ratio During Aerobic Co-Composting. 2023. Available from: https://ssrn.com/abstract=4352740.
15. Luo Y, Liang J, Zeng G, Chen M, Mo D, Li G, et al. Seed germination test for toxicity evaluation of compost: its roles, problems and prospects. Waste Manag. 2018;71:109-14. doi: 10.1016/j.wasman.2017.09.023.
16. Xu S, Li L, Zhan J, Guo X. Variation and factors on heavy metal speciation during co-composting of rural sewage sludge and typical rural organic solid waste. J Environ Manage. 2022;306:114418. doi: 10.1016/j.jenvman.2021.114418.
17. Dzulkurnain Z, Hassan MA, Zakaria MR, Wahab PE, Hasan MY, Shirai Y. Co-composting of municipal sewage sludge and landscaping waste: a pilot scale study. Waste Biomass Valorization. 2017;8(3):695-705. doi: 10.1007/s12649-016-9645-7.
18. Jafariniya Parizi H, Mokhtari M, Eslami H, Madadizadeh F, Jalili M, Mobini M, et al. Comparison and toxicity assessment of co-composting process by pistachio wastes and date-palm straw combined with municipal sewage sludge. Biomass Convers Biorefin. 2024;14(3):3565-73. doi: 10.1007/s13399-022-02563-5.
19. Bian R, Sun Y, Li W, Ma Q, Chai X. Co-composting of municipal solid waste mixed with matured sewage sludge: the relationship between N2O emissions and denitrifying gene abundance. Chemosphere. 2017;189:581-9. doi: 10.1016/j.chemosphere.2017.09.070.
20. de Nijs EA, Maas LM, Bol R, Tietema A. Assessing the potential of co-composting rose waste as a sustainable waste management strategy: nutrient availability and disease control. J Clean Prod. 2023;399:136685. doi: 10.1016/j.jclepro.2023.136685.
21. Rice EW, Baird RB, Eaton AD. Standard Methods for the Examination of Water and Wastewater. 23rd ed. American Water Works Association (AWWA), American Public Health Association (APHA), Water Environment Federation (WEF); 2017. p. 1545.
22. El Fels L, Hafidi M, Ouhdouch Y. *Artemia salina* as a new index for assessment of acute cytotoxicity during co-composting of sewage sludge and lignocellulose waste. Waste Manag. 2016;50:194-200. doi: 10.1016/j.wasman.2016.02.002.
23. Aghili SM, Mehrdadi N, Aminzadeh B, Zazouli MA. An investigation of agricultural use potential of dewatered sewage sludge. Environ Health Eng Manag. 2019;6(3):179. doi: 10.15171/ehem.2019.20.
24. Radojevic M, Bashkin VN. Practical Environmental Analysis. 2nd ed. Royal Society of Chemistry; 2006. p. 469.

25. Guo R, Li G, Jiang T, Schuchardt F, Chen T, Zhao Y, et al. Effect of aeration rate, C/N ratio and moisture content on the stability and maturity of compost. Bioresour Technol. 2012;112:171-8. doi: 10.1016/j.biortech.2012.02.099.
26. Hyder US, AlSayed A, Elbeshbishy E, McPhee J, Misir R. Iron and hydrogen peroxidation-induced post-treatment improvement of municipal mesophilic digestate in an alkaline environment and its impact on biosolids quality. Processes. 2023;11(9):2752. doi: 10.3390/pr11092752.
27. Farzadkia M, Bazrafshan E. Lime stabilization of waste activated sludge. Health Scope. 2014;3(1):e16035. doi: 10.17795/jhealthscope-16035.
28. Milon AR, Chang SW, Ravindran B. Biochar amended compost maturity evaluation using commercial vegetable crops seedlings through phytotoxicity germination bioassay. J King Saud Univ Sci. 2022;34(2):101770. doi: 10.1016/j.jksus.2021.101770.
29. Hwang HY, Kim SH, Kim MS, Park SJ, Lee CH. Co-composting of chicken manure with organic wastes: characterization of gases emissions and compost quality. Appl Biol Chem. 2020;63(1):3. doi: 10.1186/s13765-019-0483-8.
30. Grgas D, Štefanac T, Barešić M, Toromanović M, Ibrahimpašić J, Vukušić Pavičić T, et al. Co-composting of sewage sludge, green waste, and food waste. J Sustain Dev Energy Water Environ Syst. 2023;11(1):1-14. doi: 10.13044/j.sdewes.d10.0415.
31. Zhang D, Luo W, Li Y, Wang G, Li G. Performance of co-composting sewage sludge and organic fraction of municipal solid waste at different proportions. Bioresour Technol. 2018;250:853-9. doi: 10.1016/j.biortech.2017.08.136.
32. Okoh E, Patrick IO, Yelebe ZR, Oruabena B. Co-composted faecal sludge as organic fertilizer to restore crude oil-contaminated soil. Res Sq [Preprint]. January 16, 2023. Available from: https://www.researchsquare.com/article/rs-2437560/v1.
33. Kumar M, Ou YL, Lin JG. Co-composting of green waste and food waste at low C/N ratio. Waste Manag. 2010;30(4):602-9. doi: 10.1016/j.wasman.2009.11.023.
34. Manohara B, Belagali SL. Characterization of essential nutrients and heavy metals during municipal solid waste composting. Int J Innov Res Sci Eng Technol. 2014;3(2):9664-72.
35. Şevik F, Tosun İ, Ekinci K. The effect of FAS and C/N ratios on co-composting of sewage sludge, dairy manure and tomato stalks. Waste Manag. 2018;80:450-6. doi: 10.1016/j.wasman.2018.07.051.
36. Li X, Xing M, Yang J, Huang Z. Compositional and functional features of humic acid-like fractions from vermicomposting of sewage sludge and cow dung. J Hazard Mater. 2011;185(2-3):740-8. doi: 10.1016/j.jhazmat.2010.09.081.
37. Wang D, Lin JY, Sayre JM, Schmidt R, Fonte SJ, Rodrigues JL, et al. Compost amendment maintains soil structure and carbon storage by increasing available carbon and microbial biomass in agricultural soil–a six-year field study. Geoderma. 2022;427:116117. doi: 10.1016/j.geoderma.2022.116117.
38. Cofie O, Kone D, Rothenberger S, Moser D, Zubruegg C. Co-composting of faecal sludge and organic solid waste for agriculture: process dynamics. Water Res. 2009;43(18):4665-75. doi: 10.1016/j.watres.2009.07.021.
39. Wang G, Yang Y, Kong Y, Ma R, Yuan J, Li G. Key factors affecting seed germination in phytotoxicity tests during sheep manure composting with carbon additives. J Hazard Mater. 2022;421:126809. doi: 10.1016/j.jhazmat.2021.126809.
40. Chang JI, Hsu TE. Effects of compositions on food waste composting. Bioresour Technol. 2008;99(17):8068-74. doi: 10.1016/j.biortech.2008.03.043.
41. Farrell M, Jones DL. Heavy metal contamination of a mixed waste compost: metal speciation and fate. Bioresour Technol. 2009;100(19):4423-32. doi: 10.1016/j.biortech.2009.04.023.
42. Golbaz S, Zamanzadeh MZ, Pasalari H, Farzadkia M. Assessment of co-composting of sewage sludge, woodchips, and sawdust: feedstock quality and design and compilation of computational model. Environ Sci Pollut Res Int. 2021;28(10):12414-27. doi: 10.1007/s11356-020-11237-6.
43. Podgaiskyte V, Vaitiekūnas P. Determination of cadmium in a municipal sewage sludge-based compost by spectrophotometric method. J Environ Eng Landsc Manag. 2009;17(4):219-25. doi: 10.3846/1648-6897.2009.17.219-225.
44. Parmoozeh Z, Reza Mostafaii GR, Rabbani D, Akbari H, Salem A, Miranzadeh MB. Investigation of heavy metal concentrations (lead, cadmium, and arsenic) in vegetables irrigated with synthetic effluent and well water: risk assessment of carcinogenicity and non-carcinogenicity. Environ Health Eng Manag. 2024;11(3):327-36. doi: 10.34172/ehem.2024.32.
45. Belyaeva ON, Haynes RJ, Sturm EC. Chemical, physical and microbial properties and microbial diversity in manufactured soils produced from co-composting green waste and biosolids. Waste Manag. 2012;32(12):2248-57. doi: 10.1016/j.wasman.2012.05.034.
46. Mohsenzadeh S, Zamanpour Shahmansouri H, Janbazi Z, Hossen Khani Hezaveh M. Evaluation of municipal waste compost toxicity by seed germination and seedlings growth of wheat, barley and rapeseed and comparison of two methods of assessment. J Environ Sci Stud. 2019;4(3):1810-6. [Persian].
47. Tiquia SM, Tam NF. Co-composting of spent pig litter and sludge with forced-aeration. Bioresour Technol. 2000;72(1):1-7. doi: 10.1016/s0960-8524(99)90092-5.