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Composting of Organic Waste: A Sustainable Alternative Solution for Solid Waste Management in Jordan

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ABSTRACT

Composting is an economical, sustainable and environmentally benign alternative option for solid waste management. In this study, organic wastes generated at Al-Karak Governorate/ Jordan were used as substrates for compost production. Three windrow piles containing different proportions of organic wastes (fruits, vegetables, garden waste, poultry and sheep manure) were initiated for compost production. Plant residues and sawdust were added and mixed with the substrates and used as bulking agents to improve aeration and provide the required carbon/nitrogen (C/N) ratio needed for efficient decomposition of organic matter. Continuous monitoring of the chemical, biological and physical properties of composted matter was conducted and the end product quality was assessed against the German standard. The physico-chemical parameters examined demonstrated that the biological conditions were sufficiently developed. The results of the monitored experimental process showed overall decreasing profiles *versus* composting time for moisture content, organic carbon, C/N ratio and pile volume, as well as overall increasing profiles for electrical conductivity, pH, total nitrogen, total phosphorus, total potassium and bulk density. Furthermore, compost respiration (AT4) in the samples varied from 2.57 to 5.43 mg O_2/g DM, indicating that all the compost samples are stable and can be rated as class V end product.

KEYWORDS: Biological treatment, Bio-waste, Manure, Compost, German standard, End-product quality, Jordan.

INTRODUCTION

The quantities of solid waste (SW) in Jordan are increasing annually due to population growth, influx of refugees as well as industrial, commercial and agricultural expansion. In 2015, the total municipal solid waste (MSW) generation by the residential population reached 2.6 million tons of MSW. It is anticipated to reach up to 6.0 million tons by 2039 (Aldayyat et al., 2019). This, of course, increased pressure on the existing waste management infrastructure and increased the economic costs related to waste collection and transport.

Up-to-date, Jordan's waste management system relies primarily on landfills as a waste disposal method. Separate collection is still not practiced efficiently in the county. MSW is collected as a mixed waste which contains all kinds of waste, including hazardous materials. Up to 95% of it is sent to different controlled landfills and dumping sites without any treatment, which generates high levels of methane gas due to the high amount of organic and water content. Only 5-10% is the rate of recyclable material recovered from the waste stream, as there is no large-scale and effective government-run solid waste sorting practices or recycling system yet in place.

Improper solid waste management threatens public

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health and environmental quality in Jordan. Therefore, a fresh look is required and there is a need for action. In order to overcome these problems, first a technical solution should be made with the required modifications and proper implementation considering the legal, financial and management aspects (Hemidat, 2019; Shatnawi, 2018; Aljaradin, 2014).

An effective system of solid waste management involves the adoption of various treatment methods, technologies and practices. All technologies and systems adopted must ensure the protection of public health and the environment. There is a wide variety of alternative waste management approaches and strategies available to deal with mixed solid waste to limit the residual amount that ends up on landfill sites. With proper solid waste management and the right control of its polluting effects on the environment, solid waste has the opportunity to become a precious resource.

Among several solid waste treatment options, composting remains the most widespread method of organic waste recycling worldwide. Composting is an aerobic biological decomposition process which involves thermophilic temperature development due to biologically exothermic heat (Oazana et al., 2018). Composting is a reliable waste treatment option that could be beneficial in the recycling of the organic fraction of the solid waste, reducing as much as 30% of the volume of organic matter entering the already overcrowded landfill sites (Khater, 2015).

Recently, utilization of organic residuals for organic fertilizers has gained the attention of local authorities in Jordan. The sources of organic waste include biomass residues from agricultural and industrial activities as well as an organic fraction of MSW and animal manure (Ammari et al., 2012; Abbassi et al., 2015). The potential of providing raw materials in the country as well as the low content of organic matter in soil imply that composting can play a pivotal role in SWM, improving soil fertility in the country.

As is the case in other Jordanian cities, organic waste is the largest MSW fraction in Al-Karak city, representing about 50% of the collected MSW (Alhyasat et al., 2014).

Diverting municipal solid waste organic materials from landfills by composting has many economic and environmental benefits, such as reducing the volume and weight of the raw materials and greenhouse gas emissions (Abu Qdais et al., 2019), decreasing leachate quantities, lowering cost of disposing of organic residues, as well as providing an income by virtue of compost being used as a substitute to other materials (chemical fertilizers and peat) that may be quite expensive (Proietti et al., 2016; Wei et al., 2017).

To this end, the focus of the present experimental study is on (1) investigating the potential of aerobic composting process by monitoring operational parameters, (2) examining the physical and chemical characteristics of different degradable SW stream materials to be used as the main input raw organic materials for compost production in Jordan and (3) assessing the quality of final product attained from practicing the state-of-the-art windrow composting process against established quality standards.

MATERIALS AND METHODS

Experimental Site

The study was carried out at the organic compost plant in El-Lajjun area of Al-Karak governorate. The composting plant is well-equipped with necessary machines for composting. The plant has a turner machine used for mixing pile components and to ensure proper aeration. A rotary screen device is used for screening the final product. A shredding machine is used for chopping and grinding wood, twigs and plant residues. A bobcat loader is used to transport the materials and to build the piles.

Input Raw Organic Materials

Several available types of organic and inorganic wastes: market waste (fruits and vegetables), garden waste (plant residues) and manure (poultry and sheep), were used as the composting input materials. Moreover, sawdust was used as bulking agent to provide the required C/N ratio necessary for effective decomposition. Market waste includes inorganic materials, such as plastic bags, which need to be sorted manually. Garden waste mainly consists of dry leaves, clippings and wood particles which are subjected to shredding and screening before use.

METHODOLOGY

After receiving the different raw organic materials, three different types of compost pile are prepared. During preparing each pile, the different organic raw materials (fruit, vegetable and sheep/ chicken manure) were blended in certain ratios and gently mixed with bulking agents (plant residues, tree clippings and sawdust) in order to ensure the C/N ratio needed to obtain efficient decomposition (Table 1).

Table 1. Pile composition

Pile No.	Pile Composition
Pile-1	(70 wt% mixed fruit and vegetables + 30 wt% plant residues)
Pile-2	(50 wt% plant residues + 25 wt% sheep manure. + 25 wt% chicken manure)
Pile-3	(49.32 wt% sheep manure + 49.32 wt% chicken manure + 1.36 wt% sawdust)

The waste mixtures were aligned in long windrow piles (1.5 m high, 2.5 m wide and 14 m long) by using the loader. The piles were turned periodically by using the windrow turner, to maintain adequate oxygen levels and to promote rapid composting. Pile moisture was controlled by adding sufficient water to ensure a moisture content around 50% or higher. Overall, 12 weeks were required to produce the final compost products. The required composting time was determined based on continuous monitoring of the chemical, biological and physical properties of composted matter and comparing the results with Jordanian and International standards for final compost product.

Several *in-situ* and off-line measurements of operating parameters were carried out during and at the end of the composting process.

The ambient temperature and the temperature within each pile were monitored daily by using a digital dry bulb thermometer (compost systems). The temperature of the pile was measured at different sites of each pile. These sites are located in the bottom, middle and top of the pile at a depth ranging from (30-40) cm. The CO_2 and O_2 concentrations are measured once a week by using portable oxygen meter (Model 117, Testoryt Compost Systems) and carbon dioxide meter (Model 115, Testoryt Compost Systems).

The moisture content of piles was determined following standard methods based on oven drying at 105°C for 24 hr. The ash content is determined based on the percentage of residues after muffle furnace ignition at 550°C for 6 hr. Total Kjeldahl Nitrogen (TKN) is determined by using the regular Kjeldahl method (FOSS Kjeltec™ 2300 Analyzer Unit). The total phosphorus (P)was measured calorimetrically, while total potassium (K) was measured using flame photometry. The compost respiration index (AT4) was determined following the method described in (ISO 16072:2002) (ISO-16072 2002). The total organic carbon (TOC) was estimated following the method of Mercer and Rose (Mercer and Rose, 1968). The electrical conductivity was measured by using EC-meter with glass electrode. The pH was measured *via* a pH-meter with a glass electrode Redox-Electrode (GPRT 1400).

Samples were then taken over the different phases of the composting process as well as at the end of the process to determine the chemical and physical properties. Each sample was constructed by mixing five subsamples taken from five points in the pile. These were then placed in polyethylene bags and transferred to the laboratory for analysis. The collected representative samples were analyzed at National Agricultural Research Center (NARC) laboratories, Jordan. The AT4 analysis was carried out at Rostock University laboratories, Germany.

RESULTS AND DISCUSSION

Characteristics of the Initial Composting Piles

In this study, four types of primary organic substrates were used for compost production; namely: mixed vegetables and fruits, plant residues, sheep manure and chicken manure. These organic substrates are mixed in different proportions to ensure appropriate starting conditions for an efficient aerobic decomposition process. Sawdust and tree clippings were used as bulking agents to adjust the initial C/N ratio to be within the recommended value of 25 to 35 w/w (Gajalakshmi and Abbasi, 2008).

Table 2. The physical and chemical properties of the initial composting piles

Parameter	Pile-1	Pile-2	Pile-3
Ash Content (%)	58.3	62.7	66.4
Volatile Solids (%)	41.7	37.3	33.6
TOC (%)	33.4	41.3	42.5
TKN (%)	1.15	1.53	1.7
C/N Ratio (w/w)	29	27	25
Moisture Content MC (%)	35	27	25
pH	6.71	7.21	7.56
EC (dS/m)	2.33	2.51	3.31
Total P (%)	1.1	1.2	1.56
Total K (%)	1.95	2.32	2.58
Initial Pile Volume (m^3)	28	24	25
Initial Bulk Density (kg/m^3)	460	455	430

The results shown in Table 2 indicate that the initial C/N ratio for the three piles is within the recommended values for stimulating degradation and immobilization of nitrogen. The initial pH values for the three piles are within the recommended values for microbial development. The optimum pH for most microorganisms is between 6 and 7.5 (Kapetanios et al., 1993).

The moisture content of the three piles initially were below the recommended value of 50-60 %. Having low moisture content at the beginning of the composting process will slow down the rate of organic substrate decomposition. Therefore, water was added when required and moisture was kept close to 50% for the first 6 weeks to ensure optimum microbial activity through readily transport of dissolved nutrients for microorganisms.

The initial bulk density of piles was in the range of (430-460 kg/m^3). The reported initial bulk densities in this study are in agreement with those reported in literature for similar systems (Hemidat et al., 2018). The reported initial bulk densities for piles reflect the presence of proper pile porosity. Proper porosity within piles assists in the liberation of gases to the atmosphere, enhancing the aerobic decomposition of organic substrate and ensuring abundant liberation of heat (Gajalakshmi and Abbasi, 2008).

Temperature Profile of the Composting Process

The temperature profile reflects the profile of the microbial activity within the pile. Having piles prepared with optimum composition and adequate bulking and moisture content will initiate microbial growth and activity. The exothermic nature of the aerobic degradation process will increase the temperature. The temperature is monitored daily and the difference of raw input material between the three trials is shown in (Figure 1).

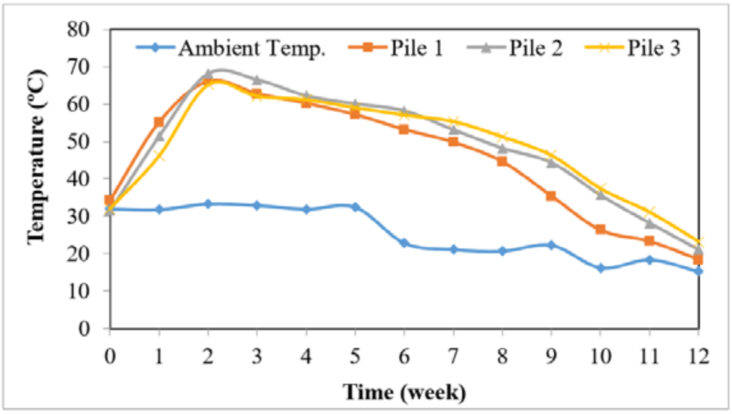

Figure (1): Temperature profiles for piles and ambient temperature during the composting process

The temperature within all piles increased linearly in the first two weeks, reaching a maximum at the end of the second week. pile 2 reached a temperature of 68.1°C, while pile 1 and pile 3 reached 66.1 and 65.3°C, respectively. The piles maintained constant maximum temperature for almost three days before starting to decrease. It is recommended that a five-day period at 55°C (EPA 1999) or a three-day period at 65°C and moist conditions (de Bertoldi et al., 1988) are required for pathogen destruction. Accordingly, the three piles employed in this study achieved the required time period and temperature for pathogen inactivation.

At the end of week 2, temperature of piles decreased with time at the same rate until the end of week 9 after which temperature decreased more sharply and approached the ambient temperature at the end of week 12. This sharp reduction in temperature with time is an indication of a decreased rate of organic substrate biodegradation. This phase in the composting process is essential for stabilization and drying.

Oxygen and Carbon Dioxide Concentrations

The oxygen and carbon dioxide concentrations during the composting process for the three piles were measured on weekly basis. The concentrations of O_2 and CO_2 were used as an indicator for turning the piles, regardless of the turning schedule previously discussed in the research methodology. If the O_2 concentration was found to be close to zero in any sampling location, turning was immediately applied to provide the microorganisms in the pile with the required oxygen. As Figure 2 shows, the initial concentration of oxygen within the body of the piles was very low due to the high rate of biological activity. This was also evident from the results of CO_2 concentrations in the initial phases, which were very high. As the composting process progressed, the O_2 concentration increased and CO_2 concentration decreased, which is attributed to the decreasing rate of biological degradation.

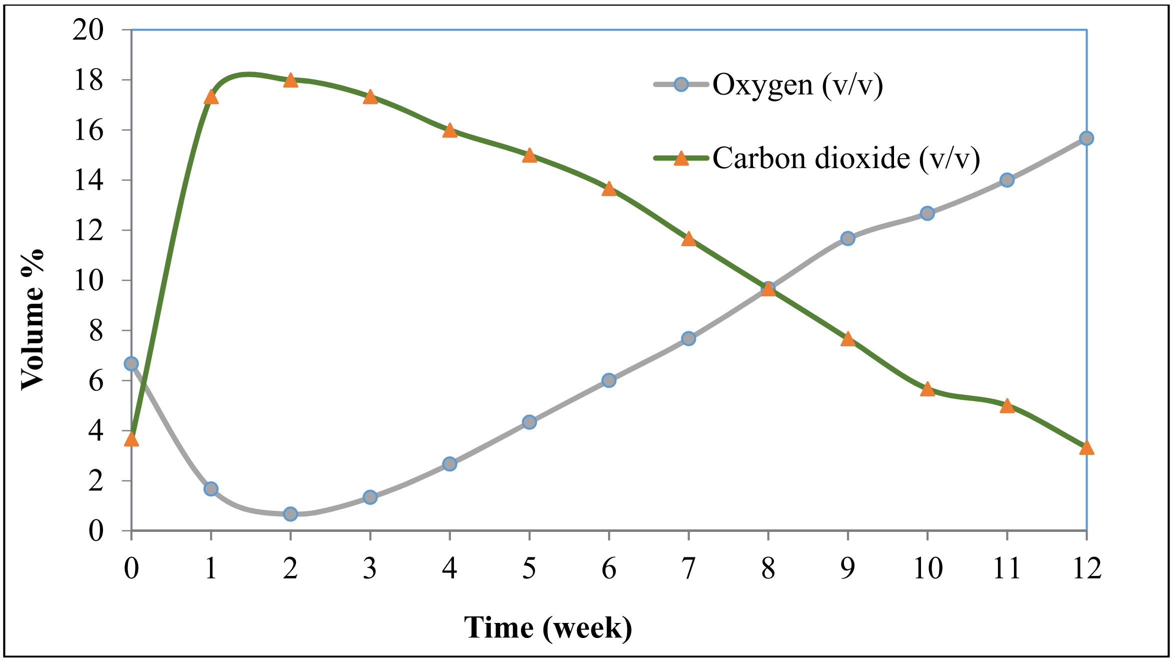

Figure (2): O_2 and CO_2 concentrations for pile 2 during composting period

The presence of oxygen in windrow-type composting is essential for aerobic microbial activity. Aeration *via* pile turning ensures adequate supply of oxygen for the aerobic bacteria. At the beginning of the composting process, the availability of high organic substrate concentration will promote high biodegradation rate, thereby causing abundant heat evolution and oxygen depletion within the pile. As it can be seen from the results shown in Fig. 2, the oxygen concentration dropped down to extremely low levels in the first two weeks. On the other hand, increasing levels of CO_2 concentration were confirmed. At the end of week 2, the CO_2 concentration reached 18 vol%. Having an opposite trend in O_2 and CO_2 concentrations is an indication of a typical aerobic bacterial process. After the end of week 2, the O_2 concentration linearly increased, while the concentration of CO_2 linearly decreased with time. At the end of week 12, very low CO_2 concentration was noticed, indicating that existing biological degradation proceeds at a very low rate.

Moisture Content

Moisture is essential to maintain the metabolic process. Microbial metabolism requires aqueous medium to gain nutrients and energy from chemical reactions. Moisture content impacts the process in terms of oxygen uptake rate, free air space and temperature (Hemidat et al., 2018). The moisture content during the composting process for the three piles was measured and the results are shown in Fig. 3.

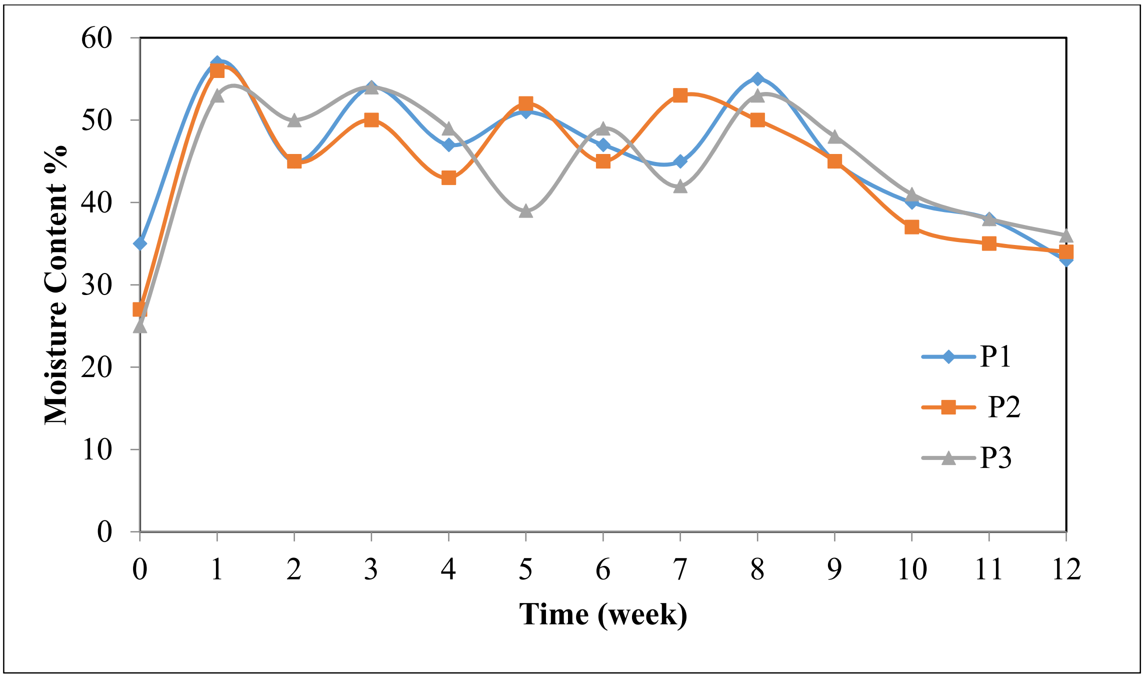

Figure (3): The moisture content during the composting process for the three piles

The piles initially contained low moisture content. The proximate analysis for samples representing the piles indicated initial moisture content of 35, 27 and 25 wt% for pile 1, pile 2 and pile 3, respectively. Water was added and the moisture content was kept close to 50 wt % for the first 6-8 weeks. The presence of adequate moisture content is crucial for microbial activity. Water assists in dissolving the nutrients to be consumed by the aerobic bacteria. The mechanism of substrate decomposition is dominated by the decomposition that occurs in the thin liquid films on the surfaces of particles (Gajalakshmi and Abbasi, 2008). It should be mentioned that, on the other hand, excess moisture content must be avoided, as this will add extra resistance toward oxygen transport.

With the progress of the composting process, it is expected that the moisture content is reduced and the pile will possess dehydration. This reduction in the moisture content must be always substituted by sufficient water to promote continuous substrate biodegradability.

The fluctuation in moisture content for all piles (40~57 wt%) can be attributed to the periodic water supply and pile turning. The level of moisture content at the end of the process for the three piles is between (33~36)%. The lowest value for the moisture content was for pile 1 (about 33 wt%).

The internal heat generated due to microbial activity and the ambient environment affected the provision of optimum moisture levels inside the composting piles and the amount of water needed. However, the total amount of water consumed in each pile is shown in Fig. 4.

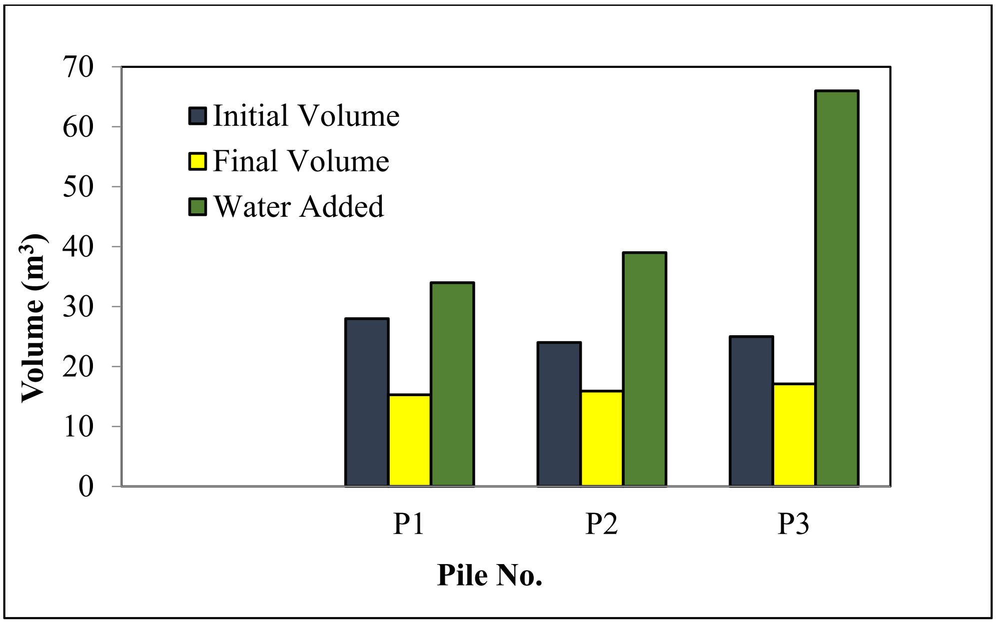

Figure (4): Volume of piles and water consumption

The volume ratio of water added in relation to the volume of organic compost produced was about 1:2.2, 1:2.5 and 1:3.9 for pile 1, pile 2 and pile 3, respectively. The volume ratio of water added in relation to the initial raw material volume was about 1:2, 1:1.6 and 1:2.6 for pile 1, pile 2 and pile 3, respectively. Pile 3 needed the largest amount of water due to the nature of its constituent materials and the absence of a bulking agent compared to the other piles where plant residues were used. Hemidat et al. (2018) reported that the volume of added water was more or less equal to the volume of final composts prepared from similar starting raw materials.

Results in Fig. 4 indicate that pile volumes decreased in the range of 31-46 % by the end of the composting process. This decrease in pile volumes might be attributed to the perfect biodegradation which occurred inside the compost windrow piles. These results are in good agreement with the findings of other researchers. For example, Breitenbeck and Schellinger (2004) reported an average reduction of 40.7% of initial volume of various feedstocks during windrow composting. In addition, Hemidat et al. (2018) reported a decrease in pile volumes in the range of 25-35%.

C/N Ratio Profile

Monitoring the C/N ratio within piles is a good indication of the performance of the composting process. In addition, the final compost C/N ratio is an important parameter in judging the compost acceptability as a fertilizer. Practically, starting with higher values of C/N ratio will hinder microorganism population due to a decrease in the amount of nitrogen. In contrast, lower values of C/N ratio indicate high excess nitrogen availability that caused ammonia and other nitrous compounds release, thereby generating bad smells and inducing a negative environmental impact (Proietti et al., 2016). Many studies indicated an optimum starting value of C/N ratio in the range of 25-35w/w (Gajalakshmi and Abbasi, 2008). Figure 5 shows the C/N ratio profiles for the three piles during the composting process.

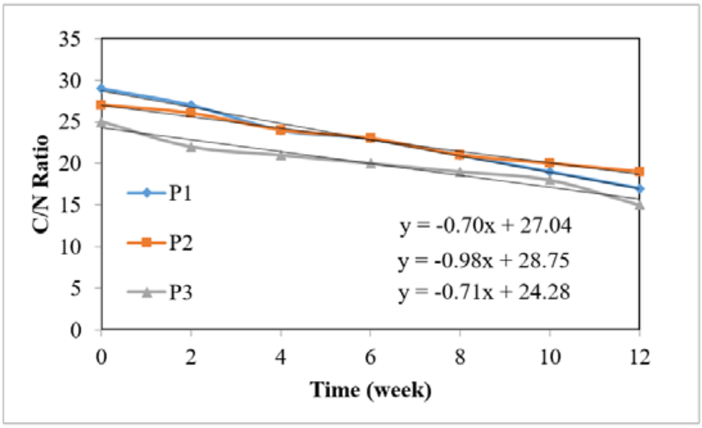

Figure (5): The C/N ratio profiles for the three piles during the composting period

The results indicate that the three piles exhibited a decreasing profile in the C/N ratio. The C/N ratio decreased linearly with the progress of composting time. The rate of change in the C/N ratio with time was 0.98, 0.70 and 0.71 unit mass ratio change/week for pile 1, pile 2 and pile 3, respectively. The rate of change in the C/N ratio with time in this study is comparable to other reported studies. Based on data reported by Eiland et al. (2001), the rate of change in the C/N ratio with time during the first 3- month composting period was in the range of 1.56-2.1. Sadaka and El-Taweel (2003) reported a rate of change in the C/N ratio with time in the range of 0.4 - 1.4 for composts made from different initial C/N ratios and subjected to different aeration levels. Hemidat et al. (2018) reported a rate of change in the C/N ratio with time in the range of 1.2-1.6 for composts made from different initial C/N ratios. Chaher et al. (2020) reported a rate of change in the C/N ratio with time in the range of 0.61-1.2 for composts made from different initial C/N ratios.

At the end of week 12, the C/N ratios were 17, 19 and 15 w/w for pile 1, pile 2 and pile 3, respectively. Having a compost with C/N ratio in the range of 15 to 20 is an indication of an ideal and usable compost (Dougherty, 1999). The final measured values of the C/N ratio correspond to a 41, 29 and 40% reduction in the initial C/N ratio in pile 1, pile 2 and pile 3, respectively.

pH Profile

The pH value of the compost is important because applying compost to the soil can alter the pH of the soil which, in turn, can affect the availability of nutrients to plants (Hemidat et al., 2018). The pH profiles of the pile materials during the three trials are shown in Figure 6. Indeed, the experimental windrow piles exhibited a similar temporal sequence with a phase of increasing pH followed by a decreasing phase (although with a final increased value in week 6).

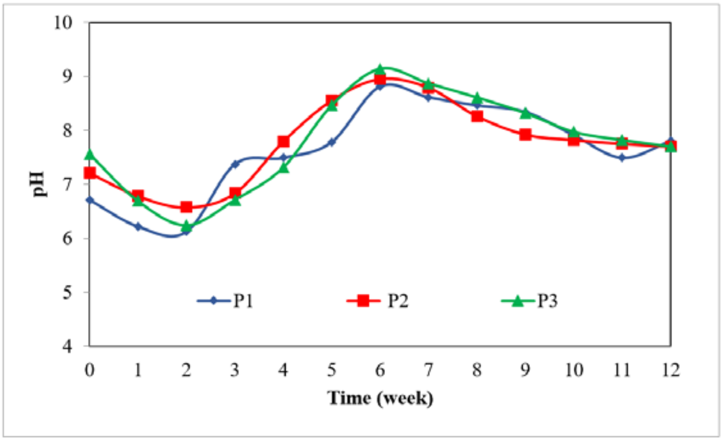

Figure (6): Average pH profiles for all piles during the composting period

In the first two weeks of the composting process, the three piles exhibited a decrease in the pH values. By the end of week 2, pile 1, pile 2 and pile 3 attained a pH value of 6.1, 6.6 and 6.2, respectively. This slight reduction in the pH value is attributed to the release of acidic species and their accumulation within the pile (Chaher et al., 2020). Another possible explanation of the decrease in the pH value (An et al., 2012) is the large evolution of CO_2 during the decomposition of the organic matter, as shown in Fig. 2.

At the beginning of the third week, the pH value of the three piles increased noticeably, which eventually reached 8.8, 8.9 and 9.1 within pile 1, pile 2 and pile 3, respectively. This stage of increased level in the pH value represents the thermophilic stage of the composting process, which is characterized by increased rates of substrate degradation and ammonification and mineralization of organic nitrogen *via* microbial activities (Wong et al., 2001).

At the end of the sixth week, another decrease in pH was noticed for all piles. The final product of the three piles had pH values ranging between 7.5 and 8.0, which are all in a reasonable range of a finished compost and within the optimum range for growing media (Hemidat, 2019).

Electrical Conductivity

Electrical conductivity (EC) is usually measured in soil and compost to estimate the salinity of growth media (Thompson et al., 2002; Van der Gheynst et al., 2004). It is an indicator of total salt content of materials and commonly defined in the water extract of the samples. The initial and final EC values of composting experiments indicate obviously the difference of raw materials inside the piles (Figure 7).

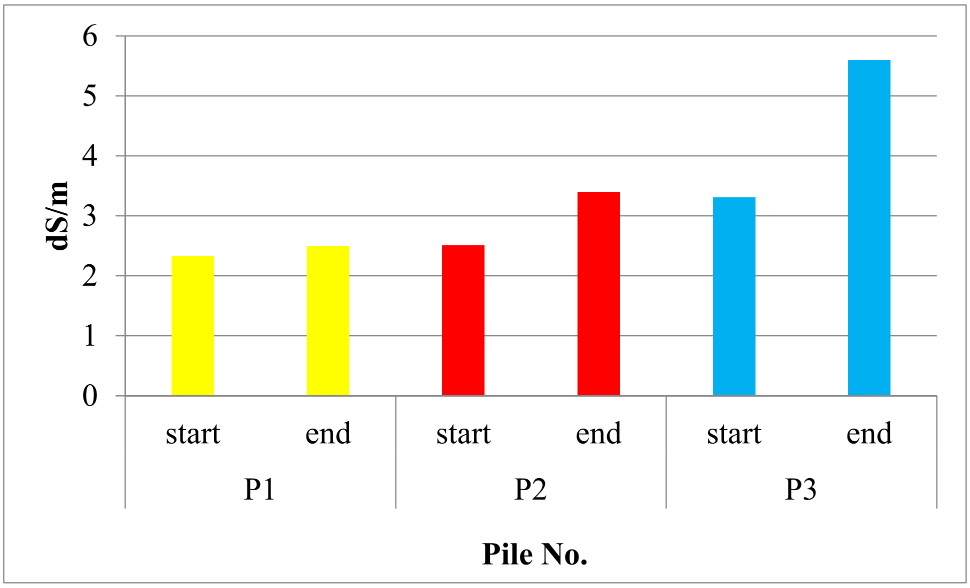

Figure (7): Initial and final EC values for all piles

The results indicate an increase in the electrical conductivity in all compost windrow piles. The electrical conductivity is an important parameter used to monitor the performance of the composting process. Substrate decomposition *via* the aerobic activity will cause mineralization that will increase the concentration of various metal ions. The EC values for the three windrow piles ranged between (2.5-5.6) dS/m. The final electrical conductivity values showed an increase of 6.8, 26.1 and 40.8% for pile 1, pile 2 and pile 3, respectively.

Nutrient Content

From an agricultural point of view, fertilizers should provide the soil with essential nutrient elements to support the crop development stages. Nitrogen (N), potassium (K_2O) and phosphorus (P_2O_5) are the macro-nutrient elements that significantly affect the plant growth. Compost improves soil properties and increases the rate of plant growth *via* providing the soil with the necessary nutrients. Compost enhances the structure of soil by increasing its porosity, which helps the roots grow better. In addition, compost enables sandy soil to retain water, which helps increase the effectiveness of irrigation and reduces the water needs of plants and crops. Among various nutrients present in the compost, nitrogen, phosphorous and potassium are the essential nutrients needed for plant production. The amount of nutrients present in the final compost depends on the type of raw material used in the manufacture of compost. The trend of nitrogen (N), phosphorous (P_2O_5) and potassium (K_2O) content obviously shows the difference in the origin of experimental piles (Figure 8).

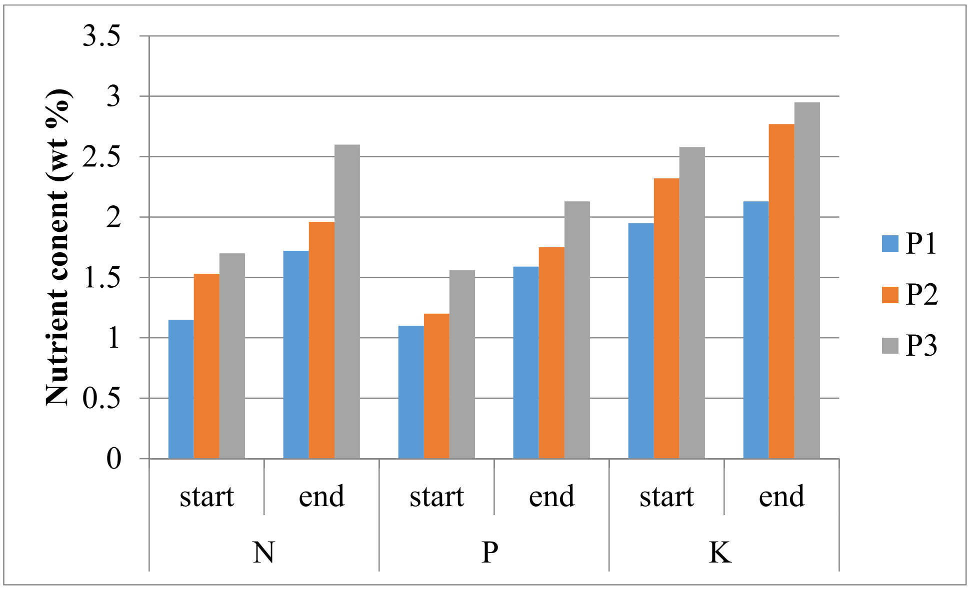

Figure (8): Nutrient content wt (%) for all piles during the composting period

The results indicate generally an increase in the nutrient content in the three piles during the composting period. The final concentrations of nitrogen were 1.72, 1.96 and 2.6 % in pile 1, pile 2 and pile 3, respectively. The final concentrations of phosphorous were 1.59, 1.75 and 2.13% in pile 1, pile 2 and pile 3, respectively. The final concentrations of potassium were 2.13, 2.77 and 2.95% in pile 1, pile 2 and pile 3, respectively. This data on essential nutrients indicates ratios of 1:0.92:1.24, 1:0.88:1.41 and 1:0.82:1.13 for N: P_2O_5: K_2O in pile 1, pile 2 and pile 3, respectively. Fricke and Vogtmann (1994) conducted an extensive survey of composts produced from biogenic waste, where the analyzed data on essential nutrients resulted in a ratio of 1:0.54:0.88 for N:P_2O_5:K_2O. Based on the optimum ratio referenced by Fricke and Vogtmann (1994) of the macro-nutrient uptake for various cultivated plants, it might be proposed that the ratios of nutrients found in this compost can be classified as favorable for winter wheat, oats and ryegrass plants.

The composting process increased the nitrogen concentrations by a factor of 22, 22 and 35% in pile 1, pile 2 and pile 3, 6 respectively. It also increased the phosphorus concentrations by a factor of 31, 27 and 27% in pile 1, pile 2 and pile 3, respectively. It also increased the potassium concentrations by a factor of 8, 16 and 13 in pile 1, pile 2 and pile 3, respectively. This increase in nutrient concentrations is attributed to compost volume reduction as well as to the increase in the bulk density of the piles (Hemidat et al., 2018).

Organic Matter

In this study, the organic matter contents for several compost samples were analyzed. The total amount of organic matter is determined by measuring the biodegradable volatile solids' content of oven-dried samples using the ignition method at 550°C. Four samples from each pile were analyzed. The organic matter contents in the analyzed compost samples are given in Table 3.

Table 3. Organic matter content in the analyzed compost samples

	Total organic matter (%)		
	Pile 1	**Pile 2**	**Pile 3**
Sample 1	18	33	40
Sample 2	33	35	33
Sample 3	27	33	35
Sample 4	39	37	37
Average	29.3	34.5	36.3

Brinton (2000) reported organic matter content > 15, > 20 and > 30 % based on German, Austrian and WERL (USA) compost end-use test values, respectively. In this study, the value of organic matter after 12 weeks of composting in all of the samples analyzed ranged from 18% to 40%, which meets the afore-mentioned standards.

Kinetics of the Composting Process

Several experimental investigations on composting revealed that the composting process follows first-order kinetics (Hamoda et al., 1998; Külcu and Yaldiz, 2004; Petric et al., 2012; Abu Qdais and Al-Widyan, 2016). The rate of organic matter biodegradation as a function of time can be represented as:

$$-\frac{dC}{dt} = k.C \qquad (1)$$

where C is the biodegradable volatile solid content at any time and k is the first-order rate constant [day^{-1}].

Integrating Equation (1) with the initial condition $C = C_0$ yields:

$$C = C_o.\exp(-k.t) \qquad (2)$$

Equation (2) in a linearized form is:

$$-ln\frac{C}{C_o} = k.t \qquad (3)$$

Figure 9 shows the kinetic plots for the determination of the first-order rate constant based on initial and final TOC contents.

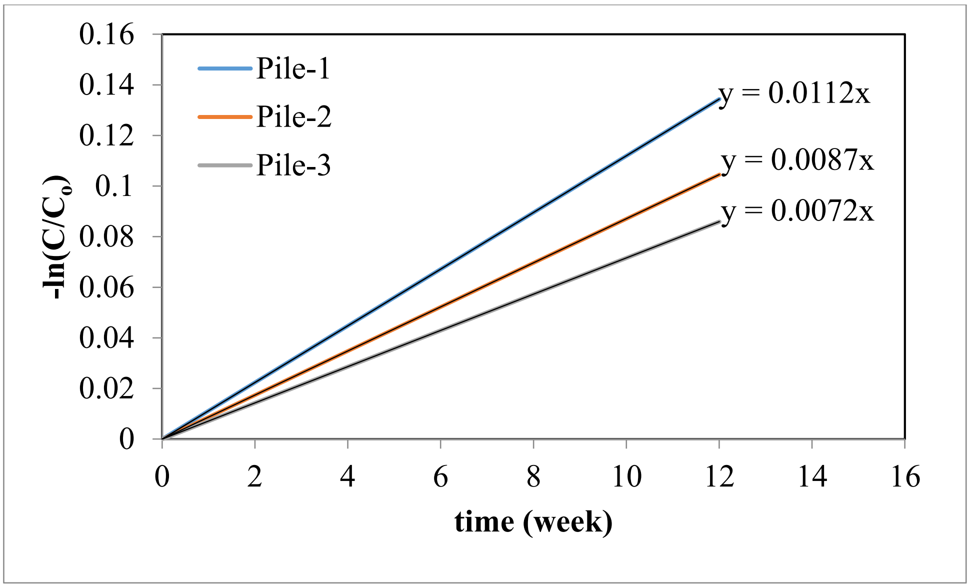

Figure (9): Kinetic plots for the composting process

The results shown in Figure 9 indicate that the first-order rate constants are 0.00157, 0.0011 and 0.0010 day^{-1} for pile 1, pile 2 and pile 3, respectively. Pile 1 exhibited the fastest biodegradation rate compared to both pile 2 and pile 3.

Respiration Activities

Compost maturity can be judged by monitoring oxygen consumption or carbon dioxide production in the compost. Consuming O_2 and producing CO_2 indicate a microorganism activity in the compost, revealing the presence of a remained biodegradable substrate in the immature compost. Hue and Liu (1995) and references therein reported that an O_2 consumption rate of ≤40 mg O_2/kg DM/hour is an indication of a stable compost. On the other hand, CO_2 production at a rate of 100 mg CO_2/kg/hour can be used as the cut-off value for compost stability. In this study, compost maturity is examined by measuring the O_2 uptake necessary for the decomposition of waste within four days (AT4) and the results for the three compost are shown in Table 4.

Table 4. AT4 in the analyzed compost samples

	AT4 (mg O_2/g DM)		
	Pile-1	**Pile-2**	**Pile-3**
Sample 1	4.78	2.59	5.24
Sample 2	4.30	2.58	4.81
Sample 3	4.18	2.57	5.43
Average	**4.42**	**2.58**	**5.16**

The AT4 results indicate that compost respiration in the samples ranged from 2.57 to 5.43 mg O_2/g DM. Compost stabilization is ensured when respiration activity after 4 days is less than 7 mg O_2/g DM (Binner et al., 2012). Accordingly, compost produced in this study possessed stability and maturity, where all of the compost samples appeared to be stable and thus can be classified as class V end products (finished compost) according to the German standards (Chaher et al., 2020).

In the case of source-separated organic waste, the findings indicate that the state-of-the-art of the composting process is performed successfully under ideal conditions. The chemical and physical characteristics of the final product (Table 5) demonstrate a complete degradation of organic waste within a relatively short period of time (12 weeks).

Table 5. Physical and chemical characteristics of the final compost

Parameter	**Pile-1**	**Pile-2**	**Pile-3**
TOC (wt%)	29.2	37.2	39
TKN (wt%)	1.72	1.96	2.6
C/N Ratio (w/w)	17	19	15
Moisture Content (wt%)	33	34	36
pH	7.8	7.7	7.7
EC (dS/m)	2.5	3.4	5.6
Total P (wt%)	1.59	1.75	2.13
Total K (wt%)	2.13	2.77	2.95
Final Pile Volume (m^3)	15.3	15.9	17.1
Volume Reduction (%)	45.4	33.8	31.6
Final Bulk Density (kg/m^3)	540	520	495
Bulk Density Increase (%)	15.88	14.29	15.12
Water Added (m^3)	34	39	66
m^3 water / m^3 fresh waste	1.2	1.6	2.6

Overall, the results obtained from the research experiments look good and the compost produced has the potential to be utilized in agricultural purposes, practically the compost derived from source-separated organic waste.

CONCLUSIONS

In this research work, different available types of organic waste; market waste (fruits and vegetables), garden waste (plant residues) and manure (poultry and sheep), were used as the composting input material. Sawdust and tree clipping were used as bulking agents to ensure the required C/N ratio necessary for effective decomposition.

All piles demonstrated a typical composting temperature trend, achieving thermophilic temperatures of more than 55°C, reaching approx. 68°C within 2 weeks and remaining above 50°C from week 4 to week 6, before dropping further. Water was added when required and the moisture content level inside the composting piles was kept close to 50% for the first 6-8 weeks, which ensures high organic matter degradation. The final moisture content value at the end of the process for the three piles ranged between 33 and 36%. High reduction of C/N ratio took place in all piles, where more than 40% reduction was achieved. The final C/N ratio ranged from 15 to 20 for all the piles. Most of the samples had organic matter content within the range set by the German standard (BioAbfV), which should be between 15 and 45%. The results also showed that all of the compost samples tested appeared to be stable and considered as a finished product of class V.

Overall, the findings obtained indicated that the compost produced in Jordan was a high-quality, pathogen- free, mature and market-oriented end product.

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REFERENCES

Abbassi, B. E., Abubaker, S., Al-Manaseer, E., Nassour, A., Dababneh, B., Shqairat, W., and Al-Jaar, M. (2015). "Optimization of operating parameters of windrow composting of animal manures”. Journal of Solid Waste Technology and Management, 41 (1), 60-67.

Abu Qdais, H., and Al-Widyan, M. (2016). "Evaluating composting and co-composting kinetics of various agro-industrial wastes." International Journal of Recycling of Organic Waste in Agriculture, 5(3), 273-280.

Abu Qdais, H., Wuensch, C., Dornack, C., and Nassour, A. (2019). "The role of solid-waste composting in mitigating climate change in Jordan". Waste Management & Research, 37 (8), 833-842.

Aldayyat, E.A., Saidan, M.N., Abu Saleh, M.A., Hamdan, S., and Linton, C. (2019). "Solid-waste managment in Jordan: Impacts and analysis". Journal of Chemical Technology and Metallurgy, 54, 454-462.

Alhyasat, A., Al-Nsour, Z., and Majar. H.M. (2014). "Country report on solid waste management in Jordan". The Regional Solid Waste Exchange of Information and Expertise Network in Mashreq and Maghreb Countries, GIZ, Jordan.

Aljaradin, M. (2014). "Solid-waste management in Jordan". International Journal of Academic Research in Business Social Sciences, 4, 138-150.

Ammari, T.G., Al-Omari, Q., and Abbassi, B.E. (2012). "Composting sewage sludge amended with different sawdust proportions and textures and organic waste of food industry: Assessment of quality". Environmental Technology, 33 (14), 1641-1649.

An, C.-J., Huang, G.-H., Yao, Y., Sun, W., and An, K. (2012). "Performance of in-vessel composting of food waste in the presence of coal ash and uric acid." Journal of Hazardous Materials, 203, 38-45.

Binner, E., Böhm, K., and Lechner, P. (2012). "Large-scale study on measurement of respiration activity (AT4) by Sapromat and OxiTop". Waste Management, 32, 1752-1759.

Breitenbeck, G.A., and Schellinger, D. (2004). "Calculating the reduction in material mass and volume during composting". Compost Science and Utilization, 12, 365-371.

Brinton, W.F. (2000). "Compost quality standards and guidelines". Final Report by Woods End Research Laboratories for the New York State Association of Recyclers.

Chaher, N.E.H., Chakchouk, M., Nassour, A., Nelles, M., and Hamdi, M. (2020). "Potential of windrow food and green waste composting in Tunisia". Environmental Science Pollution Research, 1-13.

De Bertoldi, M., Zucconi, F., and Civilini, M. (1988). "Temperature, pathogen control and product quality". Biocycle, 29, 43-50.

Dougherty, M. (1999). "Field guide to on-farm composting". Natural Resource, Agriculture and Engineering Service, Cooperative Extension.

Eiland, F., Klamer, M., Lind, A.-M., Leth, M., and Bňňth, E. (2001). "Influence of initial C/N ratio on chemical and microbial composition during long-term composting of straw". Microbial Ecology, 41, 272-280.

Epa. (1999). "Biosolids: Generation, use and disposal in the United States". Municipal and Industrial Solid Waste Division, Office of Solid Waste, Washington, DC, USA.

Fricke, K., and Vogtmann, H. (1994). "Compost quality: Physical characteristics, nutrient content, heavy metals and organic chemicals." Toxicological Environmental Chemistry, 43, 95-114.

Gajalakshmi, S., and Abbasi, S. (2008). "Solid-waste management by composting: State-of-the-art." Critical Reviews in Environmental Science and Technology, 38, 311-400.

Hamoda, M.F., Qdais, H.A., and Newham, J. (1998). "Evaluation of municipal solid-waste composting kinetics". Resources, Conservation and Recycling, 23 (4), 209-223.

Hemidat, S. (2019). Feasibility assessment of waste management and treatment in Jordan". Universität Rostock, Germany.

Hemidat, S., Jaar, M., Nassour, A., and Nelles, M. (2018). "Monitoring of composting process parameters: A case study in Jordan". Waste and Biomass Valorization, 9, 2257-2274.

Hue, N., and Liu, J. (1995). "Predicting compost stability". Compost Science and Utilization, 3, 8-15.

ISO-16072. (2002). "Soil quality: Laboratory methods for determination of microbial soil respiration". International Organization for Standardization, Geneva.

Kapetanios, E., Loizidou, M., and Valkanas, G. (1993). "Compost production from Greek domestic refuse". Bioresource Technology, 44, 13-16.

Khater, E.-S.G. (2015). "Some physical and chemical properties of compost." International Journal of Waste Resources, 5, 1-5.

Kulcu, R., and Yaldiz, O. (2004). "Determination of aeration rate and kinetics of composting some agricultural wastes." Bioresource Technology, 93(1), 49-57.

Mercer, W.A., and Rose, W.W. (1968). "Investigation of windrow composting as a means for disposal of fruit-waste solid". National Canners Association Research Foundation, Washington, DC, USA.

Oazana, S., Naor, M., Grinshpun, J., Halachmi, I., Raviv, M., Saadi, I., Avidov, R., Varma, V.S., Rosenfeld, L., and Gross, A. (2018). "A flexible control system designed for lab-scale simulations and optimization of composting processes." Waste Management, 72, 150-160.

Petric, I., Helić, A., and Avdić, E. A. (2012). "Evolution of process parameters and determination of kinetics for co-composting of organic fraction of municipal solid waste with poultry manure." Bioresource Technology, 117, 107-116.

Proietti, P., Calisti, R., Gigliotti, G., Nasini, L., Regni, L., and Marchini, A. (2016). "Composting optimization: Integrating cost analysis with the physical-chemical properties of materials to be composted". Journal of Cleaner Production, 137, 1086-1099.

Sadaka, S., and El–Taweel, A. (2003). "Effects of aeration and C: N ratio on household waste composting in Egypt". Compost Science and Utilization, 11, 36-40.

Shatnawi, R.S. (2018). "Solid-waste management: Classification and public perception on management options at Applied Science University". Jordan Journal of Civil Engineering, 12 (3), 379-388.

Thompson, W., Leege, P., Millner, P., and Watson, M. (2002). "Test methods for the examination of composts and composting". The US Composting Council, US Government Printing Office, CDROM.

Vandergheynst, J.S., Pettygrove, S., Dooley, T.M., and Arnold, K.A. (2004). "Estimating electrical conductivity of compost extracts at different extraction ratios." Compost Science and Utilization, 12, 202-207.

Wei, Y., Li, J., Shi, D., Liu, G., Zhao, Y., and Shimaoka, T. (2017). "Environmental challenges impeding the composting of biodegradable municipal solid waste: A critical review." Resources, Conservation and Recycling, 122, 51-65.

Wong, J., Mak, K., Chan, N., Lam, A., Fang, M., Zhou, L., Wu, Q., and Liao, X. (2001). "Co-composting of soybean residues and leaves in Hong Kong." Bioresource Technology, 76, 99-106.