

Szent István University

Doctoral School of Environmental Sciences

The Thesis of the Ph.D. Dissertation

**ASSESSMENT OF THE EVOLUTION AND EFFICIENCY OF DIFFERENT
INDUSTRIAL COMPOSTING TECHNOLOGIES**

By

Mutaz Al-Alawi

Gödöllő, Hungary

2020

Title: Assessment of the evolution and efficiency of different industrial composting technologies

Discipline: Environmental Sciences

Name of Doctoral School: Doctoral School of Environmental Sciences

Head: Csákiné Dr. Erika Michéli, CMHAS
Szent István University, Faculty of Agricultural and Environmental Sciences, Institute of Environmental Science, Department of Soil Science

Supervisor: Dr. Barbara Simon
Szent István University, Faculty of Agricultural and Environmental Sciences, Institute of Environmental Science, Department of Soil Science

Co-Supervisor: Dr. Miklós Gulyás
Szent István University, Faculty of Agricultural and Environmental Sciences, Institute of Environmental Science, Department of Soil Science

.....
Approval of Head of Doctoral School

.....
Approval of Supervisor

.....
Approval of Co-Supervisor

1. BACKGROUND AND OBJECTIVES

The momentous rise of populations on a worldwide scale due to advanced levels of industrialization and urbanization has led directly rise in the generation of solid waste (Singh et al., 2011). Globally, it has been estimated that 1.3 billion metric tons of waste are generated annually, which will rise to 38-67 % by the close of 2025. It includes sewage sludge (SS), industrial, agricultural, and municipal waste (García-Sánchez et al., 2017). Wastes, such as animal wastes, garden wastes, municipal solid waste (MSW), food and kitchen waste, agricultural wastes, agro-industrial wastes, SS, etc. can be classified as solid organic wastes with an organic biodegradable fraction and a moisture level of less than 85-90 % (Mata-Alvarez et al., 2000). The majority of developing countries globally produce massive volumes of solid waste that is handling and managed badly owing to the absence of waste segregation and suitable disposal facilities (Ngoc and Schnitzer, 2009). Moreover, inappropriate waste management practices such as open dumping or burning of waste can lead to pollution and destruction of the urban landscape (Amritha and Kumar, 2019), but also make sustainable means of waste management, which is a great challenge. There is greater risk of soil pollution in regions adjacent to open waste dumping sites due to leaching of contaminants such as heavy metals. Furthermore, erosion, runoff and leaching from these sites can also result in pollution of surface water and ground water (Mor et al., 2006). These can all lead to many water-borne diseases that are transmitted via water e.g. diarrhea, cholera and typhoid. Burning or incineration of MSW can also lead to the releases of noxious, toxic gases and polychlorinated dibenzo-p-dioxins, dibenzofurans (PCDD/Fs), and putrefaction of MSW due to open dumping results in release of greenhouse gases (GHGs) such as CO₂, CH₄, and N₂O causing global warming and air pollution (Vaish et al., 2019). The biodegradable organic fraction predominates the MSW stream in developing nations and is one of the biggest causes of anthropogenic GHGs emissions (Narayana, 2009; Tian et al., 2013). Finally, open dumping of wastes affects also the esthetic look of a region by becoming a collection point for flies, insects and pathogens and lead to the release of bad odors. Such unscientific conventional waste disposal methods are a danger to the quality of the environment and to public health, moreover, they lead to loss of nutrients present in the organic waste and economic loss (Yadav and Garg, 2011).

One means of ensuring the eco-friendly and sustainable recycling of organic waste (compared to conventional methods of waste disposal and energy recovery) is through use of

integrated waste management hierarchy (Sharma et al., 2017). Keeping to the rules of resource/nutrient recovery and recycling, scientific methods of conversion (via. such as composting, vermicomposting) and uses of organic wastes for agriculture purposes can provide useful nutrients for improving plant growth and soil fertility. The purpose of uses organic wastes in agronomy is to sustain a sustainability cycle in which the organic fraction of biodegradable waste is transformed into fertilizer or beneficial organic manure via vermicomposting, composting or anaerobic digestion to produce slurry and compost for agricultural purpose. Today's European policy aims to reduce, recycle and revalorize waste to ensure a circular economy. Therefore, in this light, organic wastes constitute a reservoir of nutrients with a large amount of inorganic and organic substances that must be recycled (Kacprzak et al., 2017).

Composting is one such management strategy that has been gaining global popularity due to its ability to hygienization of waste, cost effectiveness and conversion of waste to value-added products (Sharma et al., 2019). Composting imply biological conversion of heterogenous solid organic wastes (e.g. crop residues, garden waste, SS, kitchen and food waste, paper, wood) into humus-like substances with the help of microorganisms like fungi, bacteria and actinomycetes under controlled conditions of aeration, temperature and moisture (Atalia et al., 2015). The primary objectives of composting are to: (1) decreasing both volume and mass of the solid organic wastes, (2) destruction of pathogens and weed seeds present in the substrate, (3) decrease and or even eliminate inorganic and organic contaminants, and (4) obtain organic materials that are both stable and mature (Senesi et al., 2007).

However, to obtain a high-quality compost product, efficient composting technologies must be used (Cesaro et al., 2015). Currently, various composting technologies are available; the choice of technology depends on the operational cost, the time needed to reach compost maturity, the land availability, and the source of raw materials. In recent years, composting technologies have been subjected to considerable modifications (e.g., cocomposting, vermicomposting, and windrow composting) to make composting technology more cost effective (Zhou et al., 2018).

1.1. Objectives

Many previous studies have focused on evaluating the effects of composting process using a semi-permeable cover, in combination with an air-insufflation system on GHGs and odor emissions (González et al., 2016; Komilis et al., 2004; Ma et al., 2018, 2017; Robledo-Mahón et al., 2019; Sun et al., 2018, 2016; Turan et al., 2009; Van Haaren et al., 2010). On the other hand, other studies focused on assessment of microbial community succession in a full-scale composting with a semi-permeable membrane under slight positive pressure (Robledo-Mahón et al., 2020, 2018). However, no studies so far have analyzed in detail the physico-chemical properties of composts and provided insight into the mechanisms of how these properties changed while composting through using relatively new composting technologies that are aerated static windrow (ASW) with GORE® Cover membrane and encapsulated lifting system (ELS) with GORE® Cover membrane. Therefore, this study tested the hypothesis that these two relatively new composting technologies will produce mature compost within a shorter time than conventional composting process. This research has three main objectives: (1) characterize the changes in the physico-chemical properties during composting, (2) monitor the composting process using UV-visible and Fourier transform infrared (FTIR) spectroscopy to evaluate the humification degree, and (3) evaluate the quality of the final compost product.

The results obtained can help to safely use dewatered stabilized sewage sludge (DSSS) and green waste (GW) while avoiding their secondary contamination resulting from the improper treatment of these wastes. In addition, the results can improve and develop these two relatively new composting technologies to produce a compost product that is useful as a soil amendment or fertilizer.

2. MATERIALS AND METHODS

2.1. Composting setup and description of encapsulated lifting system with GORE® Cover membrane

2.1.1 Composting materials

The DSSS and GW were used for composting. The DSSS was obtained by centrifuging stabilized sludge from a biogas digester, while the GW (grass, wood chips, tree leaves, etc.) was collected from the parks and gardens in Kecskemét. The DSSS was mixed with the GW materials, which acted as bulking agents, at a 1:4 proportion of sludge to bulking agent to obtain optimum moisture and a C/N ratio of approximately 65 % and 25:1, respectively.

2.1.2 Composting process

Composting processes were carried out using an ELS with GORE® Cover membrane at an industrial scale (**Figure 1**). The composting process consisted of two phases of ASW treatment under GORE® Cover membrane: an intensive phase (4 weeks) and a maturation phase (3 weeks).

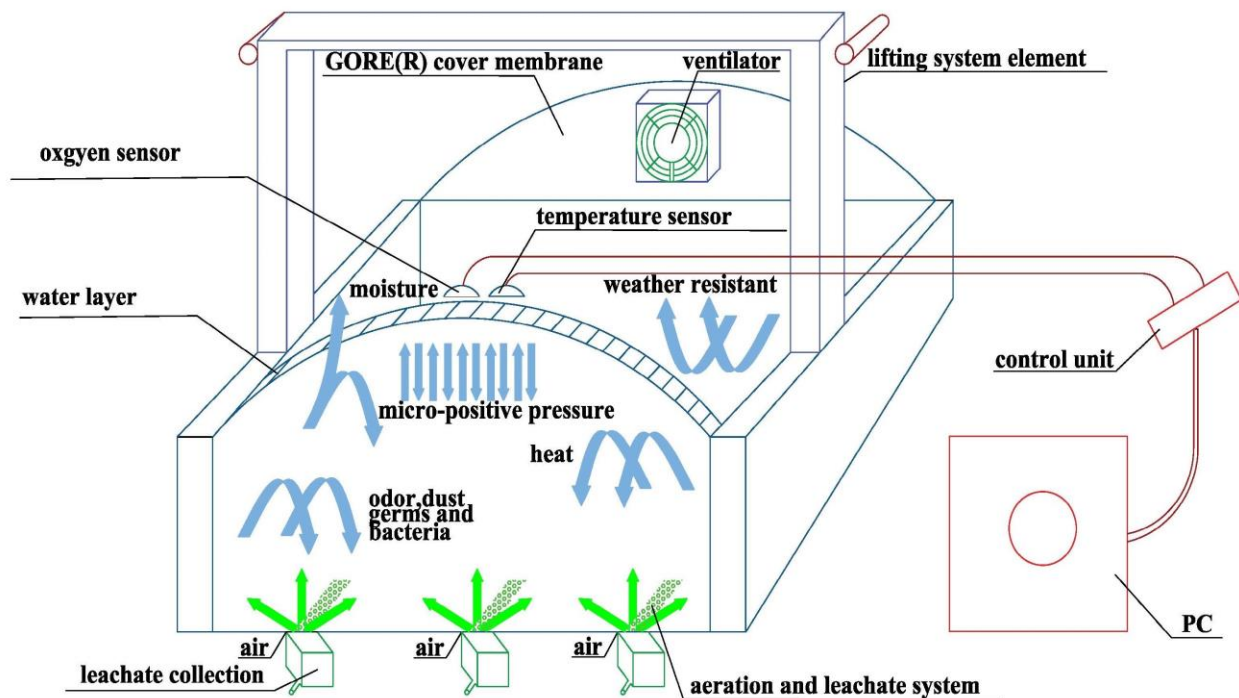


Figure 1. Schematic diagram of the encapsulated lifting system with GORE® Cover membrane

2.2. Composting setup and description of aerated static windrow with GORE® Cover membrane

2.2.1 Composting materials

This research study was undertaken in a composting industrial plant located in Gödöllő city, Hungary. The GW consisted mainly of fallen leaves and branch cuttings generated by urban landscape maintenance. The GW was reduced to a particle size of about 1 cm with a shredder to increase the reactive surfaces for microorganisms, before the composting began. The MC was then adjusted to 60 % by the addition of water.

2.2.2 Composting process

Composting was carried out by ASW with GORE® Cover membrane at industry-scale (**Figure. 2**). The GW was stacked to 35 m in length, 8 m in width, and 2.5 m in height in trapezoidal windrow, which were covered with GORE® Cover membrane and had a ventilation system to ensure oxygen supply. The windrow had a 3-sided reinforced concrete wall to retain the material in the row on the compost pad. The composting process was considered complete when the windrow temperature dropped to ambient temperature. Then the material was screened using a screening drum with size holes that were 12 x 12 mm.

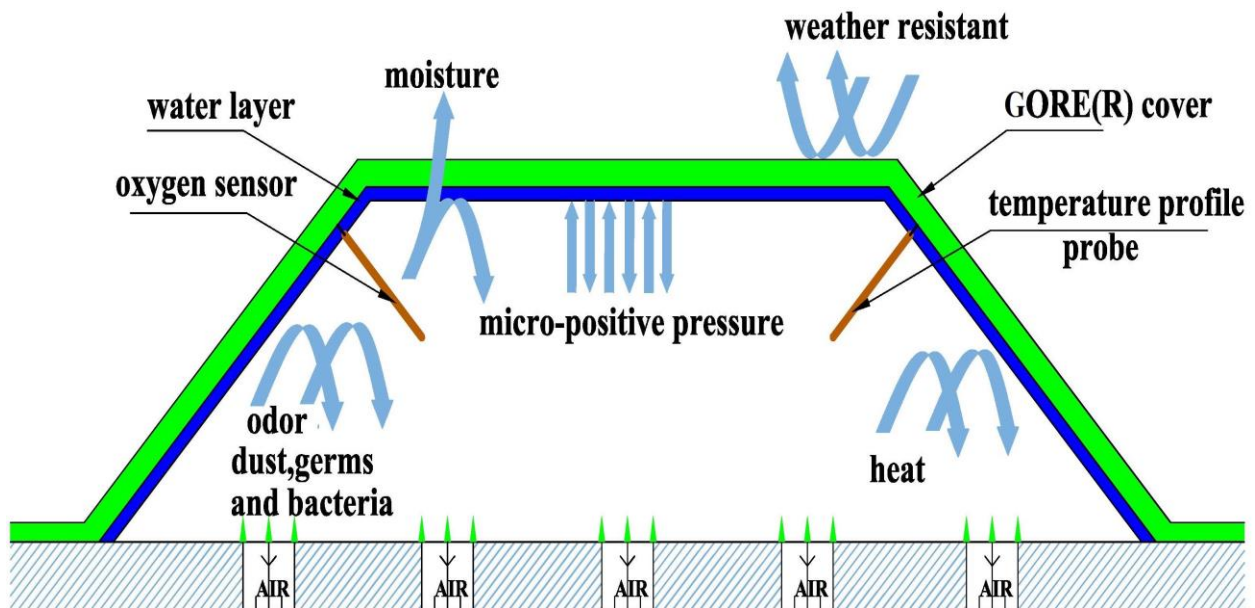


Figure 2. Schematic diagram of the aerated static windrow with GORE® Cover membrane

2.3. Physico-chemical analyses of compost samples

Ash content was determined by burning samples (previously dried at 105°C) at 550°C for 7 h in a muffle furnace (TMECC, 2002). The organic matter (OM) was estimated as follows (TMECC, 2002): $OM (\%) = 100 - ash (\%)$. Losses of OM due to OM mineralization were calculated based on the initial and final ash content for each time interval according to the equation (Paredes et al., 2000):

Equation 1. Losses of organic matter

$$OM_{loss}(\%) = 100 - 100 \left[\frac{x_1(100 - x_2)}{x_2(100 - x_1)} \right]$$

where X_1 and X_2 are the initial and final ash concentrations, respectively.

Total nitrogen (TN) and total carbon (TC) were determined by subjecting air-dried samples to dry combustion at a temperature of 1100-1200°C using a CNS analyzer (Fisons NA 1500 Series II CNS analyzer). The cation exchange capacity (CEC) of the air-dried samples was determined according to Harada and Inoko (1980a). The ammoniacal nitrogen (NH_4^+ -N) and nitrate nitrogen (NO_3^- -N) were extracted by mixing air-dried samples with 0.5 M K_2SO_4 at a ratio of 1:10 (w/v), mechanically shaking for 1 h, and filtering through 0.45- μ m membrane filters. The filtrate was used for NH_4^+ -N and NO_3^- -N determination using the colorimetric method, as described by Okalebo et al. (2002). The Ca, Na, Mg, Cr, Cu, Fe, Mn, Ni, Zn, Cd, Co, and Pb concentrations were measured after microwave HNO_3/H_2O_2 digestion by Inductively Coupled Plasma-Optical Emission Spectroscopy (ICP-OES) (TMECC, 2002).

2.4. UV-visible spectroscopic analysis

UV-visible spectroscopy analysis was performed according to the following method by (Zbytniewski and Buszewski, 2005). One gram of air-dried compost and 50 ml of 0.5 M NaOH were shaken for 2 h and then centrifuged at 3000 rpm for 25 min. The absorbance of the supernatant was measured at $\lambda = 280$ nm (A280), 472 nm (A472), and 664 nm (A664) using a UV-2000 spectrophotometer covering a frequency range of 200 to 800 nm.

2.5. FTIR spectroscopic analysis

Air-dried samples from each composting step were analyzed with a Bruker DRIFT (diffuse reflectance infrared fourier transform)-FTIR spectrometer covering a frequency range of 4000 – 400 cm^{-1} . The resolution was set to 4 cm^{-1} , and 32 scans were recorded before being averaged for each spectrum and corrected against ambient air, which acted as the background.

2.6. Statistical analyses

The data shown in the tables and figures represent the means of three replicate subsamples for each composite sample with standard deviations calculated using Microsoft Excel 2016. Each set of three subsamples was prepared from the corresponding composite sample (representing the average conditions of the entire windrow in question) and analyzed independently.

3. RESULTS AND DISCUSSION

3.1. Encapsulated lifting system with GORE® Cover membrane

3.1.1 Losses of organic matter and ash content

Approximately 50 % of OM is fully mineralized (Bernal et al., 2017). The degradation of OM during composting can be estimated based on the loss of OM, and here, OM_{loss} increased sharply to 52.5 % within the first 35 days of composting (**Figure 3**) due to the greater availability of substances which are easily biodegradable by microorganisms. Then, it slowed down, reaching 56.7 % at the end of composting due to the depletion of easily biodegradable carbon and the synthesis reactions of the new complex polymerized organic substances (humification), processes which prevail over mineralisation during the maturation stage (Bernal et al., 2009). This transformation matched well with the remarkable reduction in OM, indicating a rapid decomposition rate. Expected OM loss during composting is between 30 % and 60 % and OM loss > 42 % may be accepted as an index value for mature compost (Raj and Antil, 2011). Based on this, the compost could be considered matured during 28 days. Composting is an exothermic aerobic process in which the OM in SS are decomposed and mineralized to CO_2 by microorganisms. As a result, a reduction in OM is always observed in SS composting. The higher OM_{loss} observed in this case could be due to the presence of two thermophilic temperature peaks and the longer thermophilic periods experienced during composting using this new composting technology. It has previously been found that high composting temperatures accelerate the growth of thermophilic microorganisms, allowing further biodegradation of OM (Meng et al., 2017).

During composting, there was an increase in ash content in the windrow. The ash content increased by 62.3 % after 49 days (**Figure 3**). Several authors have stated that increased ash content during composting results from the mineralisation of OM by microbes (Bernal et al., 2017; Rudnik, 2019), and this parameter indicates decomposition and mineralization of the OM, consequently reflecting the degree of stabilisation achieved during the process. A final compost with a higher ash content and lower OM is considered mature.

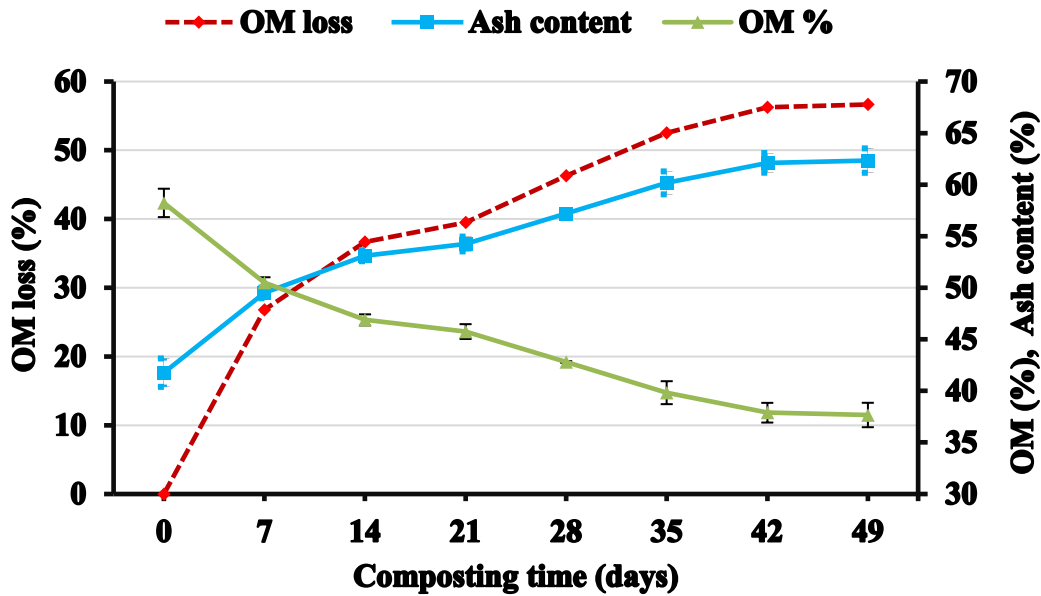


Figure 3. Evolution of OM_{loss} and ash content during DSSS-GW composting

3.1.2 C/N ratio

The C/N ratio is one of the most significant parameters used to evaluate the stabilization of compost. In this case, the C/N ratio decreased to reach a value of approximately 6.7 (Figure 4) after 49 days of composting. The continuous and rapid reduction in the C/N ratio was due to loss of TC and an increase in the proportion of TN due to the concentration effects resulting from the intense biodegradation of OM over the composting period (Huang et al., 2004). The TN value might have been also increased within the compost under the GORE® Cover membrane due to the contribution of the free-living N-fixing microorganisms that are generated during later stages of the composting process (de Bertoldi et al., 1983). In the present study, the C/N ratio of the final compost reached a value of 6.7, which indicated that compost stabilization was achieved after 49 days of composting. Using this technology, the C/N ratio reduction rate was higher than the C/N ratios achieved in conventional methods of composting with the same substrate, in which C/N ratios were found reduce to 10.1 (El Fels et al., 2014), 11.7 (Raj and Antil, 2011), and 12.9 (Lahsaini et al., 2017). This is due to the forced bottom-up aeration system, which improves aeration conditions, accelerates decomposition, and results in a greater loss of carbon. The results

thus agree with the findings of Sundberg and Jönsson (2008), who demonstrated that higher rates of aeration lead to faster decomposition in biowaste composting.

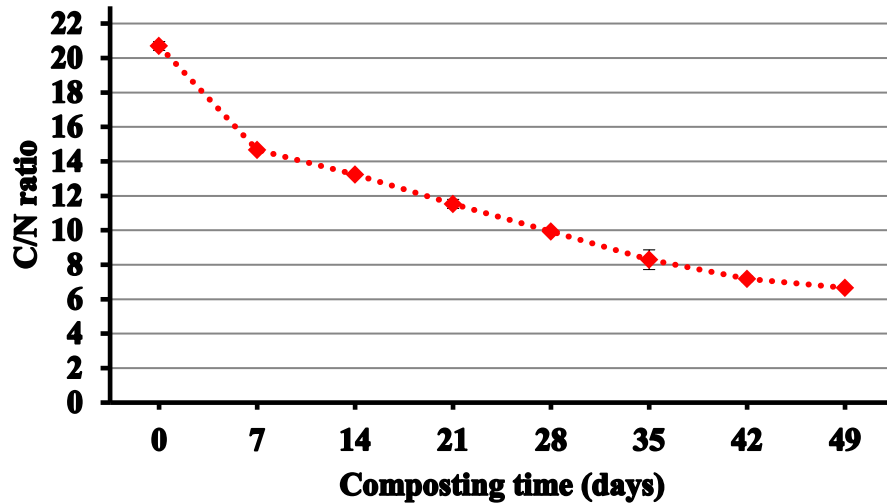


Figure 4. Evolution of the C/N ratio during DSSS-GW composting

3.1.3 $\text{NH}_4^+/\text{NO}_3^-$ ratio

The $\text{NH}_4^+/\text{NO}_3^-$ ratio ranged from 22.3 to 0.1 after 49 days of composting (Figure 5). The $\text{NH}_4^+/\text{NO}_3^-$ ratio is used to indicate the maturity of compost; a ratio below the limit of 0.16 for composting materials such as SS, municipal solid waste, and pig slurry indicates maturity (Bernal et al., 2009). The recorded value of approximately 0.1 indicated that the final product reached maturity in this case, and that the substrate had been changed to yield a non-phytotoxic compost. For comparison, the critical limits for maturity during composting of SS by conventional composting technology have been found to be fulfilled after 6 months (El Fels et al., 2014), 220 days (Jouraiphy et al., 2005), and 135 days (Raj and Antil, 2011), while the new composting technology achieved maturity critical limits by the 49th day, implying that the conventional composting technology takes much longer to achieve the index value for maturity than the new composting technology, most likely due to the differences in aeration. These results indicate that this new technology is highly suitable for ensuring compost maturity in a shorter time frame due to improved aeration conditions and the flow of oxygen throughout the entire composting vessel using forced bottom-up aeration that increase intensity of nitrification processes (Wang et al., 2018).

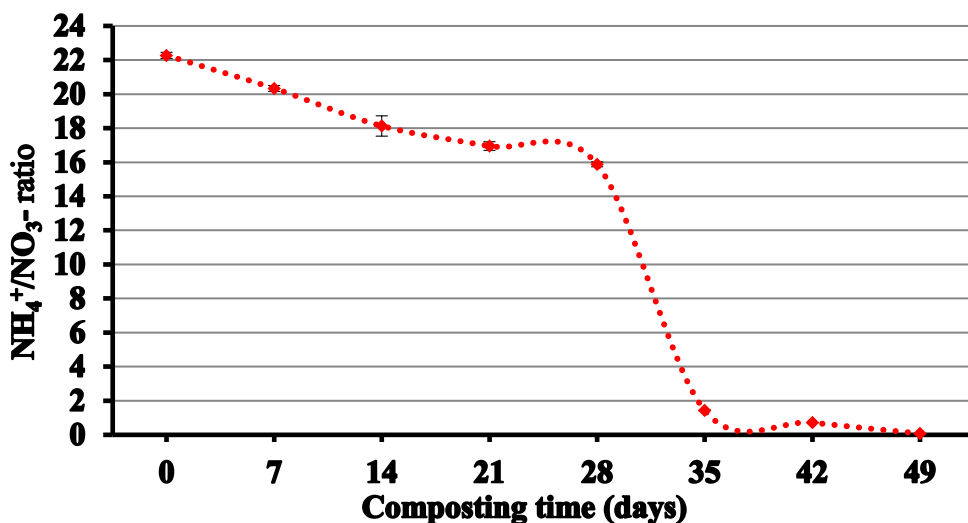


Figure 5. Evolution of the $\text{NH}_4^+/\text{NO}_3^-$ ratio during DSSS-GW composting

3.1.4 Cation exchange capacity

During composting, CEC increased substantially from $51.3 \text{ cmol kg}^{-1}$ to $170.3 \text{ cmol kg}^{-1}$ after 49 days (**Figure 6**). CEC can be used to evaluate the degree of humification and the nutrient retention capacity of compost (Roig et al., 1988; Zhang and Sun, 2014). According to Harada and Inoko (1980a), the CEC of a mature compost should be $> 60 \text{ cmol kg}^{-1}$. In the current study, the CEC value of the final product was $170.3 \text{ cmol kg}^{-1}$, which indicates that the compost is mature. Zhang and Sun (2014a) confirmed that high CEC values are due to larger proportions of carboxyl functional groups in the substrates, while Lax et al. (1986) concluded that increases in CEC values during composting could be the result of the accumulation of compounds bearing a negative charge, such as lignin-derived products, carboxyl groups, and phenolic hydroxyl groups.

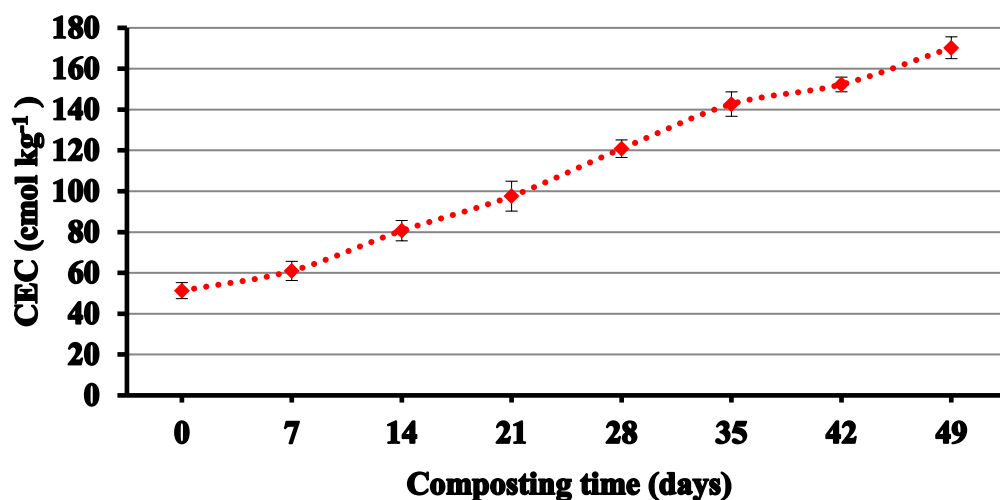


Figure 6. CEC evolution during DSSS-GW composting

3.1.5 UV-visible spectroscopic analysis

The evolution of the $E_{2/6}$, $E_{2/4}$, and $E_{4/6}$ ratios provides information on the degree of OM maturity during composting. The $E_{2/4}$, $E_{2/6}$ and $E_{4/6}$ ratios decreased sharply to 5.1, 25.4, and 3.8, respectively, after 49 days of composting (**Figure 7**). These decreases indicate the occurrence of the humification process. The decreases in the $E_{2/6}$ and $E_{4/6}$ ratios at the end of composting demonstrated a strong increase in the humification of OM (Lahsaini et al., 2017). Chen et al. (1977) used the $E_{4/6}$ ratio as a humification index, and Zbytniewski and Buszewski (2005) reported that low $E_{2/6}$ or $E_{4/6}$ ratios reflected high degrees of aromatic condensation and indicated a higher level of organic material humification. $E_{4/6}$ can also be used as an estimator of molecular weight (Chen et al., 1977). Guo et al. (2019) showed that during the thermophilic stage, rapid breakdown of lignin and quinone moieties occurred as the $E_{2/4}$ ratio decreased, indicating a higher degree of aromatic condensation, as well as a higher level of organic material humification. Therefore, a continuous decrease in $E_{2/4}$ reflects a high degree of aromatic condensation.

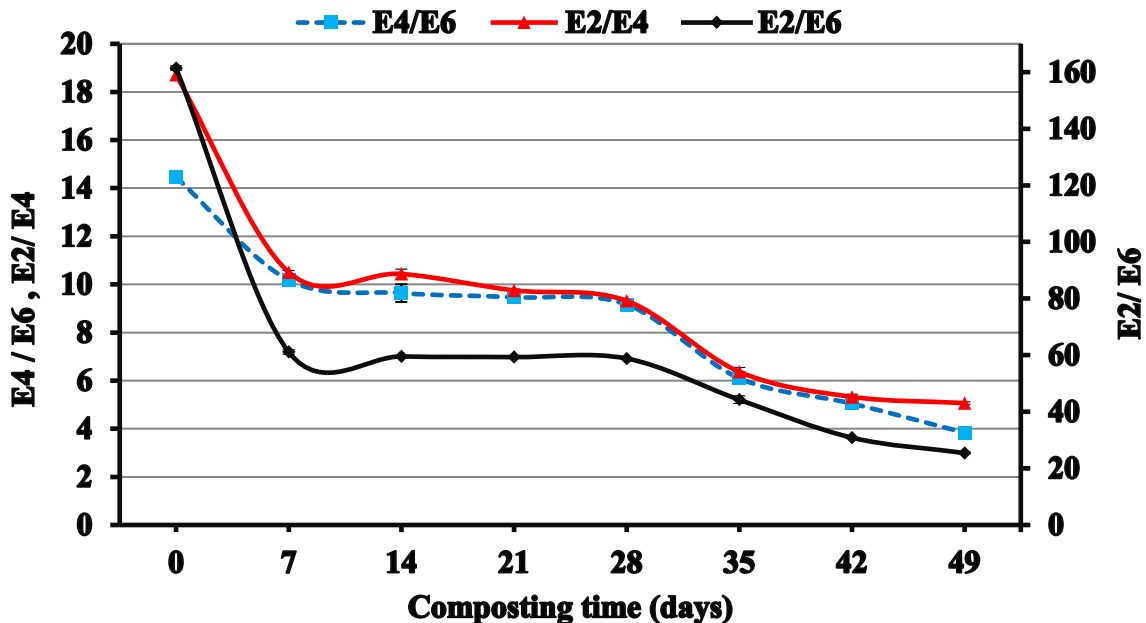


Figure 7. Evolution of the $E_{2/4}$ (280/472 nm), $E_{2/6}$ (280/664 nm), and $E_{4/6}$ (472/664 nm) ratios at different stages of composting DSSS-GW

3.1.6 FTIR spectroscopic analysis

FTIR spectrometry is a non-destructive qualitative or finger printing method used to characterize the principal classes of chemical groups that make up OM (Chen, 2003), in order to determine the changes seen in OM during composting (El Mezouari El Glauoi et al., 2018). The FTIR spectra thus derived are presented in **Figure 8**. A very wide band located at 3460 cm^{-1} was detected during the process that can be attributed to the stretching vibrations of OH in hydroxyl groups. El Mezouari El Glauoi et al. (2018) attributed this band to the hydrogenic vibrations of OH groups of alcohols and to phenols or to the OH of the carboxyl groups (COOH). The peak observed at 2950 cm^{-1} is due to methylene C-H aliphatic groups. The intensity of these bands decreases during composting, which is a good indication of the microbial oxidation of OM, especially the aliphatic compounds, during composting (El Fels et al., 2014).

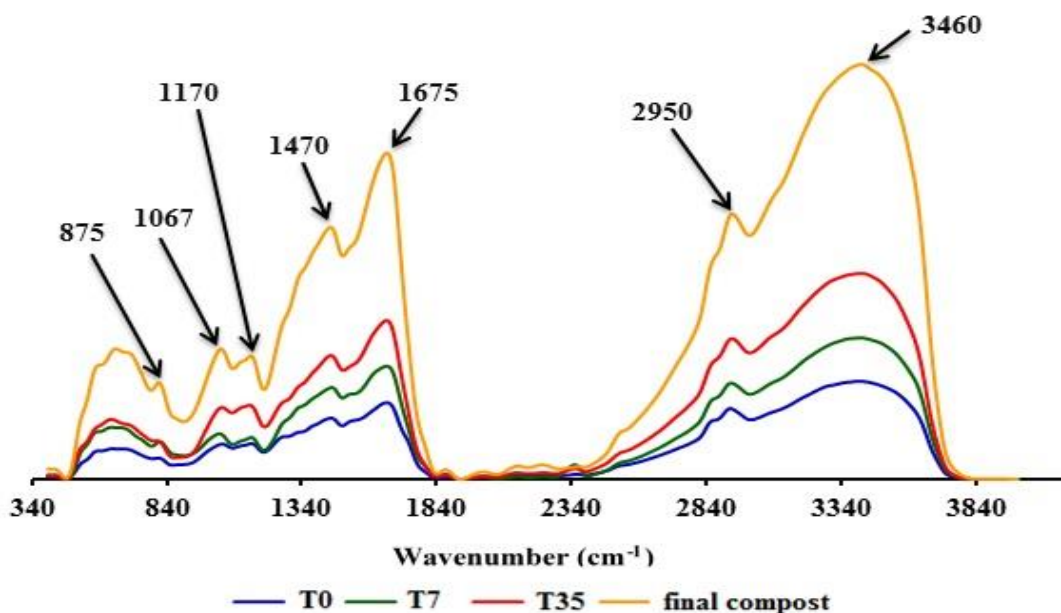


Figure 8. FTIR spectra of DSSS-GW at various stages of composting. T0: day 0; T7: day 7; T35: day 35; and final compost

The band located at approximately 1675 cm^{-1} showed an increase during composting. El Fels et al. (2014) attributed the region from $1750\text{--}1700\text{ cm}^{-1}$ to $\nu\text{C=O}$ stretching of the carboxyl group in its nonionized form, and the peaks that appear at approximately 1650 cm^{-1} to $\nu\text{C=O}$ of ionized carboxyl (COO^-). The bands at 1470 cm^{-1} are attributed to aromatic benzene compounds. Droussi et al. (2009) attributed the region from $1442\text{--}1472$ to C=C stretching vibrations arising from aromatic components. An increase in the intensity of the aromatic absorbance indicates progress in the humification process (El Fels et al., 2014; El Mezouari El Glaoui et al., 2018). The 1170 cm^{-1} band can be attributed to C-O vibrations. While analysing fulvic acids, Zhou et al. (2014) attributed the band at 1170 cm^{-1} to C-O stretching in alcohols, and El Fels et al. (2014) reported that the change in intensity of the observed bands at 1740 and 1155 cm^{-1} indicated the presence of a carboxyl functional group in the first, while that seen in the second is probably a characteristic of an ester bond. The 1067 cm^{-1} band remained constant during composting. The region at $1080\text{--}1030\text{ cm}^{-1}$ was attributed to the C-O stretching of polysaccharides or polysaccharide-like substances and the Si-O asymmetric stretch of silicate impurities (Filip and Bielek, 2002; Smidt et al., 2002). The band at 875 cm^{-1} could be attributed to the C-O out of plane vibration of carbonates. Reig et al. (2002) attributed the 875 cm^{-1} band to the C-O out-of-plane bending of carbonate.

3.2. Aerated static windrow with GORE® Cover membrane

3.2.1 Losses of organic matter and ash content

In a well-managed process, approximately 50 % of the biodegradable OM becomes fully-mineralized, mostly due to the degradation of protein, cellulose and hemicellulose, which are used by microorganisms as a source of energy (Chefetz et al., 1998).

During the composting process, OM is degraded progressively by microbes and converted to carbon dioxide, water, ammonia and new microbial biomass. The loss of OM at each time interval during composting was calculated in order to quantify the rate of OM mineralization (**Figure 9**). OM_{loss} increased sharply with time to 46.9 % within the first 14 days of composting (mesophilic and thermophilic phases) due to the greater availability of substances that are easily biodegradable by microorganisms. Then, it increased slowly during the cooling and maturation stages to reach 51.9 % at the end of composting. This was due to the depletion of easily biodegradable carbon and the synthesis reactions of new complex and polymerized organic compounds (humification), processes which prevail over mineralization during the maturation stage (Bernal et al., 2009). The expected losses of OM during composting are between 30 % and 60 %, and an OM loss >42 % is acceptable as a value for mature compost (Raj and Antil, 2011). According to this index, the compost matured in 14 days.

The higher OM_{loss} could be due to longer thermophilic periods (24 days) and higher temperature during composting because of this new composting technology. It has been found that high composting temperature accelerated the growth of thermophilic microorganisms for further biodegradation of lignin, cellulose and hemicellulose (Reyes-Torres et al., 2018).

Changes in ash content as a function of time is displayed in **Figure 9**. During composting, the ash content increased by 60.8 % after 30 days of composting. Several researchers have reported that increased ash content during composting resulted from the mineralization of OM by microbial degradation (Kalamdhad et al., 2009; Rihani et al., 2010; Tognetti et al., 2007) Thus, this parameter measured the degradation and mineralization of OM and indicated stabilization during the composting process (Hsu and Lo, 1999).

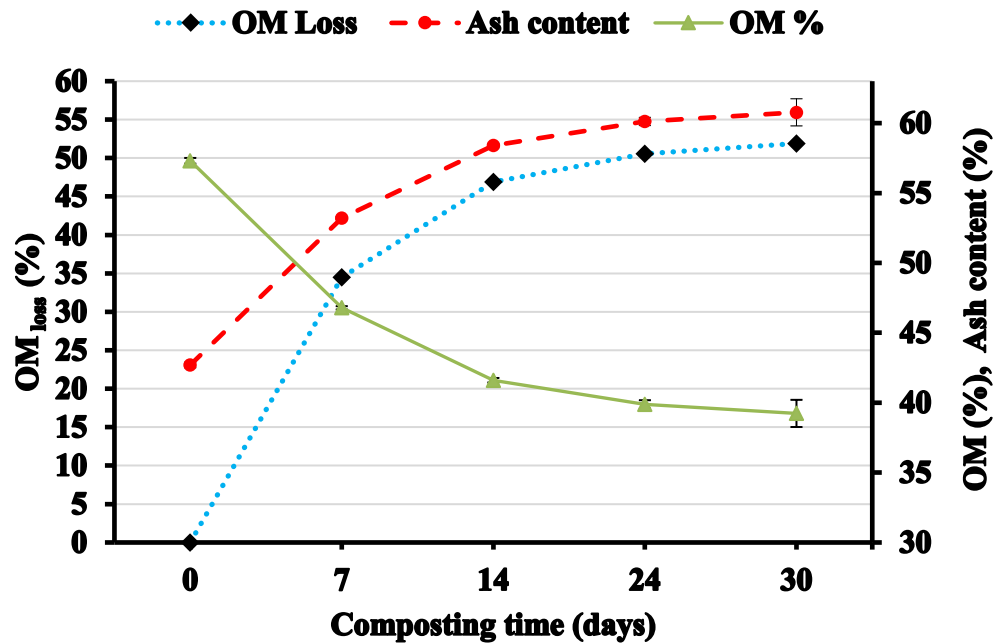


Figure 9. Evolution of OM_{loss} and ash content during GW composting

3.2.2 C/N ratio

The C/N ratio, which is normally used to determine compost stabilization, is expected to decrease with the progress of composting (Bernai et al., 1998). In this case, the C/N ratio decreased substantially as composting progressed and reached 11.4 at the end of the composting period (Figure 10). The present study results align closely to Azim et al. (2018), who confirmed that the C/N ratio gradually decreased with composting time. The reduction in C:N ratio was due to the loss of TC in the form of carbon dioxide and the related increase in the proportion of TN resulted from the intense biological oxidation of OM during the composting period (Azim et al., 2018) and the contribution of nitrogen fixing bacteria (Garcia et al., 1992).

In the present study, the C/N ratio of the final compost reached a value of 11.4, indicating that the compost became mature after 30 days of composting. Composting of pruning residues by conventional open windrow results in a final C/N ratio of 24.8 after 18 weeks of composting (Fontanive et al., 2004), which indicates failure to achieve maturity, possibly due to poor aeration conditions. This suggests that this new technology facilitates reaching a maturity in a shorter period

thanks to a forced bottom-up aeration system that improved aeration conditions, accelerated degradation and resulted in higher loss of OM. The results align with the findings of Guo et al. (2012), who demonstrated that higher rates of aeration lead to increased carbon loss.

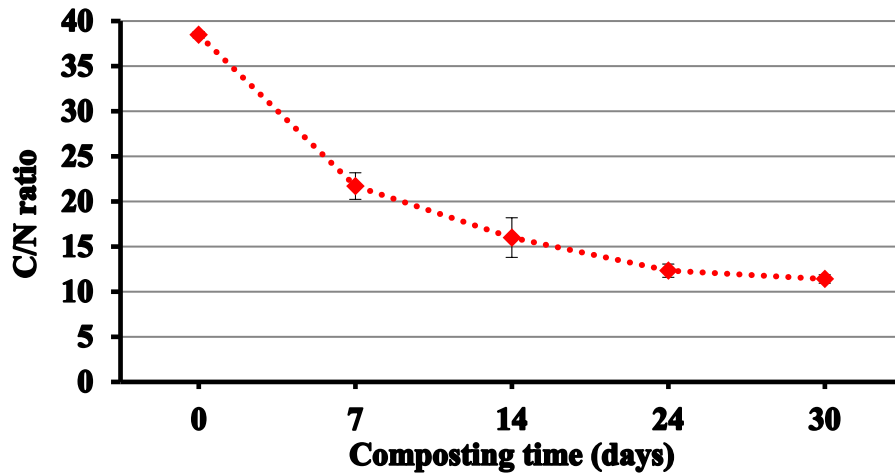


Figure 10. Evolution of the C/N ratio during GW composting

3.2.3 $\text{NH}_4^+/\text{NO}_3^-$ ratio

Nitrification index ($\text{NH}_4^+/\text{NO}_3^-$ ratio) has also been used as an indicator to estimate the compost maturity with values of <1 (Jouraiphy et al., 2005) or even <0.16 (Bernai et al., 1998) denoting a mature compost. The $\text{NH}_4^+/\text{NO}_3^-$ ratio (**Figure 11**) shows a gradual decline until the end of composting, reaching a final value of 0.1, so indicating an effective nitrification process occurring during composting and the achievement of a mature compost after 30 days. Differently, during composting of pruning residues using conventional open windrows an acceptable maturity index value was recorded after 18 weeks (Fontanive et al., 2004). Thus, the new technology results in a shortened the period to reach maturity due to improved aeration conditions by forced bottom-up aeration that led to increase of nitrification process (Hao and Chang, 2001).

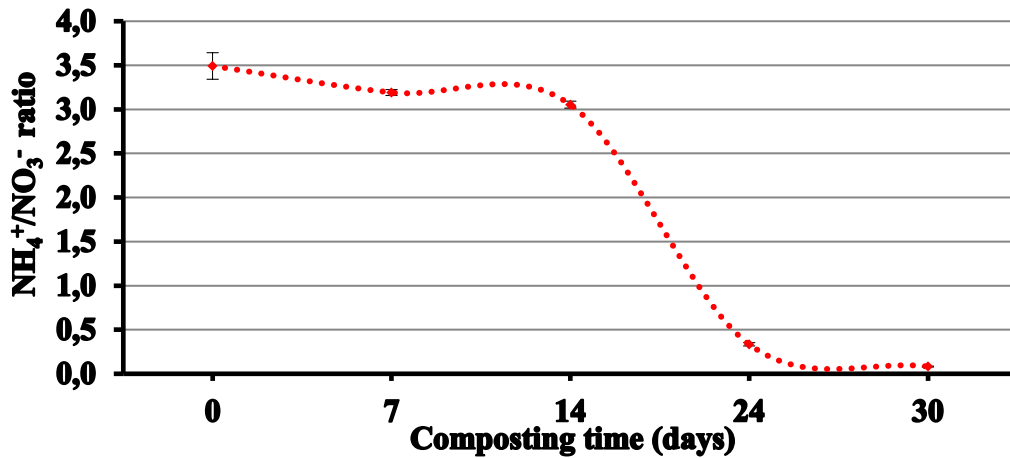


Figure 11. Evolution of the $\text{NH}_4^+/\text{NO}_3^-$ ratio during GW composting

3.2.4 Cation exchange capacity

Several studies have found a correlation between the CEC and degree of OM degradation (Azim et al. 2018; Senesi 1989), thus CEC is considered an important indicator of compost maturity and indicates the ability of compost to retain nutrients (Senesi 1989). The CEC value rose substantially over time from $37.1 \text{ cmol kg}^{-1}$ to $160.1 \text{ cmol kg}^{-1}$ after 30 days of composting (**Figure 12**), as expected by the increasing temperature that accelerated the oxidation and humification of OM, so increasing the formation of ionized carboxyl and phenolic functional groups which contribute to enhance CEC values and nutrient conservation (Senesi and Plaza, 2007). According to Harada and Inoko (1980b), the CEC of the final compost should be $> 60 \text{ cmol kg}^{-1}$ to be considered mature. The higher CEC value at the end of the composting period increased the capacity of the compost to maintain nutrients and increased the GI (Ameen et al., 2016). In the current study, the CEC value of the final product was $160.1 \text{ cmol kg}^{-1}$, which indicated that the compost was mature (Senesi, 1989).

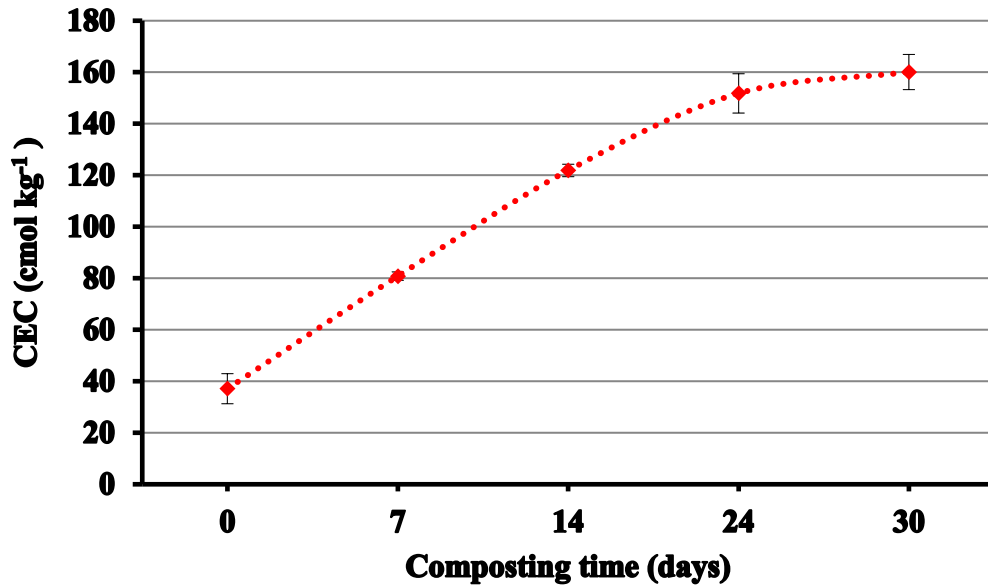


Figure 12. CEC evolution during GW composting

3.2.5 $E_{4/6}$

Another important index of compost maturity is the humification degree of OM, i.e. the generation of humic-like substances (Senesi, 1989). **Figure. 13** depicts the evolution of the absorbance ratios $E_{4/6}$ (the absorbance ratio of wavelength 465 and 665 nm), a traditional indicator of the degree of polymerization of OM and an inverse index of molecular size and aromaticity (Guo et al., 2019).

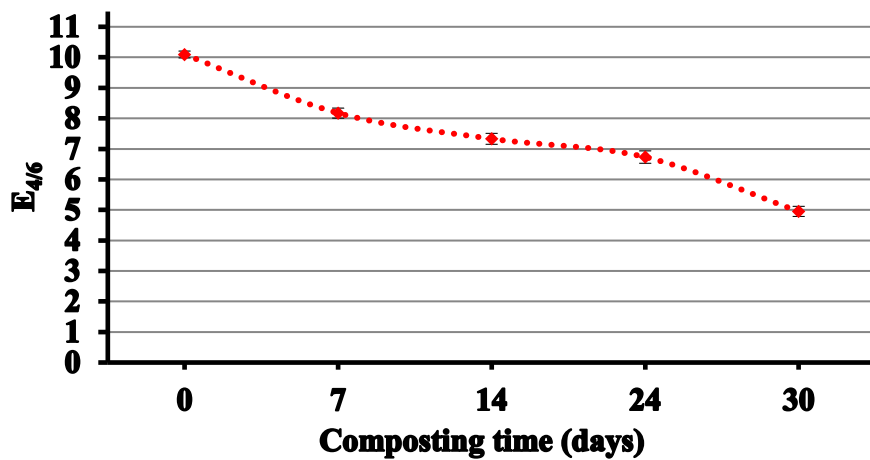


Figure 13. Changes in $E_{4/6}$ ratio during GW composting

High values of $E_{4/6}$ ratio at the beginning of composting indicate the presence of smaller sized organic molecules and/or high proportions of aliphatic structures (Guo et al., 2019). As composting time progresses, the $E_{4/6}$ ratio decreased markedly suggesting a progressive condensation of aromatic OM constituents, mineralization of carbohydrates, and oxidization of phenolic compounds and bound to methoxyl groups and/or aliphatic side chains in humic substance; this demonstrated an increasing OM humification (Guo et al., 2019). At the end of composting, the attainment of a value of $E_{4/6}$ lower than 5 indicated an adequate degree of OM maturity in a stable compost, which similar to native humified OM in soil (Chen et al., 1977).

3.2.6 FTIR spectroscopic analysis

FTIR spectroscopy analysis is widely used to characterize the principal classes of chemical groups that make up OM and determine changes in the OM decomposition in waste materials during composting (Lü et al., 2018). The FTIR spectra are presented in **Figure 14**.

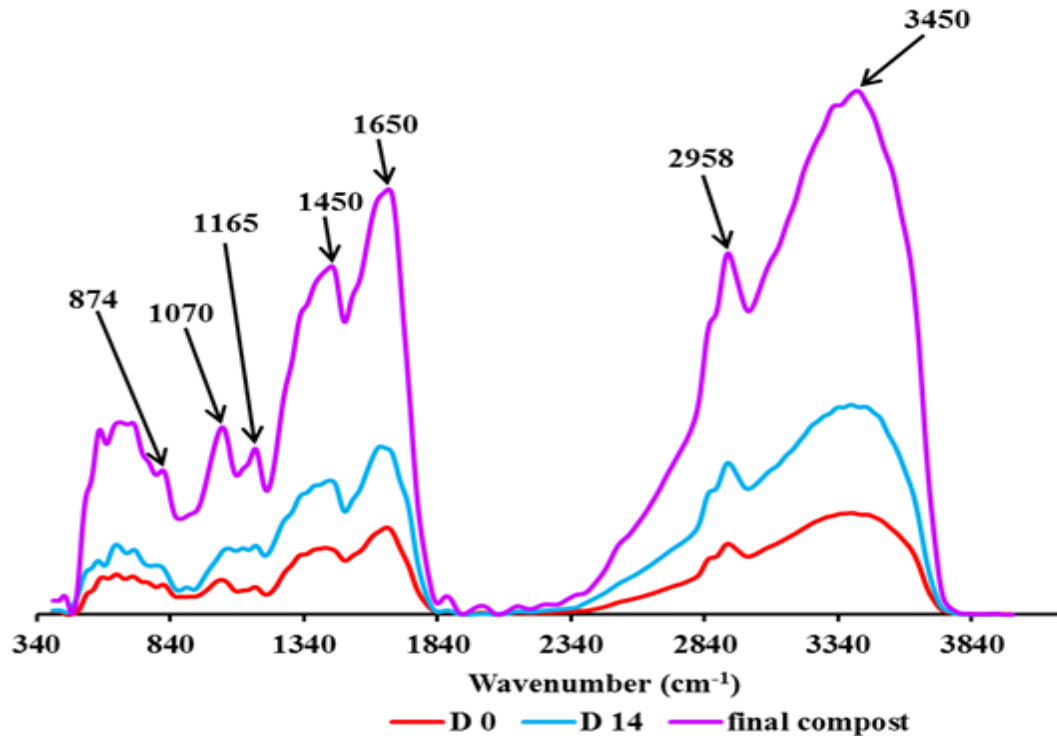


Figure 14. FTIR spectra of GW at various stages of composting (D 0: day 0, D 14: day 14, and final compost)

A very broad band from 3700 to 2800 cm^{-1} and centered on 3450 cm^{-1} was detected during the process; this band can be attributed to stretching vibrations of OH hydroxyl groups. Soobhany et al. (2017) attributed this band to the hydrogenic vibrations of the OH groups of alcohols and to the phenols or the OH of the carboxyl groups (COOH). The 3000-2800 cm^{-1} region reflects the hydrophobic properties of the aliphatic OM (El Fels et al., 2015, 2014).

The very strong peak observed at 2958 cm^{-1} is due the $\nu\text{C-H}$ methyl, and methylene C-H aliphatic groups. The intensity of the bands at 2958 cm^{-1} decreased during composting and was consistent with the microbial degradation of aliphatic carbon chains and peptidic compounds, this was an indicator of the OM degradation during the composting process and can be used to evaluate the composting processes (Amir et al., 2005).

A distinctively sharp peak at band 1650 cm^{-1} increased during composting. This band is associated with the absorption of aromatic C=C bonds (Smith, 1998) and to stretching vibration of the C=O group that is part of carboxylic acids, ketones, and aldehydes (Kaiser and Ellerbrock, 2005). The decrease in peak at 2958 cm^{-1} , together with the appreciable increase in the intensity at bands 1650 cm^{-1} , were also observed by FTIR spectroscopy previous studies (El Fels et al., 2014; Hsu and Lo, 1999; Huang et al., 2006; Makni et al., 2010). These changes demonstrated that easily degradable OM components, such as aliphatic and peptidic compounds, are oxidized, and as a result, more aromatic compounds are contained in the mature compost.

The bands at 1450 cm^{-1} are attributed to aromatic benzene compounds. Droussi et al. (2009) attributed the region from 1442-1472 to C=C stretching vibrations from aromatic components. The 1165 cm^{-1} band could be attributed to C-O-C stretching. Ouatmane et al. (2000) and Wu et al. (2011) attributed the 1165 cm^{-1} band to C-O-C stretching which could be used as an indicator of the biodegradation process. The 1070 cm^{-1} band was constant during composting. The region at 1080-1030 cm^{-1} was attributed to the C-O stretching of polysaccharides or polysaccharide-like substances, and the Si-O asymmetric stretch of silicate impurities (Filip and Bielek, 2002; Senesi et al., 2003). El Fels et al. (2015) attributed this band to the mineral phase provided by the sludge. The band at 874 cm^{-1} could be attributed to calcite.

3.3. Comparison of FTIR spectra

The FTIR spectra of DSSS-GW and GW collected during and at the end of composting (**Figures 8 and 14**) are qualitatively similar to one another. This suggests that the relatively new composting technologies that are ELS with GORE® Cover membrane and ASW with GORE® Cover membrane impacts the stabilization of OM and compost maturation.

3.4. Characteristics of the final compost

Compost product can be safely used as organic fertilizer or conditioner once it is mature or stable and does not present toxicity to plant growth (Sharma et al., 2019). **Table 1** shows the main physico-chemical properties of the final composts obtained by using ELS with GORE® Cover membrane and ASW with GORE® Cover membrane. The final compost product satisfied the threshold levels established in the literature for common maturation indices, suggesting that it can be used as an organic fertilizer. These findings indicated that composting was carried out successfully under optimized conditions.

Table 1. Summary of the characteristics of final compost obtained by using ELS with GORE® Cover membrane and ASW with GORE® Cover membrane, in comparison with guidelines for acceptable quality of compost

Physico-chemical properties	ELS compost	ASW compost	Threshold values	References
pH	7.1 ± 0.1	7.1 ± 0.0	7.1-7.7	Forster et al. (1993)
EC (mS cm ⁻¹)	3.0 ± 0.0	3.0 ± 0.1	< 4	Lasaridi et al. (2006)
BD _{wet} (g cm ⁻³)	0.6 ± 0.0	0.9 ± 0.1	≥ 0.4	Abad et al. (2001)
BD _{dry} (g cm ⁻³)	0.4 ± 0.0	0.8 ± 0.0		
OM %	37.5 ± 1.0	38.8 ± 0.5	33.3–55.4	Fricke and Vogtmann (1994)
C/N	6.6 ± 0.5	11.4 ± 0.4	< 20, preferable < 10	Bernai et al. (1998)
CEC (cmol kg ⁻¹)	171.9 ± 2.8	161.7 ± 5.8	> 60	Harada and Inoko (1980a)
TC (%)	20.2 ± 0.0	20.9 ± 0.3	> 20	Lasaridi et al. (2006)
TN (%)	3.1 ± 0.2	1.8 ± 0.1	≥ 1	Cheng et al. (2013)
TP (%)	1.7 ± 0.0	0.7 ± 0.1	0.6-1.7	Fricke and Vogtmann (1994)
TK (%)	1.5 ± 0.0	1.5 ± 0.1	1-1.5	Anthonis (1994)
WSC (g kg ⁻¹)	3.9 ± 0.9	8.8 ± 0.8	≤ 10	Hue and Liu (1995)
			≤ 4	Zmora-Nahum et al. (2005)
			< 17	Bernai et al. (1998)
NH ₄ ⁺ (mg kg ⁻¹)	350.2 ± 9.9	73.4 ± 7.4	< 400	Bernai et al. (1998)
NH ₄ ⁺ /NO ₃ ⁻	0.1 ± 0.0	0.1 ± 0.0	< 0.16	Bernai et al. (1998)
Ca (mg kg ⁻¹)	43203 ± 238	30107 ± 105	≥ 12000	Hungarian law of fertilizers (2006)
Na (mg kg ⁻¹)	434 ± 10	210 ± 24	-	
Mg (mg kg ⁻¹)	6953 ± 18	6734 ± 28	≥ 5000	Hungarian law of fertilizers (2006)
Cr (mg kg ⁻¹)	56.6 ± 0.8	80.4 ± 1.4	≤ 100	Hungarian law of fertilizers (2006)
Cu (mg kg ⁻¹)	144 ± 1	100 ± 3	≤ 300	Hungarian law of fertilizers (2006)
Fe (mg kg ⁻¹)	22248 ± 71	13648 ± 135	-	
Mn (mg kg ⁻¹)	327 ± 1	362 ± 3	-	
Ni (mg kg ⁻¹)	19.8 ± 0.2	21.1 ± 0.4	≤ 50	Hungarian law of fertilizers (2006)
Zn (mg kg ⁻¹)	621 ± 2	70.0 ± 0.4	-	
Cd (mg kg ⁻¹)	1.68 ± 0.03	1.79 ± 0.17	≤ 2	Hungarian law of fertilizers (2006)
Co (mg kg ⁻¹)	4.63 ± 0.04	2.54 ± 0.25	≤ 50	Hungarian law of fertilizers (2006)
Pb (mg kg ⁻¹)	13.5 ± 0.2	11.7 ± 0.4	≤ 100	Hungarian law of fertilizers (2006)

(-) – there is no threshold in 36/2006. (V. 18.) FVM regulation

4. NEW SCIENTIFIC RESULTS

1-The FTIR spectra showed that the chemical composition of the OM, while composting using ELS with GORE® Cover membrane and ASW with GORE® Cover membrane is characterized by a decrease in methylene C-H aliphatic groups and enrichment of aromatic compounds, which is confirmed by drastic decreases in $E_{2/4}$, $E_{2/6}$, and $E_{4/6}$ ratios. This indicates a rise in the humification degree, stabilization of the final compost, and confirms the efficiency of composting.

2-The FTIR spectra of DSSS-GW and GW collected during and at the end of composting are qualitatively similar to one another. This suggests that the relatively new composting technologies that are ELS with GORE® Cover membrane and ASW with GORE® Cover membrane impacts the stabilization of OM and compost maturation.

3-It is recommended to shorten the composting period during composting using ELS composting technology with GORE® Cover membrane and ASW with GORE® Cover membrane to 28 days and 14 days, respectively, because the DSSS-GW and GW compost product is considered to mature at 28th and 14th day, respectively, as per loss of OM maturity index >42 %.

4-In the ELS composting process with GORE® Cover membrane and ASW with GORE® Cover membrane, the DSSS-GW and GW compost satisfied the maturity by the day 49th and 30th, respectively, based on the following maturity index namely: $\text{NH}_4^+/\text{NO}_3^-$ ratio, CEC value, and C/N ratio. This suggests that this new technology can effectively ensure compost maturity in a shorter time frame because of improved aeration conditions and oxygen flow throughout the entire composting vessel using forced bottom-up aeration that enhances the decomposition of OM.

5. CONCLUSIONS AND RECOMMENDATIONS

Composting is one of the most effective integrated waste management approach for recycling organic waste and generating a useful product. There are various composting methods in terms of potency of stability and duration of degradation. However, traditional composting technology is generating foul smells, produces immature compost, and time consuming. An ELS and ASW along with GORE® Cover membrane and an air-floor aeration system are relatively new industrial-scale composting technologies that previously have not yet explored. Therefore, the aim of this research study was to evaluate the effectiveness of these new composting technologies. The composting process was monitored in terms of changes in the physico-chemical properties, UV-visible spectra, and FTIR spectra.

It is observed that the ELS composting process with GORE® Cover membrane and aerated static windrow with GORE® Cover membrane is an effective waste management option. The final compost produced by these two composting technologies satisfied the threshold levels established in the literature regarding its use as an organic fertilizer. These findings indicated that composting was performed successfully under optimized conditions and that these relatively new composting technologies are a suitable choice for converting the organic waste into a useful product.

Data from the FTIR spectra and UV-visible spectroscopic analysis showed that the chemical composition of OM during composting using ELS with GORE® Cover membrane and ASW with GORE® Cover membrane, is characterized by enrichment in aromatic structures and a degradation of both aliphatic and peptide structures. These changes suggested that there was an increase in humification degree, stabilization of the final compost, and confirmed the efficiency of composting. The compost obtained, which included a substantial richness of stabilized OM, can be considered as a suitable soil amendment or organic fertilizer without risking the soil–plant system. Future studies should focus on examining enzymatic activities such as dehydrogenase, protease, β -glucosidase, arylsulphatase, and phosphatases during composting as indicators of microbial action. The bacterial dynamic and community structure should also be evaluated using next generation sequencing techniques that may be a powerful tool for designing effective composting systems.

6. BIBLIOGRAPHY (LIST OF WORKS CONSULTED)

Peer-reviewed articles with impact factor

1-Q2; impact factor: 1.087

Al-Alawi, M., El Fels, L., Benjreid, R., Szegi, T., Hafidi, M., Simon, B., Gulyás, M., 2020. Evaluation of the performance of encapsulated lifting system composting technology with a GORE(R) cover membrane: Physico-chemical properties and spectroscopic analysis. *Environmental Engineering Research* 25, 299–308. <https://doi.org/10.4491/eer.2019.061>

2-Q2; impact factor:1.54

Al-Alawi, M., Szegi, T., El Fels, L., Hafidi, M., Simon, B., Gulyás, M., 2019. Green waste composting under GORE(R) cover membrane at industrial scale: physico-chemical properties and spectroscopic assessment. *International Journal of Recycling of Organic Waste in Agriculture* 8, 385–397. <https://doi.org/10.1007/s40093-019-00311-w>

3-Q3; impact factor: 0.869

Benjreid, R., Matouq, M., Al-Alawi, M., György, F., 2018. Kinetics study of the ability of compost material for removing Cu²⁺ from wastewater. *Global Nest Journal* 20, 610–619. <https://doi.org/10.30955/gnj.002865>

Peer-reviewed articles in English

Al-Alawi, M., Szegi, T., Simon, B., Gulyás, M., 2019c. Investigate biotransformation of green waste during composting by aerated static windrow with GORE (R) cover membrane technology. *Jordanian Journal of Engineering and Chemical Industries* 2, 32–40.

Conference abstracts in English

Al-Alawi, M., Simon, B., Szegi, T., Gulyás, M., 2019a. Aerated static windrow with a semipermeable film as a promising composting technology, in: 8th ISMOM (International Symposium on Interactions of Soil Minerals with Organic Components and Microorganisms), 23-28 June, 2019, Seville-Spain. p. 170.

Al-Alawi, M., Simon, B., Szegi, T., Gulyás, M., Benjreid, R., Andras, S., 2018. Comparative evaluation of different composting technologies and effects on the quality of final composts and soil–plant system, in: *Soil – Waste – Water Workshop “Reusing Wastewater and Solid Residues in Agriculture”*, 26– 28 March 2018, Landau-Germany. p. 58.

Gulyás, M., Al-Alawi, M., Simon, B., Füleky, G., 2018. Possible agricultural effects of combined application of digestate and biochar, in: *Soil – Waste – Water Workshop “Reusing Wastewater and Solid Residues in Agriculture”*, 26– 28 March 2018, Landau-Germany. p. 50.

Benjreid, R., Füleky, G., Al-Alawi, M., 2018. Removal of Cu, Cd and Cd from wastewater by compost application, in: *Soil – Waste – Water Workshop “Reusing Wastewater and Solid Residues in Agriculture”*, 26– 28 March 2018, Landau-Germany. p. 22.

7. REFERENCES

- Abad, M., Noguera, P., Burés, S. (2001). National inventory of organic wastes for use as growing media for ornamental potted plant production: case study in Spain. *Bioresource Technology* 77, 197–200. [https://doi.org/10.1016/S0960-8524\(00\)00152-8](https://doi.org/10.1016/S0960-8524(00)00152-8)
- Ameen, A., Ahmad, J., Raza, S. (2016). Determination of CEC to evaluate the quality and maturity of compost prepared by using municipal solid waste. *International Journal of Scientific and Research Publications* 6, 42–44.
- Amir, S., Hafidi, M., Merlina, G., Revel, J.-C. (2005). Structural characterization of fulvic acids during composting of sewage sludge. *Process Biochemistry* 40, 1693–1700. <https://doi.org/10.1016/j.procbio.2004.06.037>
- Amritha, P.K., Kumar, P.P.A. (2019). Productive landscapes as a sustainable organic waste management option in urban areas. *Environment, Development and Sustainability* 21, 709–726. <https://doi.org/10.1007/s10668-017-0056-0>
- Anthonis, G. (1994). Standards for organic fertilizer agro-chemicals news-in-brief (ESCAP/FAO/UNIDO).
- Atalia, K.R., Buha, D.M., Bhavsar, K.A., Shah, N.K. (2015). A review on composting of municipal solid waste. *IOSR Journal of Environmental Science, Toxicology and Food Technology* 9, 20–29. <https://doi.org/10.9790/2402-09512029>
- Azim, K., Soudi, B., Boukhari, S., Perissol, C., Roussos, S., Thami Alami, I. (2018). Composting parameters and compost quality: a literature review. *Organic Agriculture* 8, 141–158. <https://doi.org/10.1007/s13165-017-0180-z>
- Bernai, M.P., Paredes, C., Sánchez-Monedero, M.A., Cegarra, J. (1998). Maturity and stability parameters of composts prepared with a wide range of organic wastes. *Bioresource Technology* 63, 91–99. [https://doi.org/10.1016/S0960-8524\(97\)00084-9](https://doi.org/10.1016/S0960-8524(97)00084-9)
- Bernal, M.P., Alburquerque, J.A., Moral, R. (2009). Composting of animal manures and chemical criteria for compost maturity assessment: a review. *Bioresource Technology* 100, 5444–5453. <https://doi.org/10.1016/j.biortech.2008.11.027>
- Bernal, M.P., Sommer, S.G., Chadwick, D., Qing, C., Guoxue, L., Michel, F.C. (2017). Current approaches and future trends in compost quality criteria for agronomic, environmental, and human health benefits, in: *Advances in Agronomy*. pp. 143–233. <https://doi.org/10.1016/bs.agron.2017.03.002>
- Cesaro, A., Belgiorno, V., Guida, M. (2015). Compost from organic solid waste: quality assessment and European regulations for its sustainable use. *Resources, Conservation and Recycling* 94, 72–79. <https://doi.org/10.1016/j.resconrec.2014.11.003>
- Chefetz, B., Adani, F., Genevini, P., Tambone, F., Hadar, Y., Chen, Y. (1998). Humic-acid transformation during composting of municipal solid waste. *Journal of Environment Quality* 27, 794. <https://doi.org/10.2134/jeq1998.00472425002700040011x>

- Chen, Y. (2003). Nuclear magnetic resonance, infra-red and pyrolysis: application of spectroscopic methodologies to maturity determination of composts. *Compost Science & Utilization* 11, 152–168. <https://doi.org/10.1080/1065657X.2003.10702121>
- Chen, Y., Senesi, N., Schnitzer, M. (1977). Information provided on humic substances by E4/E6 ratios. *Soil Science Society of America Journal* 41, 352–358. <https://doi.org/10.2136/sssaj1977.03615995004100020037x>
- Cheng, K.H., Lu, M.F., Huang, M.C., Chou, Y.J., Lin, J.J.M. (2013). Assessment of degree of maturity of compost produced by different kitchen waste composting methods. *Advanced Materials Research* 652–654, 1642–1651. <https://doi.org/10.4028/www.scientific.net/amr.652-654.1642>
- de Bertoldi, M., Vallini, G., Pera, A. (1983). The biology of composting: a review. *Waste Management & Research* 1, 157–176. <https://doi.org/10.1177/0734242X8300100118>
- Droussi, Z., D'orazio, V., Provenzano, M.R., Hafidi, M., Ouattmane, A. (2009). Study of the biodegradation and transformation of olive-mill residues during composting using FTIR spectroscopy and differential scanning calorimetry. *Journal of Hazardous Materials* 164, 1281–1285. <https://doi.org/10.1016/j.jhazmat.2008.09.081>
- El Fels, L., Zamama, M., El Asli, A., Hafidi, M. (2014). Assessment of biotransformation of organic matter during co-composting of sewage sludge-lignocelulosic waste by chemical, FTIR analyses, and phytotoxicity tests. *International Biodeterioration & Biodegradation* 87, 128–137. <https://doi.org/10.1016/j.ibiod.2013.09.024>
- El Fels, L., Zamama, M., Hafidi, M. (2015). Advantages and limitations of using FTIR spectroscopy for assessing the maturity of sewage sludge and olive oil waste co-composts, in: *Biodegradation and Bioremediation of Polluted Systems - New Advances and Technologies*. InTech. <https://doi.org/10.5772/60943>
- El Mezouari El Glauoi, G., El Hayany, B., El Fels, L., El Faiz, A., Ezzariai, A., Rihani, M., Lebrihi, A., Bekkaoui, F., Hafidi, M. (2018). Physico-chemical and spectroscopy assessment of sludge biodegradation during semi-industrial composting under semi-arid climate. *Waste and Biomass Valorization* 1–12. <https://doi.org/10.1007/s12649-018-0442-3>
- Filip, Z., Bielek, P. (2002). Susceptibility of humic acids from soils with various contents of metals to microbial utilization and transformation. *Biology and Fertility of Soils* 36, 426–433. <https://doi.org/10.1007/s00374-002-0559-0>
- Fontanive, V., Effron, D., Tortarolo, F., Arrigo, N. (2004). Evaluation of parameters during composting of two contrasting raw materials. *Compost Science and Utilization* 12, 268–272. <https://doi.org/10.1080/1065657X.2004.10702191>
- Forster, J.C., Zech, W., Wurdinger, E. (1993). Comparison of chemical and microbiological methods for the characterization of the maturity of composts from contrasting sources. *Biology and Fertility of Soils* 16, 93–99. <https://doi.org/10.1007/BF00369409>
- Fricke, K., Vogtmann, H. (1994). Compost quality: physical characteristics, nutrient content, heavy metals and organic chemicals. *Toxicological & Environmental Chemistry* 43, 95–114. <https://doi.org/10.1080/02772249409358021>

- García-Sánchez, M., Taušnerová, H., Hanč, A., Tlustoš, P. (2017). Stabilization of different starting materials through vermicomposting in a continuous-feeding system: changes in chemical and biological parameters. *Waste Management* 62, 33–42. <https://doi.org/10.1016/j.wasman.2017.02.008>
- Garcia, C., Hernandez, T., Costa, F., Ayuso, M. (1992). Evaluation of the maturity of municipal waste compost using simple chemical parameters. *Communications in Soil Science and Plant Analysis* 23, 1501–1512. <https://doi.org/10.1080/00103629209368683>
- González, I., Robledo-Mahón, T., Silva-Castro, G.A., Rodríguez-Calvo, A., Gutiérrez, M.C., Martín, M.Á., Chica, A.F., Calvo, C. (2016). Evolution of the composting process with semi-permeable film technology at industrial scale. *Journal of Cleaner Production* 115, 245–254. <https://doi.org/10.1016/j.jclepro.2015.12.033>
- Guo, R., Li, G., Jiang, T., Schuchardt, F., Chen, T., Zhao, Y., Shen, Y. (2012). Effect of aeration rate, C/N ratio and moisture content on the stability and maturity of compost. *Bioresource Technology* 112, 171–178. <https://doi.org/10.1016/j.biortech.2012.02.099>
- Guo, X. xia, Liu, H. tao, Wu, S. biao. (2019). Humic substances developed during organic waste composting: formation mechanisms, structural properties, and agronomic functions. *Science of the Total Environment* 662, 501–510. <https://doi.org/10.1016/j.scitotenv.2019.01.137>
- Hao, X., Chang, C. (2001). Gaseous NO, NO₂, NH₃ loss during cattle feedlot manure composting. *Phyton* 41, 81–94.
- Harada, Y., Inoko, A. (1980a). Relationship between cation-exchange capacity and degree of maturity of city refuse composts. *Soil Science and Plant Nutrition* 26, 353–362. <https://doi.org/10.1080/00380768.1980.10431220>
- Harada, Y., Inoko, A. (1980b). The measurement of the cation-exchange capacity of composts for the estimation of the degree of maturity. *Soil Science and Plant Nutrition* 26, 127–134. <https://doi.org/10.1080/00380768.1980.10433219>
- Hsu, J.H., Lo, S.L. (1999). Chemical and spectroscopic analysis of organic matter transformations during composting of pig manure. *Environmental Pollution* 104, 189–196. [https://doi.org/10.1016/S0269-7491\(98\)00193-6](https://doi.org/10.1016/S0269-7491(98)00193-6)
- Huang, G.F., Wong, J.W.C., Wu, Q.T., Nagar, B.B. (2004). Effect of C/N on composting of pig manure with sawdust. *Waste Management* 24, 805–813. <https://doi.org/10.1016/j.wasman.2004.03.011>
- Huang, G.F., Wu, Q.T., Wong, J.W.C., Nagar, B.B. (2006). Transformation of organic matter during co-composting of pig manure with sawdust. *Bioresource Technology* 97, 1834–1842. <https://doi.org/10.1016/j.biortech.2005.08.024>
- Hue, N.V., Liu, J. (1995). Predicting compost stability. *Compost Science & Utilization* 3, 8–15. <https://doi.org/10.1080/1065657X.1995.10701777>
- Hungarian law of fertilizers. (2006). in: 36/2006. (V. 18.) FVM Order about the Licensing, Storage, Marketing and Utilisation of Agricultural Yield Increasing Materials. *Magyar Közlöny*

(Hungarian Official Gazette). 59. pp. 4784–4808.

- Jouraihy, A., Amir, S., El Gharous, M., Revel, J.-C., Hafidi, M. (2005). Chemical and spectroscopic analysis of organic matter transformation during composting of sewage sludge and green plant waste. *International Biodeterioration & Biodegradation* 56, 101–108. <https://doi.org/10.1016/j.ibiod.2005.06.002>
- Kacprzak, M., Neczaj, E., Fijałkowski, K., Grobelak, A., Grosser, A., Worwag, M., Rorat, A., Brattebo, H., Almås, Å., Singh, B.R. (2017). Sewage sludge disposal strategies for sustainable development. *Environmental Research* 156, 39–46. <https://doi.org/10.1016/j.envres.2017.03.010>
- Kaiser, M., Ellerbrock, R.H. (2005). Functional characterization of soil organic matter fractions different in solubility originating from a long-term field experiment. *Geoderma* 127, 196–206. <https://doi.org/10.1016/j.geoderma.2004.12.002>
- Kalamdhad, A.S., Singh, Y.K., Ali, M., Khwairakpam, M., Kazmi, A.A. (2009). Rotary drum composting of vegetable waste and tree leaves. *Bioresource Technology* 100, 6442–6450. <https://doi.org/10.1016/j.biortech.2009.07.030>
- Komilis, D.P., Ham, R.K., Park, J.K. (2004). Emission of volatile organic compounds during composting of municipal solid wastes. *Water Research* 38, 1707–1714. <https://doi.org/10.1016/j.watres.2003.12.039>
- Lahsaini, S., Aguelmous, A., El Fels, L., Idrissi, L., Souabi, S., Zamama, M., Hafidi, M. (2017). Assessment of biotransformation of sludge from vegetable oil refining by composting. *Compost Science & Utilization* 25, 130–140. <https://doi.org/10.1080/1065657X.2016.1245639>
- Lasaridi, K., Protopapa, I., Kotsou, M., Pilidis, G., Manios, T., Kyriacou, A. (2006). Quality assessment of composts in the Greek market: the need for standards and quality assurance. *Journal of Environmental Management* 80, 58–65. <https://doi.org/10.1016/j.jenvman.2005.08.011>
- Lax, A., Roig, A., Costa, F. (1986). A method for determining the cation-exchange capacity of organic materials. *Plant and Soil* 94, 349–355. <https://doi.org/10.1007/BF02374329>
- Lü, F., Shao, L.-M., Zhang, H., Fu, W.-D., Feng, S.-J., Zhan, L.-T., Chen, Y.-M., He, P.-J. (2018). Application of advanced techniques for the assessment of bio-stability of biowaste-derived residues: a minireview. *Bioresource Technology* 248, 122–133. <https://doi.org/10.1016/j.biortech.2017.06.045>
- Ma, S., Sun, X., Fang, C., He, X., Han, L., Huang, G. (2018). Exploring the mechanisms of decreased methane during pig manure and wheat straw aerobic composting covered with a semi-permeable membrane. *Waste Management* 78, 393–400. <https://doi.org/10.1016/j.wasman.2018.06.005>
- Ma, S., Sun, X., Han, L., Li, R., Uwe, S., Huang, G. (2017). Reduction of ammonia emission during membrane-covered aerobic composting. *Transactions of the Chinese Society for Agricultural Machinery* 48, 334–349. <https://doi.org/j.issn.1000-1298.2017.11.042>
- Makni, H., Ayed, L., Ben Khedher, M., Bakhrouf, A. (2010). Evaluation of the maturity of organic waste composts. *Waste Management and Research* 28, 489–495.

<https://doi.org/10.1177/0734242X09350786>

- Mata-Alvarez, J., Macé, S., Llabrés, P. (2000). Anaerobic digestion of organic solid wastes. An overview of research achievements and perspectives. *Bioresource Technology* 74, 3–16. [https://doi.org/10.1016/S0960-8524\(00\)00023-7](https://doi.org/10.1016/S0960-8524(00)00023-7)
- Meng, L., Li, W., Zhang, S., Wu, C., Lv, L. (2017). Feasibility of co-composting of sewage sludge, spent mushroom substrate and wheat straw. *Bioresource Technology* 226, 39–45. <https://doi.org/10.1016/j.biortech.2016.11.054>
- Mor, S., Ravindra, K., Dahiya, R.P., Chandra, A. (2006). Leachate characterization and assessment of groundwater pollution near municipal solid waste landfill site. *Environmental Monitoring and Assessment* 118, 435–456. <https://doi.org/10.1007/s10661-006-1505-7>
- Narayana, T. (2009). Municipal solid waste management in India: from waste disposal to recovery of resources? *Waste Management* 29, 1163–1166. <https://doi.org/10.1016/j.wasman.2008.06.038>
- Ngoc, U.N., Schnitzer, H. (2009). Sustainable solutions for solid waste management in Southeast Asian countries. *Waste Management* 29, 1982–1995. <https://doi.org/10.1016/j.wasman.2008.08.031>
- Okalebo, J.R., Gathua, K.W., Woomer, P.L. (2002). *Laboratory methods of soil and plant analysis: a working manual second edition*. Sacred Africa, Nairobi 127.
- Ouatmane, A., Provenzano, M.R., Hafidi, M., Senesi, N. (2000). Compost maturity assessment using calorimetry, spectroscopy and chemical analysis. *Compost Science & Utilization* 8, 124–134. <https://doi.org/10.1080/1065657X.2000.10701758>
- Paredes, C., Roig, A., Bernal, M.P., Sánchez-Monedero, M.A., Cegarra, J. (2000). Evolution of organic matter and nitrogen during co-composting of olive mill wastewater with solid organic wastes. *Biology and Fertility of Soils* 32, 222–227. <https://doi.org/10.1007/s003740000239>
- Raj, D., Antil, R.S. (2011). Evaluation of maturity and stability parameters of composts prepared from agro-industrial wastes. *Bioresource Technology* 102, 2868–2873. <https://doi.org/10.1016/j.biortech.2010.10.077>
- Reig, F.B., Adelantado, J.V.G., Moya Moreno, M.C.M. (2002). FTIR quantitative analysis of calcium carbonate (calcite) and silica (quartz) mixtures using the constant ratio method. Application to geological samples. *Talanta* 58, 811–821. [https://doi.org/10.1016/S0039-9140\(02\)00372-7](https://doi.org/10.1016/S0039-9140(02)00372-7)
- Reyes-Torres, M., Oviedo-Ocaña, E.R., Dominguez, I., Komilis, D., Sánchez, A. (2018). A systematic review on the composting of green waste: feedstock quality and optimization strategies. *Waste Management* 77, 486–499. <https://doi.org/10.1016/j.wasman.2018.04.037>
- Rihani, M., Malamis, D., Bihaoui, B., Etahiri, S., Loizidou, M., Assobhei, O. (2010). In-vessel treatment of urban primary sludge by aerobic composting. *Bioresource Technology* 101, 5988–5995. <https://doi.org/10.1016/j.biortech.2010.03.007>
- Robledo-Mahón, T., Aranda, E., Pesciaroli, C., Rodríguez-Calvo, A., Silva-Castro, G.A., González-López, J., Calvo, C. (2018). Effect of semi-permeable cover system on the bacterial diversity

- during sewage sludge composting. *Journal of Environmental Management* 215, 57–67. <https://doi.org/10.1016/j.jenvman.2018.03.041>
- Robledo-Mahón, T., Gómez-Silván, C., Andersen, G.L., Calvo, C., Aranda, E. (2020). Assessment of bacterial and fungal communities in a full-scale thermophilic sewage sludge composting pile under a semipermeable cover. *Bioresource Technology* 298. <https://doi.org/10.1016/j.biortech.2019.122550>
- Robledo-Mahón, T., Martín, M.A., Gutiérrez, M.C., Toledo, M., González, I., Aranda, E., Chica, A.F., Calvo, C. (2019). Sewage sludge composting under semi-permeable film at full-scale: evaluation of odour emissions and relationships between microbiological activities and physico-chemical variables. *Environmental Research* 177, 108624. <https://doi.org/10.1016/j.envres.2019.108624>
- Roig, A., Lax, A., Cegarra, J., Costa, F., Hernandez, M.T., (1988). Cation exchange capacity as a parameter for measuring the humification degree of manures. *Soil Science* 146, 311–316. <https://doi.org/10.1097/00010694-198811000-00003>
- Rudnik, E. (2019). Composting methods and legislation, in: *Compostable Polymer Materials*. Elsevier, pp. 127–161. <https://doi.org/10.1016/B978-0-08-099438-3.00005-7>
- Senesi, N. (1989). Composted materials as organic fertilizers. *Science of The Total Environment* 81–82, 521–542. [https://doi.org/10.1016/0048-9697\(89\)90161-7](https://doi.org/10.1016/0048-9697(89)90161-7)
- Senesi, N., D’Orazio, V., Ricca, G. (2003). Humic acids in the first generation of EUROSOLS. *Geoderma* 116, 325–344. [https://doi.org/10.1016/S0016-7061\(03\)00107-1](https://doi.org/10.1016/S0016-7061(03)00107-1)
- Senesi, N., Plaza, C. (2007). Role of humification processes in recycling organic wastes of various nature and sources as soil amendments. *Clean - Soil, Air, Water* 35, 26–41. <https://doi.org/10.1002/clen.200600018>
- Senesi, N., Plaza, C., Brunetti, G., Polo, A. (2007). A comparative survey of recent results on humic-like fractions in organic amendments and effects on native soil humic substances. *Soil Biology and Biochemistry* 39, 1244–1262. <https://doi.org/10.1016/j.soilbio.2006.12.002>
- Sharma, B., Sarkar, A., Singh, P., Singh, R.P. (2017). Agricultural utilization of biosolids: a review on potential effects on soil and plant grown. *Waste Management* 64, 117–132. <https://doi.org/10.1016/j.wasman.2017.03.002>
- Sharma, B., Vaish, B., Monika, Singh, U.K., Singh, P., Singh, R.P. (2019). Recycling of organic wastes in agriculture: an environmental perspective. *International Journal of Environmental Research* 13, 409–429. <https://doi.org/10.1007/s41742-019-00175-y>
- Singh, R.P., Singh, P., Araujo, A.S.F., Hakimi Ibrahim, M., Sulaiman, O. (2011). Management of urban solid waste: vermicomposting a sustainable option. *Resources, Conservation and Recycling* 55, 719–729. <https://doi.org/10.1016/j.resconrec.2011.02.005>
- Smidt, E., Lechner, P., Schwanninger, M., Haberhauer, G., Gerzabek, M.H. (2002). Characterization of waste organic matter by FT-IR spectroscopy: application in waste science. *Applied Spectroscopy* 56, 1170–1175. <https://doi.org/10.1366/000370202760295412>

- Smidt, E., Schwanninger, M. (2005). Characterization of waste materials using FTIR spectroscopy: process monitoring and quality assessment. *Spectroscopy Letters* 38, 247–270. <https://doi.org/10.1081/SL-200042310>
- Smith, B.C. (1998). *Infrared spectral interpretation: a systematic approach*. CRC press.
- Soobhany, N., Gunasee, S., Rago, Y.P., Joyram, H., Raghoo, P., Mohee, R., Garg, V.K. (2017). Spectroscopic, thermogravimetric and structural characterization analyses for comparing municipal solid waste composts and vermicomposts stability and maturity. *Bioresource Technology* 236, 11–19. <https://doi.org/10.1016/j.biortech.2017.03.161>
- Sun, X., Ma, S., Han, L., Huang, G. (2016). Design and test on lab-scale intelligent membrane-covered aerobic composting reactor. *Transactions of the Chinese Society for Agricultural Machinery* 47, 240–245.
- Sun, X., Ma, S., Han, L., Li, R., Schlick, U., Chen, P., Huang, G. (2018). The effect of a semi-permeable membrane-covered composting system on greenhouse gas and ammonia emissions in the Tibetan Plateau. *Journal of Cleaner Production* 204, 778–787. <https://doi.org/10.1016/j.jclepro.2018.09.061>
- Sundberg, C., Jönsson, H. (2008). Higher pH and faster decomposition in biowaste composting by increased aeration. *Waste Management* 28, 518–526. <https://doi.org/10.1016/j.wasman.2007.01.011>
- Tian, H., Gao, J., Hao, J., Lu, L., Zhu, C., Qiu, P. (2013). Atmospheric pollution problems and control proposals associated with solid waste management in China: a review. *Journal of Hazardous Materials* 252–253, 142–154. <https://doi.org/10.1016/j.jhazmat.2013.02.013>
- TMECC. (2002). *Test methods for the examination of composting and compost*. The United States Composting Council Research and Education Foundation. The United States Department of Agriculture.
- Tognetti, C., Mazzarino, M.J., Laos, F. (2007). Improving the quality of municipal organic waste compost. *Bioresource Technology* 98, 1067–1076. <https://doi.org/10.1016/j.biortech.2006.04.025>
- Turan, N.G., Akdemir, A., Ergun, O.N. (2009). Removal of volatile organic compounds by natural materials during composting of poultry litter. *Bioresource Technology* 100, 798–803. <https://doi.org/10.1016/j.biortech.2008.07.010>
- Vaish, B., Sharma, B., Srivastava, V., Singh, P., Ibrahim, M.H., Singh, R.P. (2019). Energy recovery potential and environmental impact of gasification for municipal solid waste. *Biofuels* 10, 87–100. <https://doi.org/10.1080/17597269.2017.1368061>
- Van Haaren, R., Themelis, N.J., Barlaz, M. (2010). LCA comparison of windrow composting of yard wastes with use as alternative daily cover (ADC). *Waste Management* 30, 2649–2656. <https://doi.org/10.1016/j.wasman.2010.06.007>
- Wang, X., Bai, Z., Yao, Y., Gao, B., Chadwick, D., Chen, Q., Hu, C., Ma, L. (2018). Composting with negative pressure aeration for the mitigation of ammonia emissions and global warming

- potential. *Journal of Cleaner Production* 195, 448–457. <https://doi.org/10.1016/j.jclepro.2018.05.146>
- Wu, H., Zhao, Y., Long, Y., Zhu, Y., Wang, H., Lu, W. (2011). Evaluation of the biological stability of waste during landfill stabilization by thermogravimetric analysis and Fourier transform infrared spectroscopy. *Bioresource Technology* 102, 9403–9408. <https://doi.org/10.1016/j.biortech.2011.07.029>
- Yadav, A., Garg, V.K. (2011). Recycling of organic wastes by employing *Eisenia fetida*. *Bioresource Technology* 102, 2874–2880. <https://doi.org/10.1016/j.biortech.2010.10.083>
- Zbytniewski, R., Buszewski, B. (2005). Characterization of natural organic matter (NOM) derived from sewage sludge compost. Part 1: chemical and spectroscopic properties. *Bioresource Technology* 96, 471–478. <https://doi.org/10.1016/j.biortech.2004.05.018>
- Zhang, L., Sun, X. (2014). Changes in physical, chemical, and microbiological properties during the two-stage co-composting of green waste with spent mushroom compost and biochar. *Bioresource Technology* 171, 274–284. <https://doi.org/10.1016/j.biortech.2014.08.079>
- Zhou, Y., Selvam, A., Wong, J.W.C. (2018). Chinese medicinal herbal residues as a bulking agent for food waste composting. *Bioresource Technology* 249, 182–188. <https://doi.org/10.1016/j.biortech.2017.09.212>
- Zhou, Y., Selvam, A., Wong, J.W.C. (2014). Evaluation of humic substances during co-composting of food waste, sawdust and Chinese medicinal herbal residues. *Bioresource Technology* 168, 229–234. <https://doi.org/10.1016/j.biortech.2014.05.070>
- Zmora-Nahum, S., Markovitch, O., Tarchitzky, J., Chen, Y. (2005). Dissolved organic carbon (DOC) as a parameter of compost maturity. *Soil Biology and Biochemistry* 37, 2109–2116. <https://doi.org/10.1016/j.soilbio.2005.03.013>