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ORIGINAL RESEARCH

Green waste composting under GORE(R) cover membrane at industrial scale: physico-chemical properties and spectroscopic assessment

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Abstract

Purpose Green waste (GW) composting is of increasing importance to the waste management industry in addition being a useful agricultural product that is rich in nutrient and organic matter (OM). The combination of aerated static windrow with GORE(R) cover membrane and an air-floor aeration system is a relatively new industrial-scale composting technology that has not been previously explored. Therefore, the aim of this research study was to evaluate the effectiveness of composting GW using this new technology.

Methods The composting process was monitored through changes in the physico-chemical properties, $E_{4/6}$, and fourier transform infrared (FTIR) spectra.

Results Disinfection requirements were met by holding composting temperature steady in the thermophilic range for 24 days. The technology greatly improved composting conditions, and final compost product in terms of temperature, pH, electrical conductivity (EC), *C*/*N* ratio, OM degradation, nitrogen transformation, humification, and cation exchange capacity (CEC). The FTIR spectra revealed that there was enrichment of aromatic compounds and reduction in aliphatic structures and easily assimilated peptide components by microorganisms, indicating the humification degree increased, the final compost stabilized, and confirming the efficiency of composting. Consequently, the new technology produced a mature compost in only 30 days compared with the standard period of 90–270 days for traditional composting.

Conclusion Notably, the new technology may be a sustainable alternative for GW management that converts waste into compost and could be beneficial for agricultural uses.

Keywords Green waste · Physico-chemical properties · Composting · GORE(R) cover membrane · FTIR spectroscopy

Introduction

Dramatic increases in green waste (GW) due to the rapid development of urban greening areas globally has become a major environmental challenge that has created social problems in developed and developing economies (Rashad et al. 2010). GW mainly includes branch cuttings, tree wood and bark, pruning from young trees and shrubs, fallen dead and green leaves, grass clippings, garden litter and trimmings (Bustamante et al. 2016). GW is generated by municipal parks, gardens, reserves, and domestic gardens.

Inappropriate disposal of untreated GW contributes to water and soil pollution and threatens the environment and human health (Francou et al. 2008). Hence, effective GW management is crucial to reduce negative effects on individuals and the environment (Ahmad et al. 2007). A specific challenge is the difficulty and high cost of transferring GW because of its low bulk density and poor economic value.

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Positively, GW are renewable, available in large amounts, and very easy to obtain (Sabiiti 2011). Therefore, effective methods to reuse waste and reduce their negative impacts will yield significant benefits.

Traditional GW disposal methods involve incineration or disposal in landfills which can result in significant nutrient loss and cause environmental problems (Gabhane et al. 2012; Bustamante et al. 2013). Contrary to traditional disposal methods, composting is increasingly recognized as an environmentally acceptable method to dispose organic wastes and is becoming a favored method to treat organic solid wastes including sewage sludge, agricultural and forestry residues and animal manures (Li et al. 2012). Recycled GW that is converted into compost can be useful because its nitrogen (N), phosphorous (P) and humic substances can be reused to improve plant growth (Karak et al. 2013). In addition, GW is more environmentally friendly than other types of waste as it contains a lower level of micro-pollutants. This facilitates the production of a compost that is within utilization restrictions and quality standards that can be used in organic agriculture (Bustamante et al. 2016).

Compost quality can change with the use of different composting technology and amendments or control system. However, GW composting by traditional windrow methods has several disadvantages which include requiring a large area for treatment, a long time to generate a mature compost, and the emission of odorous gases (i.e., NH_3 and H_2S). Moreover, considerable nitrogen loss can occur, which decreases the availability of compost nutrients and produces a low quality compost product that is compost often unsuitable for commercial use (Francou et al. 2008). According to Tai and He (2007), if the process of composting lignocellulosic materials is not accelerated, decomposition could take 0.5–2 years to maturity. In traditional GW composting, the thermophilic phase starts during the first 2 days (due to the high content of OM), however, with a short duration (less than 4 days) and long maturation phase (between 2 and 3 months) (Khalil et al. 2008; Zhang et al. 2013). Studies have demonstrated that the length of the GW composting process is longer than composting of other substrates mainly because GW contains about 75% lignocellulosic substances which are slowly degraded by microbes in an aerobic environment (Gabhane et al. 2012). Thus, shortened processing times and improved compost quality have become important goals in composting GW (Zhang and Sun 2016a). Various strategies and methods that were developed for optimization of GW composting have led to a reduction of the processing period, minimization of gaseous emissions, and the enhancement of compost quality (Belyaeva and Haynes 2009; Zhang et al. 2013; Zhang and Sun 2016a; Bustamante et al. 2016).

The composting of GW by traditional composting can be improved by splitting the composting process in two stages, an innovative technique recently established and applied by Zhang and Sun, which involves co-composting of GW with different amendments (Zhang et al. 2013; Zhang and Sun 2014a, b 2015, 2016a, b, 2017a, b, 2018a, b, c). These studies demonstrated that this technology enabled the attainment of two peaks of thermophilic temperature with longer thermophilic periods compared to the traditional process. Thus, the decomposition of lignocellulosic GW is more effectively achieved. The authors indicated that high-value compost products were obtained in a shorter time, compared to the conventional GW composting process of one phase in composting windrows (Khalil et al. 2008; Zhang et al. 2013; Zhang and Sun 2015, 2017b).

Another innovation involves using an aerated static windrow with a semi-permeable cover to optimize GW composting. González et al. (2016) demonstrated the advantages of carrying out the composting process for sewage-sludge at an industrial scale by using aerated static windrow covered by a semi-permeable film. This technology minimized gaseous and odorous emissions and accelerated the composting process. Moreover, composting under semi-permeable films is cost-effective as it facilitates the treatment of large volumes of waste. Previous studies have also shown the environmental benefits of using semi-permeable film in the composting process which reduces liquid, solid and odorous emissions (Komilis et al. 2004; Turan et al. 2009). However, the limitation of this technology is that the infrastructure is more costly and complex than open windrow composting systems.

Membrane-covered compost technology has several advantages over traditional aerobic composting technology including even oxygen distribution, longer duration of high temperatures, rapid temperature increase, low energy consumption, and 30–40% reduction of emissions from ammonia and methane, respectively (Sun et al. 2016; Ma et al. 2017). van Haaren et al. (2010) demonstrated that composting with semi-permeable film reduces nitrogen oxides, sulfur, and carbon dioxide emissions compared to open windrow composting. The use of an integrated system of semi-permeable cover and an air-insufflation system during sewage sludge composting at an industrial scale has shown notable shifts in bacteria communities. Microorganisms with the ability to decompose recalcitrant compounds appear in an early phase due to the high temperatures that are rapidly gained during the first few days result in shorter composting time, thus the appropriateness and effectiveness of novel semi-permeable cover is confirmed as appropriate for composting sewage sludge to produce optimal compost (Robledo-Mahón et al. 2018).

A recent study showed that during composting pig manure and wheat straw using an innovative semi-permeable membrane cover with a bottom-up aeration system, the abundance of anaerobic *Clostridiales* and pathogenic *Pseudomonas* declined and *Cellvibrionales* facultative anaerobe with a complex cellulase system increased. This was due

to the enhancement of the oxygen environment of the pile under slight micro-positive pressure (Ma et al. 2018a). In another recent study, composting pig manure and wheat straw using semi-permeable membrane with a bottom-up aeration system enabled sufficient oxygen concentration to be achieved by slight positive pressure, which decreased the anaerobic zone in the compost pile and CH_4 emission by 22.42% (Ma et al. 2018b). In the same study the volatile solids content decreased quickly because the semi-permeable cover accelerated microbial activities which was conducive to accelerated fermentation and degradation. In addition, composting cattle manure with forced ventilation and semi-permeable film led to good reductions in greenhouse gases (CO_2, CH_4, and N_2O) and ammonia emissions as the temperature rose quickly to 70 °C within 2 days and remained constant (Sun et al. 2018).

Previous studies that provide a detailed analysis of compost physico-chemical properties and insight into the mechanisms of how those properties altered throughout the composting process aerated static windrow with GORE(^{R}) cover membrane remain unavailable. Consequently, the current study tested the hypothesis that composting by aerated static windrow with GORE(^{R}) cover membrane will produce a mature compost. Therefore, the specific objectives of the research were to: (1) characterize the changes in the physico-chemical properties during composting; (2) monitoring the changes in the $E_{4/6}$, and FTIR spectra to evaluate the humification degree; and (3) evaluate the maturity of the final compost product.

Materials and methods

Composting materials

This research study was undertaken in a composting industrial plant located in Godollo city, Hungary. The main characteristics of the raw materials used are presented in Table 1. 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 moisture content was then adjusted to 60% by the addition of water.

Composting process

Composting was carried out by aerated static windrow with GORE(^{R}) cover membrane at industry-scale (Fig. 1). 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(^{R}) cover membrane and had a ventilation system to ensure oxygen supply. The windrow had a three-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 × 12 mm.

The temperature was measured using Pt-100 type sensors housed in a stainless-steel sheath and connected to a data

Table 1 Characteristics of the raw materials used for composting

	Moisture (%)	Organic matter (%)	Total carbon (%)	Total nitrogen (%)	*C/N*	EC (mS cm^{-1})	pH
Green waste	23.1 ± 1.9	56.9 ± 1.4	31.3 ± 0.1	0.8 ± 0.0	38.6 ± 0.6	0.9 ± 0.0	7.0 ± 0.1

± Represents standard deviation based on three replicates

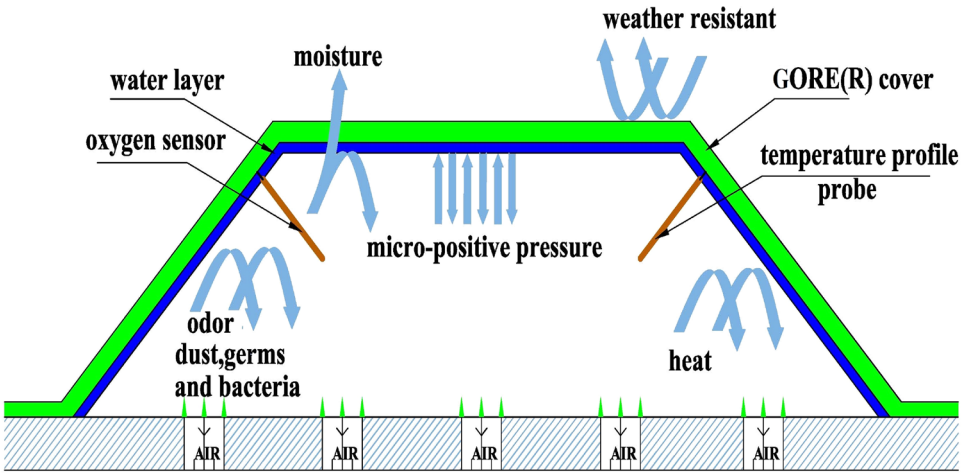

Fig. 1 Schematic diagram of the composting technology

acquisition system that was connected to a standard PC. The Pt-100 sensors were placed in the windrow at measuring points located at 1/2 the windrow height. The daily mean temperatures were calculated from hourly temperatures recorded continuously throughout the process by a digital recorder. Another temperature sensor was placed outside to measure the ambient temperature.

GORE(R) cover membrane

The GORE(R) cover membrane was waterproof and windproof. The micropore size of approximately ≤ 0.2 µm enabled the membrane to effectively prohibit the release of microbes, gaseous substances and particulate matter while remaining semipermeable to moisture (Mukhopadhyay and Midha 2016). Most of the water vapor generated during the early composting phase due to the decomposition of organic matter did not escape the membrane because its limited permeability; instead an aqueous condensate layer accumulated on the inner surface of the cover. This layer acted as a scrubber for odors by dissolving odor compounds in the condensate layer and forming droplets that returned the compounds to the composting material where they were decomposed by microorganisms.

Ventilation system

Air was supplied via ventilators and trenches placed at the base of the windrow. The trenches acted as ducts to provide air to the windrow and collect leachate from the windrow. Aeration was accomplished by ventilators with a maximum flow rate of 2400 m^3/h at 2940 rpm and 80 dB(A) using a forced aeration system placed at the base of the windrow. The ventilator engine power was 2.5 kW. A ventilation system controlled by a timer was used to control the windrow temperature. The injected flow rate diffused the air intermittently. The aeration frequency was 15 min per hour (15 min ON/45 min OFF).

Sampling strategy and collection

Composting was conducted for 30 days. Homogenous 1-kg samples that represented the average conditions of the entire windrow were collected in accordance with the US Composting Council standard (TMECC 2002) at the following intervals: 0 (first day of composting/the initial non-decomposed material), 7, 14, 24 and 30 days of composting.

Physicochemical analysis 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 according to US Composting Council standard (TMECC 2002) as follows:

$$\text{OM}\ (\%) = 100 - \text{ash}\ (\%). \quad (1)$$

A 1:10 aqueous extract of fresh compost was used to analyze the pH and EC as described previously by Guo et al. (2012). Losses of OM due to mineralization were calculated from the initial and final ash contents according to the following equation (Paredes et al. 2000) at each time interval:

$$\text{OM}_{\text{loss}}(\%) = 100 - 100\,[X_1(100 - X_2)]/[X_2(100 - X_1)], \quad (2)$$

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 CEC of 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-µm membrane filters. The filtrate was used for NH_4^+–N and NO_3^-–N determination by a colorimetric method according to a procedure described by Okalebo et al. (2002). $E_{4/6}$ ratio was determined on the extracts using 0.5 M NaOH extraction followed by UV-2000 spectrophotometer at 465 and 665 nm, respectively (Chen et al. 1977).

FTIR spectroscopic analysis

The air-dried sample of each composting step was analyzed with BRUKER DRIFT (Diffuse Reflectance Infrared Fourier Transform) FTIR spectrometer operated with the following settings: a nominal resolution of 4 cm^{-1} for the mid-infrared spectrum from 4000 to 400 cm^{-1}, absorbance type of spectra, and scans of 32.

Statistical analysis

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 analysed independently.

The principal components analysis (PCA), applied on the matrix of correlation between the variables, was used to study the variations occurring in the physicochemical

parameters during composting. The statistical treatments were carried out using the software SPSS Win version 25.

Results and discussion

Temperature evolution

Temperature monitoring is widely recognized as an excellent indicator for evaluating the degree of composting success and compost stability since compost windrow temperature is related to the rate of decomposition and to microbial activity during composting (Tiquia 2005). Temperature variation during composting (Fig. 2) showed a classic pattern exhibited by composting systems. Three distinct phases were observed: short initial mesophilic-heating phase (< 1 day), thermophilic (stabilization) phase (1–24 days), and cooling/maturing phases (25–30 days):

(i) Short initial mesophilic-heating phase (25–45 °C), where the temperature increased rapidly from ambient values to approximately 45 °C and lasted less than 1 day. During the initial mesophilic phase, mesophilic bacteria and fungi broke down the easily degradable organic compounds and produced H_2O, NH_3, CO_2, organic acids and heat (Bernal et al. 2009).

(ii) Thermophilic phase (> 45 °C), during which the temperature remains above 45 °C, exceeded the tolerance limit of mesophilic microorganisms and replaced by the thermophilic microorganisms and rapidly attained maximum value about 80.2 °C within 3 day.

Temperatures were higher and increased more quickly than those observed during the composting of the same substrate when a traditional method was used (Khalil et al. 2008). The micropositive pressure environment that resulted from the combination effects of the forced bottom-up ventilation system and the GORE(R) cover membrane on top of the windrow contributed to an even supply of sufficient oxygen for microorganisms to degrade OM. Ultimately, the microbial degradation of easily-decomposable OM was enhanced, the decomposition rate increased, and a large amount of metabolic heat was produced. Combined, these resulted in temperature increases inside the windrows, and attained the peak temperatures more quickly and maintained for a long time.

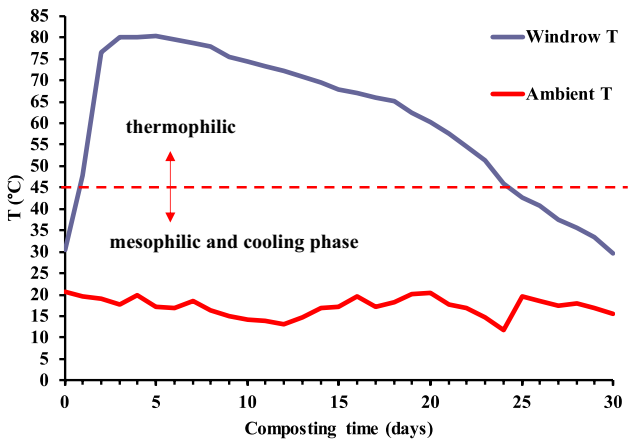

Fig. 2 Evolution of the temperature during GW composting

The application of this innovative technology resulted in higher thermophilic temperatures that are characteristic of the most active phase of composting. The temperature remained high and steady in the thermophilic temperature range for 24 days because the GORE(R) cover membrane completely enclosed the windrow and retained heat, which was consistent with results (González et al. 2016). The maintenance of high temperature for several consecutive days favors the growth of microorganisms that are responsible for the decomposition of lignocelluloses and formation of humus precursors which indicate an efficient composting process (Senesi 1989). In fact, to produce compost free from harmful pathogens organisms and weed seed, the composting temperature must remain in the thermophilic phase (> 45 °C) for at least 3 consecutive days (Bernal et al. 2009). In this study, the thermophilic phase lasted 24 days thus, composts generated by this technology met the disinfection requirements.

(iii) The cooling or maturing phase began on day 25 when the temperature of the windrow began to decline regularly below 45 °C to reach ambient temperature on the day 30th to indicate that the process was complete. The falling temperature was due to the depletion of easily degradable organic matter in the mesophilic and thermophilic phases and remaining compounds that were resistant to degradation (e.g., lignin). This phase was dominated by the humification process that consisted of the condensation and polymerization reactions of the organic compounds which were present to yield more stabilized compounds known as humic-like compounds (Senesi 1989).

This technology enabled more rapid decomposition of organic waste because of higher peak temperatures in addition to more rapid attainment and prolongation of thermophilic temperatures. Thus, high decomposition rate, accelerated GW degradation and reduced composting period result in lower operating costs for composting plants. As stated by Khalil et al. (2008), conventional composting requires 90–270 days to produce a mature product, however, the proposed new technology shortened the GW

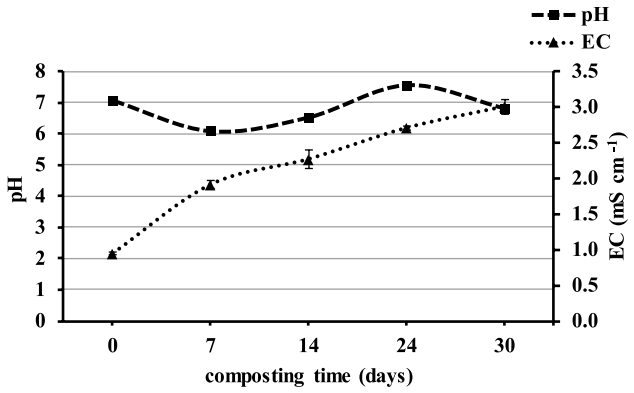

Fig. 3 Evolution of the pH and the electric conductivity during composting

composting time and produced mature compost in 30 days only.

pH variation

The pH value of the compost is one of the significant parameters used to assess compost maturity (Azim et al. 2018). Therefore, changes in pH were monitored during the composting green waste (Fig. 3).

In the first week of composting, the pH value declined from 7.1 to 6.1 (Fig. 3). This can be due to intense mesophilic microbes' activity and OM decomposition with the production of organic acids (such as acetic acid and butyric acid) under high temperatures, or due to the loss of large quantities of CO_2 during the initial stage of the decomposition of lignocellulose in the compost windrow (Senesi 1989; Azim et al. 2018). In addition, initial volatilization of ammonia following an increase in temperature during the thermophilic phase reduced the buffering capacity of the system and reduced the pH (Senesi 1989; Cáceres et al. 2018).

The increase in pH from 6.1 to 7.5 (Fig. 3) for the next 17 days (days 7–24) was attributed to the generation of ammonia during ammonification and mineralization of organic N due to microbial activities (Huang et al. 2004). Vergnoux et al. (2009) demonstrated that higher oxygen concentration causes faster decomposition of organic acids, and thus a quicker rise in pH. Alternatively, Tello-Andrade et al. (2015) and Hachicha et al. (2008) showed that the rise of pH may occur as a result of the metabolic degradation of organic acids.

At the end of the composting period, pH decreased to 6.8 because of compost maturation under aerobic conditions, synthesis of humic acids which worked as pH buffers (Amir et al. 2005), and hydrogen ion release from the nitrification process during later stages of composting (Eklind and Kirchmann 2000). Similar results were reported for organic waste composting (Gao et al. 2010).

The final pH value of the composts was 6.8, which is recommended for a matured compost (Zhang and Sun 2014b).

EC variation

The EC indicates potential phytotoxicity on plant growth and is a very useful parameter as it reflects the degree of compost salinity and the amount of ions in the composting material (Gao et al. 2010). However, the EC value depends on the rate of OM decomposition which leads to accumulation of different ionic species (Chan et al. 2016). As illustrated in Fig. 3, EC values increased sharply from 0.9 to 3.0 mS cm^{-1} during composting, which could be attributed to the release of mineral salts, such as ammonium and magnesium ions and/or to sulphates and phosphates (Huang et al. 2004) and concentration effect due to water loss from the high temperature (Zhang et al. 2016).

The higher content of mineral salts indicates progressive mineralization of OM and the release of high soluble salts into the medium (Cáceres et al. 2006). High salinity level in the compost can damage plant roots, affect nutrient uptake, limit plant-available soil water, and inhibit seed germination (Arslan et al. 2011). EC values of the final compost were 3.0 mS cm^{-1}, below 4 mS cm^{-1} which is commonly regarded as the limit for safely growing plants (Singh and Kalamdhad 2014). This indicated this compost could be applied to agricultural cultivations.

OM loss 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 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 (Fig. 4). OM_{loss} increased sharply with time to 46.9% within the first 14 days

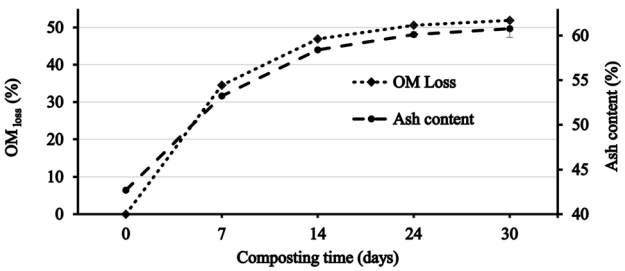

Fig. 4 Evolution of OM_{loss} and ash content during composting

of composting (mesophilic and thermophilic phases) due to the greater availability of substances that are easily biodegradable by microorganisms. It then 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 (Fig. 2). It has been found that high composting temperature accelerated the growth of thermophilic microorganisms for further biodegradation of lignin, cellulose and hemicellulose (Meng et al. 2017).

Changes in ash content as a function of time is displayed in Fig. 4. 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 (Tognetti et al. 2007; Kalamdhad et al. 2009; Rihani et al. 2010) Thus, this parameter measured the degradation and mineralization of OM and indicated stabilization during the composting process (Hsu and Lo 1999). A final compost with a high ash and low OM contents is recognized as mature.

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 (Fig. 5). 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).

Notably, in the literature there is no general agreement regarding the exact value of the *C*/*N* ratio that indicates stabilization of compost. Some authors suggest a maturity index for *C*:*N* ratio of < 20 (Azim et al. 2018), whereas Bernai et al. (1998) consider the *C*:*N* ratio < 12 as indicative of mature composts. In the present study, the *C*/*N* ratio of the

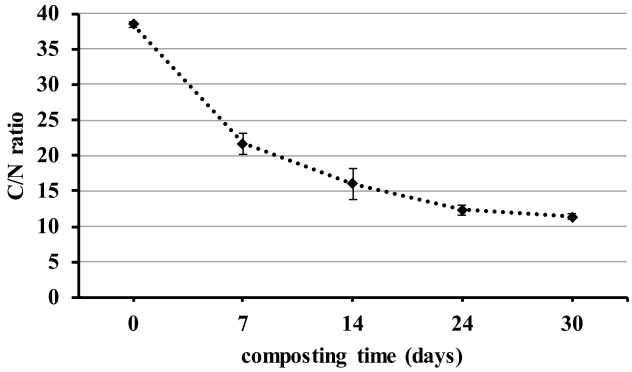

Fig. 5 Evolution of the *C*/*N* ratio during composting

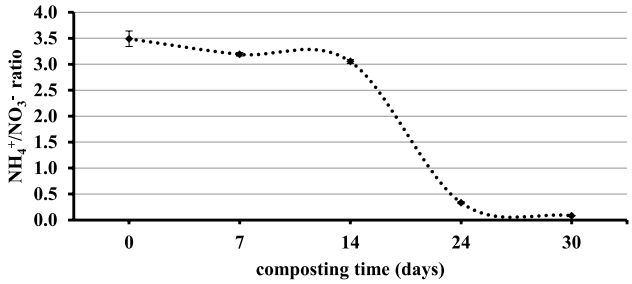

Fig. 6 Evolution of the NH_4^+/NO_3^- ratio during composting

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 decomposition and resulted in higher loss of *C* as carbon dioxide. The results align with the findings of Guo et al. (2012) who demonstrated that higher rates of aeration lead to increased carbon loss.

NH_4^+/NO_3^- ratio

Nitrification index (NH_4^+/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 NH_4^+/NO_3^- ratio (Fig. 6) 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 and oxygen flow through the entire substrate by forced bottom-up aeration that enhanced the oxidation processes and led to increased intensity of nitrification (Hao and Chang 2001).

CEC evolution

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 to 160.1 cmol kg^{-1} after 30 days of composting (Fig. 7), 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). The contribution of the phenolic groups accounted for 35% and carboxyl groups 55% (Lax et al. 1986). Harada and Inoko (1980a) found an increase in the CEC value during composting of city refuse waste, which is similar to the findings of Zhang and Sun (2014a) during co-composted green waste with spent mushroom compost and biochar. According to Harada and Inoko (1980b), the CEC of the final compost should be > 60 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 germination index (Ameen et al. 2016). In the current study, the CEC value of the final product was 160.1 cmol kg^{-1}, which indicated that the compost was mature (Senesi 1989).

$E_{4/6}$

Another important index of compost maturity is the humification degree of OM, i.e. the generation of humic-like substances (Senesi 1989). Figure 8 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 (Senesi 1989; Guo et al. 2019).

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 (Chen et al. 1977; 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 (Senesi 1989; 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).

Principal components analysis

The PCA is a statistical method that can evaluate the relationship between responses of all experimental variables which vary concurrently. The results of PCA of physicochemical parameters along the composting process demonstrated the existence of high correlations (positive or negative) shown in the circles (Fig. 9). The projection on the plane of the variables (Fig. 9) shows the affinity of variables along each axis. The PCA analysis reduces multidimensional relationships between parameters to two principal components that explain 92.9% of the total system variability. The first component (PC 1) explains 80.7% of the total variability and separates two groups of parameters. The first group has OM, $E_{4/6}$, *C/N* ratio, TC, and NH_4^+/NO_3^- ratio which are closely correlated by evolving similarly, i.e. they

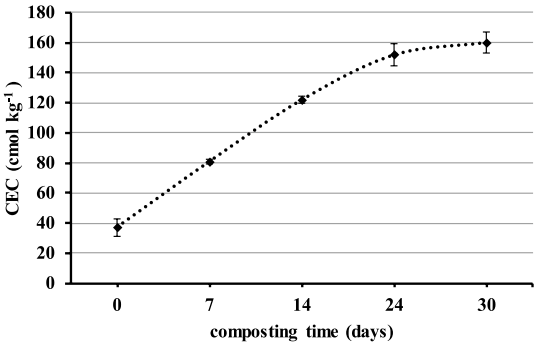

Fig. 7 CEC evolution during composting

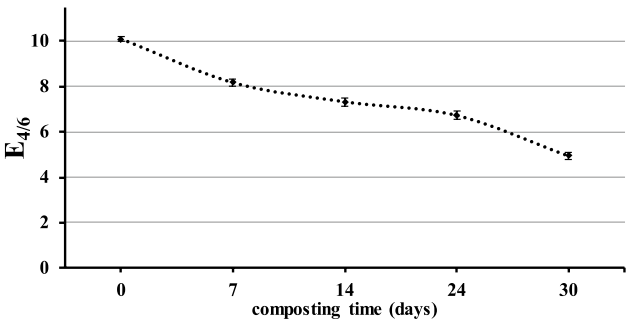

Fig. 8 Changes in $E_{4/6}$ ratio during composting of GW

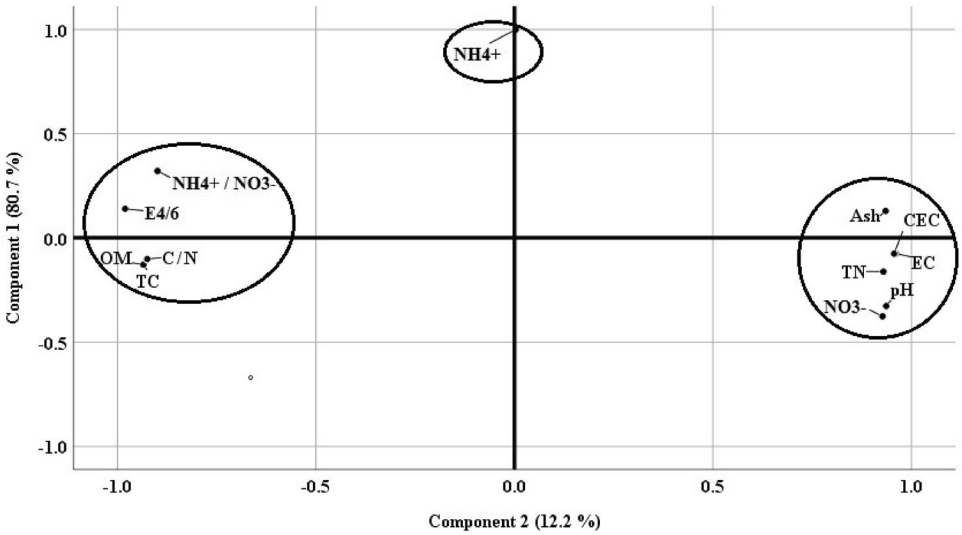

Fig. 9 Principal component analysis (PCA) of the physico-chemical parameters measured during composting

decrease toward the end of composting. The second group contained parameters such as pH, EC, ash content, CEC, TN and NO_3^-, which are also correlated by evolving similarly but increasing during composting. The second component (PC 2), which consists of NH_4^+ that initially increased during the first 14 days of composting and then followed by a decline till the end of composting, explains 12.2% of the total variability.

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 (Chen 2003). The FTIR spectra are presented in Fig. 10. The interpretation of the spectra is according to numerous works, notably (Senesi and Plaza 2007), and Lü et al. (2018).

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. 2014, 2015).

The very strong peak observed at 2958 cm^{-1} is due to the νC–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; Smidt and Schwanninger 2005). The bands between 2920 and 1640 cm^{-1} designated as aliphatic

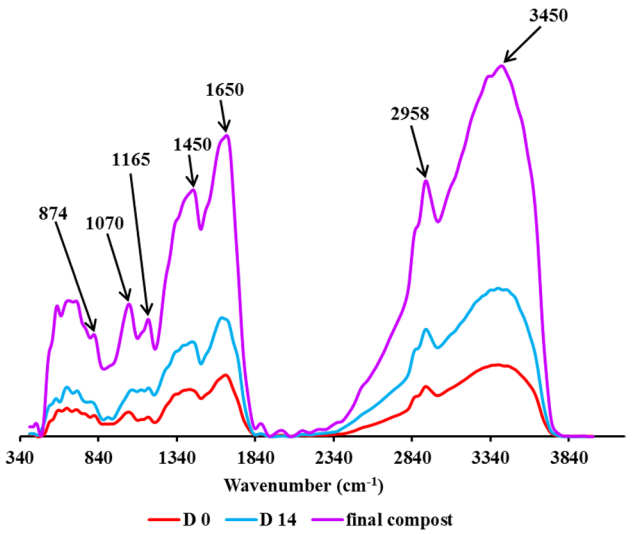

Fig. 10 FTIR spectra of GW at various stages of composting (*D 0* day 0, *D 14* day 14, and final compost)

methylene and unsaturated or aromatic C=C vibrations, respectively, is considered an indicator of OM humification (Droussi et al. 2009).

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 aldheydes (Kaiser and Ellerbrock 2005). Moreover, El Fels et al. (2014, 2015) attributed the peaks that appear at 1650 cm^{-1} to νC=O of ionized carboxyl (COO–). Given that the peak at 1640 cm^{-1} is attributed to aromatic C=C vibrations, and increasing intensity as the composting process progressed, this indicated an enrichment in aromatic C=C compared with aliphatic carbon (Baddi et al. 2004). Smidt

Table 2 Summary of the characteristics of final compost, in comparison with guidelines for acceptable quality of compost

Chemical properties	Compost	Threshold values	References
pH	7.1 ± 0.0	7.1–7.7	Forster et al. (1993)
EC (mS cm^{-1})	3.0 ± 0.1	< 4	Lasaridi et al. (2006)
OM %	38.8 ± 0.5	33.3–55.4	Fricke and Vogtmann (1994)
TC/TN	11.4 ± 0.4	< 20, preferable < 10	Bernai et al. (1998)
CEC (cmol kg^{-1})	161.7 ± 5.8	> 60	Harada and Inoko (1980b)
TC (%)	20.9 ± 0.3	> 20	Lasaridi et al. (2006)
TN (%)	1.8 ± 0.1	≥ 1	Cheng et al. (2013)
NH_4^+ (mg kg^{-1})	73.4 ± 7.4	< 400	Bernai et al. (1998)
NH_4^+/NO_3^-	0.1 ± 0.0	< 0.16	Bernai et al. (1998)

et al. (2005) found that humic acids have a strong band at 1640 cm^{-1} that increases during the composting process. In the same study, the continuous increase in the humic acid content had a positive impact on this band and formation of carboxylates due to the release of carboxylic acids from decomposed lipids, which contributed to the rise as well. 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 (Hsu and Lo 1999; Huang et al. 2006; Makni et al. 2010; El Fels et al. 2014). 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 to 1472 to C=C stretching vibrations from aromatic components. El Fels et al. (2014) demonstrated that the decrease in band intensities of aliphatic chains (νC–H and $\delta CH_2/CH_3$ at 1450 cm^{-1}) and the increased intensities of C=C functions favor a dynamic composting process leading to the formation of unsaturated and aromatic structures. 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. Aguelmous et al. (2016) observed bands located at 875 and 713 cm^{-1}, which suggest the presence of calcium carbonates. The band at 874 cm^{-1} could be attributed to calcite. Smith (1998) attributed the 875 cm^{-1} band to the C–O out-of-plane bending of carbonate.

Characteristics of the final compost

Compost product that is mature or stable and without toxicity to plant growth can be safely used as organic fertilizer (Azim et al. 2018). Table 2 shows the main chemical properties of the final composts obtained. The final compost produce by this new technology satisfied the threshold levels established in the literature for its use as an organic fertilizer (Table 2), i.e. pH 7.1–7.7, EC < 4 mS cm^{-1}, *C/N* ratio < 10, NH_4^+/NO_3^- < 0.16, CEC > 60 cmol kg^{-1}, and OM 33.3–55.4%. These findings indicated that composting was performed successfully under optimized conditions.

Conclusion

The present study demonstrated that aerated static windrow using GORE(R) cover membrane combined with an air-floor aeration system is an effective method for the recovery of GW through the production of a high mature compost.

This new technology is effective due to higher peak temperatures, more rapid attainment, and prolongation of thermophilic temperatures which led to more rapid decomposition of organic waste. Moreover, the new technology shortens the GW composting time as it produces mature compost in only 30 days, unlike conventional composting technology such as open-windrows, which requires 90–270 days and it produces immature compost. Future research is expected to focus on the evolution of microbial communities and enzymatic activities.

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