Investigate biotransformation of green waste during composting by aerated static windrow with GORE(^{R}) cover membrane technology

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Composting is considered an economic and effective method of recycling green waste (GW), because it helps protect the environment and encourages economic development. However, conventional composting technology is time consuming, generates foul smells, and produces immature compost. The GW composting process was conducted using an aerated static windrow with GORE(^{R}) cover membrane technology, in combination with an air-floor aeration system at the industrial scale. This study investigated the variation of physico-chemical properties during the green waste composting process. The composting process was monitored through the determination of moisture, dry matter (DM), bulk density, water soluble carbon (WSC), ammonium-N (NH_4^+-N), and nitrate-N (NO_3^--N) evolution. The technology greatly improved the composting conditions and compost quality in terms of bulk density, moisture, nitrogen transformation, and WSC. The results obtained in this study indicate that using an aerated static windrow with GORE(^{R}) cover membrane maintain the moisture in optimal conditions by retaining the water within the compost itself increases the microbial activity and the rate of organic matter (OM) decomposition by microorganisms. Our results support the recent research indicating that nitrification could occur above temperatures of 45 °C and might be caused by the existence of microbial communities that are resistant to high temperatures and have the capability to nitrify. The decreased of NH_4^+ content and increased of NO_3^- in the composting materials indicate that the compost has achieved maturity and is ready for use. The evolution of the GW by using an aerated static windrow with GORE(^{R}) cover membrane technology produced a mature product that can be used in agriculture.

Keywords: green waste, biotransformation, aerated static windrow, GORE(R) cover membrane

Introduction

The treatment, reuse and utilisation of organic waste is a priority for environmental policy in various European Union (EU) countries (Kvasauskas and Baltrenas, 2009). In the EU, composting is regarded as the most environmentally friendly and suitable method of recycling GW since in addition to its low cost and simple methods, the compost obtained is rich in a nutrients and useful for plants and soil (Morales *et al*., 2016). In addition, GW often contains low level of micro-pollutants, making it more environmentally friendly (Reyes-Torres *et al.* , 2018). The composting process has many advantages: (i) reduce weight and volume of the green waste (ii) destroy pathogenic microorganisms in the raw material (iii) reduce the concentration of organic and inorganic pollutants, and (iv) obtain stabilised and mature compost (Senesi *et al.* , 2007). The success of the composting process can be assessed based on the quality of the final compost product, particularly its stability and maturity. The application of immature or unstable compost can suppress seed germination and reduce plant growth due to inadequate biodegradation of organic matter because immature compost may compete for oxygen or be directly phytotoxic to plants (Bernal *et al.* , 2009). According to González *et al.* (2016), the benefits of industrial-scale sewage sludge composting are largely due to the employment of aerated static windrow systems with semi-permeable film covering. One advantage of this method is that it reduces gas and odor emissions and hastens the composting process. Furthermore, composting under semi-permeable films is cost-effective, which can be attributed to the fact that the approach can treat sizeable amounts of waste In the literature, a range of scholars, including Komilis *et al.* (2004) and Turan *et al.* (2009), documented the sustainability-related advantages associated with semi-permeable film utilization in composting, which reduces liquid, solid and odorous emissions. Nevertheless, there are limits to this approach. For example, the infrastructure is more expensive and intricate than for open windrow composting. Membrane-covered composting methods possess several advantages in comparison to conventional composting methods. These benefits include even oxygen distribution, extended duration of high temperatures, rapid temperature increases, minimal energy consumption, and 30% to 40% lower emissions from ammonia and methane, respectively (Sun *et al.* , 2016; Ma *et al.* , 2017).

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According to van Haaren *et al.* (2010), composting with semipermeable cover lower nitrogen oxides, sulfur or carbon dioxide emissions compared to open windrow composting. It is also worthwhile to note substantial changes in communities of bacteria have been observed as a consequence use of semi-permeable covers in combination with air-insufflation systems during sewage sludge composting at an industrial scale. The appropriateness and effectiveness of novel semi-permeable cover is confirmed as appropriate for composting sewage sludge due to appearance in an early phase microorganisms with the ability to decompose recalcitrant compounds result in shorter composting time (Robledo-Mahón *et al.* , 2018). A study concerning the composting of pig manure with wheat straw by Ma *et al.* (2018a) revealed that by using a novel 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 achieve adequate oxygen concentration under slight micro-positive pressure. Composting pig manure and wheat straw using semi-permeable membrane with a bottom-up aeration system, decreased the anaerobic region in the compost pile and CH_4 emission were decreased by 22.42% (Ma *et al.* , 2018b). In the same study the volatile solids content fell rapidly. This was because microbial activity was hastened by the semi-permeable cover which accelerated decomposition. In addition, composting cattle manure with forced ventilation and semi-permeable cover results in decreases greenhouse gases (CO_2, CH_4, and N_2O) and ammonia emissions (Sun *et al.* , 2018).

A considerable list of chemical, physical and biological parameters have been used to assess the evolution of compost stability and maturity during the composting process (Wichuk and McCartney, 2010) such as; temperature, moisture, bulk density, pH, electrical conductivity (EC), cation exchange capacity (CEC), oxidizable organic carbon, water-soluble organic carbon, carbon and nitrogen ratio (C/N), $NH4^+$ /NO_3^- ratios, ammoniacal nitrogen (NH_4^+-N), oxygen and CO_2 respirometry, nitrate nitrogen (NO_3^--N), humification indexes, colorimetric and spectroscopic test (UV-visible, fluorescence, FTIR, NMR), germination index (GI), enzyme activities, and microbial population, *etc*. To date, the green waste composting by using the aerated static windrow with GORE(^{R}) cover membrane technology has not been studied. Consequently, this study aims to study the physico-chemical properties' variation during the green waste composting process.

1. Materials and methods

1.1 Composting process

Composting was conducted using an aerated static windrow with GORE(^{R}) cover membrane on the industrial scale. 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 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 12x12 mm.

1.2 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 decomposition of organic matter did not escape the membrane because of the limited permeability of the membrane; 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. The GORE(^{R}) cover membrane was sealed, creating a complete in-vessel enclosure around the entire windrow, and heat was retained, which along with the bottom-up aeration, created a slight positive pressure. The positive pressure provided a homogeneous distribution of temperature and oxygen throughout the composting volume. These conditions enabled aerobic fermentation and accelerated the biological treatment process, therefore obviating the need for frequent windrow turning and ensuring the achievement of the necessary temperature for sanitization.

1.3 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 to 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 to maintain aerobic conditions in the windrow. The aeration frequency was 15 min per hour (15 min ON/45 min OFF).

1.4 Sampling strategy

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.

1.5 Physicochemical analysis of compost samples

The moisture content was determined by drying the fresh sample at 105 °C to a constant weight. The dry matter (DM) was estimated as follows:

$$\text{DM (\%)} = (\text{oven dry sample weight}/\text{wet sample weight}) * 100 \qquad (1)$$

The wet bulk density (BD_{wet}) is the mass of fresh material occupying a particular volume. The dry bulk density (BD_{dry}) is the mass of material occupying a particular volume after oven drying (Agnew and Leonard, 2003). 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 based on a procedure described by Okalebo *et al.* (2002). Water soluble carbon (WSC) was measured using air dried samples in a 1:10 (w/v) ratio of compost–water suspension by oxidation with potassium dichromate and subsequent titration with ferrous ammonium sulphate (Sánchez-Monedero *et al.* , 1996). The data shown in the tables and figures are the means of the three replicate subsamples per composite sample with standard deviations. 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.

2. Results and discussion

2.1 Moisture, dry matter and bulk density evolution

2.1.1 Moisture and dry matter

Moisture content is a crucial parameter during the composting process and plays an important role in microorganism metabolism, which directly influences the composting progress and compost quality. Loss of moisture during the composting process is recognised as an index of the decomposition rate as the heat production that accompanies decomposition causes vaporisation (Liao *et al.* , 1997). After the first week of composting, the moisture content decreased from the initial 61% to 56 % (**Figure 1**) due to a rapid temperature increase during the composting process. Thereafter, the moisture remained relatively stable at an approximately optimum value of 51% until the end of the composting process. This is most likely because the composting technology used was a closed system and much of the metabolic water generated as a result of decomposition, condensed on the inner surface of the semi-permeable membrane, dropped back into the compost and replaced the water that was initially lost through evaporation. The dry matter varies inversely with respect to moisture. Jiang *et al.* (2011) found that a high initial moisture content reduces the NH_3 emissions but delays the compost's maturation.

During composting, the water content tends to increase due to the release of metabolic water by microorganisms that decompose organic matter in the presence of oxygen. However, Zvomuya *et al.* (2005) reported that during forced ventilation, the heat and high temperature was taken by the air flow causes greater water removal within the matrix pores and the moisture decreases. However, Shan *et al.* (2018) showed that a great loss of water could be caused by intensive microbial decomposition activities. The optimal moisture value of approximately 50-60%, depending on the physical structure and the particle size change during composting, is necessary to increase the rate of decomposition by microorganisms which use water for nutrient solubilisation and cell protoplasm (El Fels *et al.* , 2014). Liang *et al.* (2003) reported that a moisture content of approximately 50 % was a minimal condition for rapid microorganism activity and should be kept in the range of 30–60 % moisture content for better microorganism activity. The results obtained in this study indicate that using an aerated static windrow with a semipermeable film kept the moisture in optimal conditions by retaining the water within the compost itself and, consequently, increasing the microbial activity and the rate of OM decomposition by microorganisms. Moreover, the vapor generated by the rise in temperature inside the windrow due to microorganism activity is responsible for the breakdown of tannin and/or lignin (tough organic material) (Sudharsan Varma and Kalamdhad, 2014). At the end of the composting process, the compost had a moisture content value which exceeded 30%, which indicates its stability (Rich *et al.* , 2018).

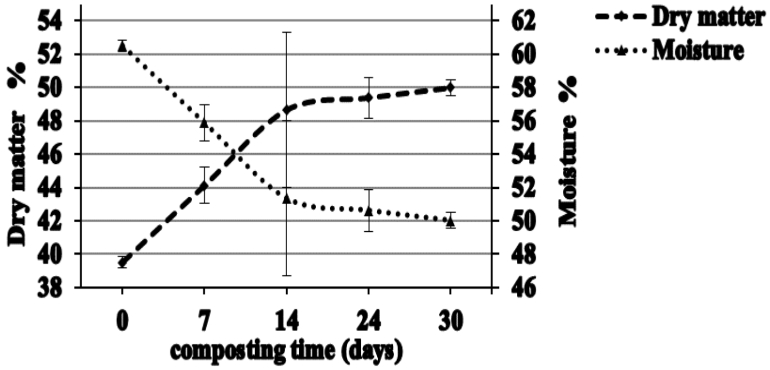

Fig 1. Moisture content and dry matter evolution during composting

2.1.2 Bulk density

Both BD_{wet} and BD_{dry} evaluations are important, as they influence the composting process and compaction of the compost. The BD_{dry} increased from an initial value of 0.4 g cm^{-3} to 0.8 g cm^{-3} after 30 days of composting, while the BD_w increased from 0.6 g cm^{-3} to 1.0 g cm^{-3} (**Figure 2**). These results are confirmed by other authors (Karak *et al.* , 2013; Karak *et al.* , 2015). As compost matures, its organic carbon content decreases due to chemical and biological conversions of organic carbon to carbon dioxide. As this occurs, the structural support provided by various carbon compounds degrades and collapses, causing the remaining inorganic materials (salts and metals) to compact. The result is a higher unit of mass per unit volume in aged, composted material than that of the original feedstock. Khater, (2015) observed a negative correlation between the bulk density and total organic matter of the compost (R^2 = -0.89). As particle size is reduced and ash content increases by decomposition, BD_{dry} increases with composting progress (Raviv *et al.* , 1987). The BD_{dry} of compost is significant when the compost comprises a large proportion of the potting media and as bulk density

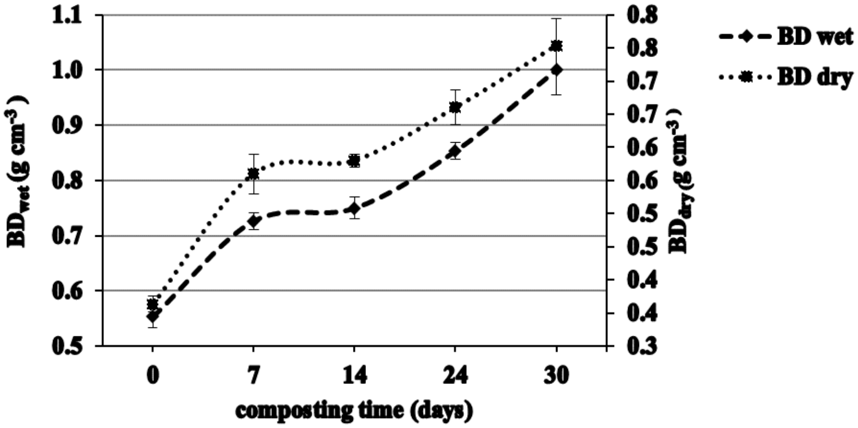

Fig 2. Changes in BD_{wet} and BD_{dry} during the composting process

increases, drainage and the air-filled porosity of the growing media (e.g., potting media) are reduced, and the water holding capacity is increased. However, the measured bulk density may decrease as the material dries out during composting due to evaporation and loss of water (Day *et al.* , 1998). The normal BD_{dry} is in the range of 100 kg m^{-3} to 400 kg m^{-3}, whereas BD_{wet} is normally 500 kg m^{-3} to 900 kg m^{-3} (Agnew and Leonard, 2003). Azim *et al.* (2018) stated that in composting, the porosity (pore space) of the windrow must allow decomposition to occur under aerobic conditions and small particle size decreases the number of large pores and increases the oxygen needed to diffuse through small pores. Higher bulk density indicates an increase in mass and a decrease of porosity and air volume. However, low wet bulk density can imply extreme substrate aeration and, indirectly, a decrease in the available water fraction (Nappi and Barberis, 1993).

2.2 WSC

The WSC is one of the most readily available carbon fractions, it represents a source of carbon compounds that is easily biodegradable by microbes and consequently, it contributes to maintaining a high level of microbial activity. In this case, the WSC increased gradually from 6.2 g kg^{-1} to 33.7 g kg^{-1} during the first 14 days of composting (**Figure 3**). Thereafter the WSC dropped sharply to reach 8.9 g kg^{-1} at the end of composting. An initial increase followed by a decline in the WSC during composting has been observed by several authors (Tumuhairwe *et al.* , 2009; Goyal *et al.* , 2005; Charest *et al.* , 2004). However, a continuous decrease in WSC was reported by Leita and De Nobili, (1991) and Inbar *et al.* (1993) for MSW and cattle manure, respectively. The observed increases of WSC suggest that these compounds were released regardless of compost feed mixtures. Ros *et al.* (2006) stated that the increase in the content of WSC during composting indicates that new glucose or other WSC originated from microbial activity during this process, since composting is a synthesis process. Charest *et al.* (2004) suggested that the increase of WSC during the thermophilic phase might be the result of hemicellulose, cellulose, and lignin decomposition. The posterior drop in WSC indicated that these substances were biodegraded during composting by microorganisms, which use it as a source of energy for their growth, and the decomposition of more recalcitrant carbon fractions (Ros *et al.* , 2006). In addition, Karak *et al.* (2013) reported that the rapid drop of WSC suggests the rapid exhaustion of reserves of easily degradable organic compounds present in the composting mass to synthesise new macromolecules with properties similar to the humic substances in soils. The decrease of WSC at the end of process could be due to the formation of complex organic molecules produced by the continuous mineralisation of soluble organic compounds and the repolymerization and condensation pathways of organic compounds, which led to the production of complex organic molecules with low solubility in water (Said-Pullicino *et al.* , 2007). WSC is one of the active parameters in defining compost maturity and a reduction in WSC is often used as an indication of compost maturity (Bernal *et al.* , 2009). Some authors proposed that the threshold maturity values for WSC in finished compost should be <0.4% (Zmora-Nahum *et al.* , 2005), <0.5% (Garcia *et al.* , 1992), <1% (Hue and Liu, 1995), and < 1.7 % (Bernai *et al.* , 1998). Nevertheless, WSC is mainly constituted of sugars, polyphenols, amino acids and apart from the soluble fraction of fulvic acids (Ros *et al.* , 2006). Iannotti *et al.* (1994) reported that immature compost contains sugar, phenolic substances, organic acids, amino acids, peptides and other easily biodegradable substances. However, in mature compost, the major components of WSC are present as humic substances, which are resistant to further biodegradation, and thus demonstrate increased compost stability (Hsu and Lo, 1999).

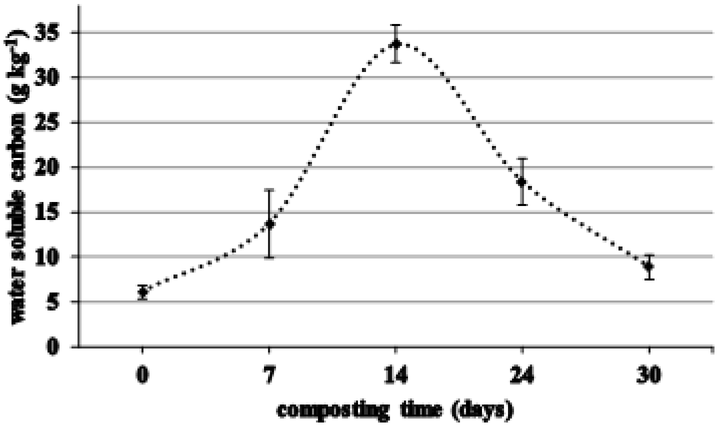

Fig. 3. Evolution of WSC during composting

The rate of decrease WSC during composting depends on the composting technique utilized and on the source material (Hsu and Lo, 1999). In the present study, the WSC of the final compost was 8.9 g kg^{-1}, which was lower than the maturity threshold of 10 g kg^{-1} as suggested by Hue and Liu, (1995), indicating that the compost became mature after 30 days of composting. Composting of pruning residues by conventional open windrow results in final a WSC of 3.6 g kg^{-1}after 18 weeks of composting (Fontanive *et al.* , 2004), which indicates it took a longer time to mature; this is due to poor aeration conditions. This suggests that this new technology facilitates reaching a maturity in a shorter period which is due to a forced bottom-up aeration system that improved composting conditions and resulted in accelerate the decomposition of WSC during GW composting.

2.3 Nitrogen forms variation

In the composting process, the nitrogen transformation reactions can happen concurrently, such as denitrification, nitrification, ammonia assimilation, and ammonification (Meng *et al.* , 2016). However, the prevailing reaction would change according to environmental conditions in composting and the substrate. In general, the mineral N was characterized by a high initial NH_4^+ content and low NO_3^- content during the thermophilic phase of composting (Brito *et al.* , 2008), whereas by the end of the process, the opposite situation was observed (high final NO_3^- levels and low NH_4^+ levels) (**Table 1**).

Table 1. Evolution of ammonium-N, and nitrate-N concentrations during composting

Composting time (days)	NH_4^+-N (mg kg^{-1})	NO_3^--N (mg kg^{-1})
0	350.1 ± 9.9	100.4 ± 5.5
7	800.3 ± 20.2	250.7 ± 3.7
14	1100.7 ± 26.3	360.4 ± 4.4
24	200.6 ± 9.9	600.5 ± 8.8
30	74.0 ± 5.0	900.2 ± 14.8

± represents standard deviation based on three replicates

The concentration of NO_3^- and NH_4^+ varied remarkably during composting. As shown by table 1, the NH_4^+ content increased rapidly in the first 14 days of composting and showed a maximum peak value of approximately 1100.7 mg kg^{-1} on the 14th day. Subsequently, after reaching the peak value, the NH_4^+ content gradually decreased and little NH_4^+ was detected at the end of composting. The mineralisation of organic matter through the conversion of organic nitrogen to NH_4^+ reflects the occurrence of the ammonification process and, consequently, the rise of the NH^+_4 content. Zhang *et al.* (2016a) showed that the increase of NH_4^+ is mainly due to the hydrolysis of the nitrogenous material in the biodegradable fractions of the waste. Whereas the decrease in NH_4^+ was probably due to NH_3 volatilisation (Gao *et al.* , 2010) and microbial immobilisation and/or oxidation to NO_3^- through nitrification (Huang *et al.* , 2004). It has been noted that the absence or decrease in NH_4^+ is an indication of maturation and good composting process (Riffaldi *et al.* , 1986). As demonstrated, the NH_4^+ content of 400 mg kg^{-1} is a maximum value which is recommended in mature compost (Bernai *et al.* , 1998). By the end of the composting period, the NH_4^+ content was 74.0 mg kg^{-1}, which indicates maturity. Conspicuously, at the start of the composting process, the increase in nitrate content was limited with no noticeable change, then it started to increase progressively at the expense of the ammonium nitrogen after the 14th day, indicating an increase in the activity of nitrifying bacteria**,** although thermophilic temperatures were still maintained (Table 1**)**. Morisaki *et al.* (1989) showed that high temperatures and ammonia suppress the activity and growth of nitrifying bacteria in the thermophilic phase. However, some authors have recently identified nitrification within the thermophilic stage of composting, mainly in the later thermophilic stage (Lopez-Gonzalez *et al.* 2013; Li *et al.* 2016). It is commonly accepted that the nitrification process occurs mostly at mesophilic temperatures (20–35°C) when the decomposition of organic substances declines, and the nitrifying microorganism grows in an aerobic environment (Kraus and Warren, 2000). Therefore, our results support the recent research indicating that nitrification could occur above temperatures of 45 °C and might be caused by the existence of microbial communities that are resistant to high temperatures and have the capability to nitrify (Zhang *et al.* , 2016b). In the cooling phase, when the temperature decreased, the intensity of the nitrification process increased rapidly and the NO_3^- content increased progressively to reach a high value of approximately 900.2 mg kg^{-1} at the end of the process, as a result of nitrifying microorganisms thriving when temperatures change from thermophilic to mesophilic levels. The decrease in NH_4^+ content and increase in NO_3^- in the composting materials indicates that the compost has achieved maturity and is ready to use. Critical limit values of <400 mg kg^{-1} for NH_4^+ –N (Bernai *et al.* , 1998) and >300 mg kg^{-1} for NO_3^--N (Forster *et al.* , 1993) has been established as a stability/ maturity indices for composts of various origins. In the present study, the new technology satisfied the critical limits for stability/maturity at the day 24th. However, during composting of pruning residues by conventional open windrow, the maturity indices value for mature composts was recorded after 18 weeks (Fontanive *et al.* , 2004). It seems that due to the better aeration by the new technology, the oxidation of NH_4^+ to NO_3^- might have been enhanced. Consequently, the new technology produced a mature compost in only 30 days compared with the standard period of 90–270 days for conventional composting technology (Khalil *et al.* , 2008).

Conclusion

This study demonstrated that the composting of GW by using an aerated static windrow with GORE(^{R}) cover membrane technology is an effective method for the disposal of GW by producing mature compost. The results met the thresholds for the subsequent use of compost as a soil amendment or organic fertiliser for soil based on the following parameters: WSC $\leq$ 10 g kg^{-1}, moisture >30%, ammonium-N (NH_4^+-N) < 400 mg kg^{-1}, and nitrate-N (NO_3^--N)> 40 mg kg^{-1}. It can be concluded that the new technology may be a viable and sustainable alternative for GW management in that it converts the waste into a useful product.

Acknowledgments

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Nomenclature

BD_{dry}	dry bulk density	[g cm^{-3}]
BD_{wet}	wet bulk density	[g cm^{-3}]
C/N	carbon and nitrogen ratio	[-]
CEC	cation exchange capacity	[-]
DM	dry matter	[-]
EC	electrical conductivity	[-]
EU	European Union	[-]
FTIR	fourier transform infrared	[-]
GI	germination index	[-]
GW	green waste	[-]
NH_4^+-N	ammonium-N	[mg kg^{-1}]
NMR	nuclear magnetic resonance	[-]
NO_3^-N	nitrate-N	[mg kg^{-1}]
OM	organic matter	[-]
WSC	Water Soluble Carbon	[g kg^{-1}]

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