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ORIGINAL PAPER

Characterization of different compost extracts using Fourier-transform infrared spectroscopy (FTIR) and thermal analysis

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Abstract Compost extract or "compost tea" is a liquid extract of compost obtained by mixing compost and water for a defined period of time. Compost tea contains nutrients and a range of different organisms and is applied to the soil or directly to plants with the principal aim of suppressing certain plant diseases. In addition, the application of compost tea supplies nutrients and organic matter to the soil. Thermal analysis and Fourier transform infrared spectroscopy (FTIR) are two widely applied analytical techniques for establishing the stability of compost, and although numerous studies have evaluated the capacity of compost tea to suppress plant diseases, there are no studies employing these techniques to characterize compost-tea. For the present study, 12 compost extracts were produced under varying conditions in a purpose-built reactor. Two different composts, an stable compost produced from manure and an unstable compost produced from municipal solid waste, respectively, two aeration systems (aerated and non-aerated extracts) and three temperatures (10, 20 and 30°C) were used in these experiments. The extracts were freeze-dried and subsequently analysed, together with the two composts, by means of FTIR and thermal analysis. Extracts produced from high stability compost, independently of the conditions of aeration and temperature, showed very similar results. In contrast, differences among extracts produced from the unstable compost were more noticeable. However, the different conditions of aeration and temperature during the production of the extracts only explained partially these differences, since the transformations undergone by compost over the 3 months that the experiments lasted were also reflected in the composition of the extracts. In spite of everything, extraction process favoured the degradation of easily oxidizable organic matter, which was more abundant in unstable compost. This degradation was more intense for non-aerated processes, probably due to the longer duration of these (10 days) with respect to aerated extractions (2 days). The effect of temperature was not clear in these experiments, although high temperatures could increase micro organism activity and consequently favour the degradation of easily oxidizable organic matter.

Keywords Compost tea · Compost extracts · FTIR · DTG · DTA

Introduction

Compost extract or "compost tea" is a liquid extract of compost obtained by mixing compost and water for a defined period of time (Ingham 2002). Compost tea contains nutrients and a range of different organisms and is applied to the soil or directly to

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plants. An increasing body of experimental evidence indicates that compost tea can suppress certain plant diseases, such as *Botrytis* on green beans, strawberries, grapes and geraniums, powdery mildew on apples, and others (Al-Dahmani et al. 2003; Scheuerell and Mahaffee 2004; Diánez et al. 2006). In addition, the application of compost tea is known to supply nutrients and organic matter to the soil.

There is evidence that the Romans used compost teas, while the ancient Egyptians used preparations based on compost extracts as long as 4,000 years ago. Interest in compost teas waned when pesticides became available in the twentieth century, because pesticides tend to provide better, more reliable control of most foliar diseases. However, the recent upsurge in sustainable and organic farming, together with problems related to the use of pesticides, have led to a growing number of scientific papers and non-referred publications related to compost teas (Litterick et al. 2004).

The methods used to produce compost tea can be classified into two groups depending on the aeration system used: aerated and non-aerated. In aerated systems, there is continuous addition of air and these methods are associated with reduced production times (generally 24 h). There are many patented designs which employ this production method. The addition of nutrients (molasses, soluble kelp, rock dust, etc.) is common in aerated systems, with the aim of increasing microbial population density. In non-aerated production methods, the mix is not disturbed or only minimally disturbed after initial mixing (Scheuerell and Mahaffee 2002) and the concentration of dissolved oxygen (DO) in the extract falls below 5.5 ppm (70%) (Ingham 2002).

Numerous studies have evaluated the capacity of compost tea to suppress plant diseases, but there is little information regarding the influence that certain factors associated with the production process, such as extraction time, aeration, temperature and pH, may have on tea quality (Line and Ramona 2003).

FTIR spectroscopy and thermal analysis are two widely-applied analytical techniques for establishing the stability of compost. *Infrared spectroscopy* has proven to be a valuable tool for the characterization of waste, with a number of applications in waste science, such as the characterization of different waste materials (Smidt and Schwanninger 2005; Smidt et al. 2005). Infrared spectra illustrate the plot of absorbed infrared radiation dependent on the wave-numbers (wavelengths) caused by the interactions of the infrared radiation with matter (Meissl et al. 2007). FTIR spectroscopy has been used to describe the composting process and to determine compost maturity (Outmane et al. 2000; Chen 2003; Smidt et al. 2005), as well as to characterize humic substances in compost (Outmane et al. 2002; Sánchez-Monedero et al. 2002).

Thermal degradation techniques, such as thermogravimetry (TG) and differential thermal analysis (DTA), have been used for many years to elucidate structural features of decayed natural heterogeneous organic matter, providing important information on the chemical characteristics of the sample (Marhuenda-Egea et al. 2007). Thermal analysis has the advantage that it is simple, fast, reproducible and can be performed on the whole sample without requiring pre-treatment. Thermogravimetry has been used to assess compost stability and maturity (Baffi et al. 2007; Dell'Abate et al. 2000; Mondini et al. 2003). Thermal methods are based on programmed heating of the samples in a controlled atmosphere. Different components in the sample, which undergo transformations at different temperatures, produce a graph whose shape reflects the chemical composition and structure of the sample (Mondini et al. 2003).

None of these techniques has yet been applied to compost extracts; therefore, the aim of this study was the application of thermogravimetric techniques and infrared spectroscopy to compost extracts produced under different conditions of aeration and temperature, and with two different composts, in order to contribute to a deeper understanding of the composition of compost extracts.

Material and methods

Production of the extracts

Twelve different compost teas were produced under varying conditions (Table 1) using a 15-l steel reactor. The extracts were produced sequentially over a period of three months. Two different composts (M and MSW), three different temperatures (10, 20, and 30°C) and two aeration systems (aerated, or A, and non-aerated, or N) were combined to produce the extracts.

Figure 1 shows the design of the reactor, which allows teas to be produced under aerated and non-

Table 1 Abbreviations designating production conditions for each extract

Extract	Compost	Aeration	Temperature (°C)	Duration (days)
M-N-10	M	10 min/12h	10	10
M-N-20	M	10 min/12h	20	10
M-N-30	M	10 min/12h	30	10
M-A-10	M	Continuous	10	2
M-A-20	M	Continuous	20	2
M-A-30	M	Continuous	30	2
MSW-N-10	MSW	10 min/12h	10	10
MSW-N-20	MSW	10 min/12h	20	10
MSW-N-30	MSW	10 min/12h	30	10
MSW-A-10	MSW	Continuous	10	2
MSW-A-20	MSW	Continuous	20	2
MSW-A-30	MSW	Continuous	30	2

aerated conditions and at different temperatures. It was designed in such a way that aeration was provided by a compressor and was automatically regulated by means of an electro-valve connected to a timer. Temperature was regulated by means of a thermal belt that surrounded the reactor and which was connected to a controller with a temperature probe for continuous temperature measurement within the reactor (Fig. 1).

The general procedure for the production of each extract began by pouring water into the reactor, which was then initially aerated continuously for 10 h to remove chloride. Thereafter, compost was placed directly into the reactor under the appropriate conditions for each trial.

The proportion of compost to water used in every compost tea production trial was 1:10 (1 kg of dry compost in 10 l of tap water), a common proportion both for aerated as non-aerated teas (Scheuerell and Mahaffee 2002).

The extraction time, or the time during which the compost is in contact with water, was established in accordance with other studies (Scheuerell and Mahaffee 2002). In aerated teas, extraction time was 48 h, 1 day longer than in the majority of patented systems. As aeration was continuous, dissolved oxygen (DO) was always higher than 5.5 parts per million (ppm). For non-aerated teas, the bibliography reports extraction times of between 1 and 21 days (Scheuerell and Mahaffee 2002). An extraction time of 10 days in length was chosen in order not to extend the experiments excessively. An aeration period of 10 min every 12 h was employed. This period was chosen on the basis of previous experiments carried out on a smaller scale (unpublished data), so that extraction was accelerated but oxygen remained below 1 ppm most of the time. Aeration was performed at 50 l/min in a continuous or discontinuous way, respectively, for aerated or non-aerated teas.

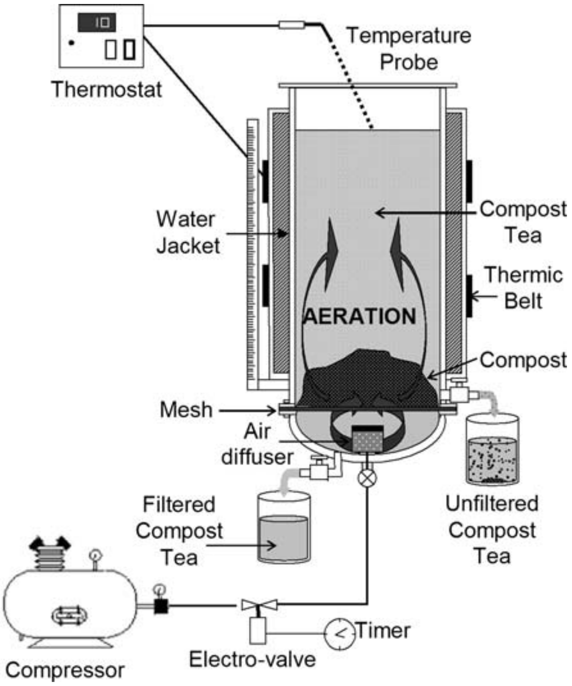

Fig. 1 Diagram of the reactor designed for producing compost tea

Composts

Two different composts were used to produce the teas: one was made from bovine manure (M compost), and the other from municipal solid waste (MSW compost).

M compost was produced by ENERVISA, a company located at Vidanes (León, NW-Spain), which fattens 13,500 head of cattle and in addition produces compost from cow manure. The decomposition stage of composting (about 2 weeks) was carried out in a fully roofed silo, where the cow dung was turned. Subsurface aeration accelerated decomposition. The maturation stage (6–8 weeks) took place in another roofed area where the material was turned repeatedly (Runge 2003). The M compost used in this study had completed the composting process.

On the other hand, MSW was produced at a waste treatment plant located in the region of Andalusia in southern Spain, which receives the waste produced by 500,000 inhabitants. MSW compost was produced from the organic fraction of non-selectively collected municipal solid waste. When the waste arrives at the plant, it is subjected to a sorting process (trommel, magnetic separator, etc.) in order to separate the organic fraction. As regards composting, an open outdoor system involving windrows, which are periodically turned, is used. The decomposition stage lasts 7 weeks. After this time, the material is screened and the maturation stage, which lasts between 1 and 2 months, begins. However, the MSW compost used in this study was collected at the end of decomposition stage without having been screened and had therefore not undergone the maturation stage.

Upon arrival at the laboratory, both composts (M and MSW) were sieved (<5 mm mesh). The fraction smaller than 5 mm was used to produce compost tea. During the 3 months that the production of the different compost teas lasted, the sieved composts were stored in the laboratory at ambient temperature (18–22°C) under anaerobic conditions. Composts should have been stored at low temperature, at which microorganism activity was slowed down, in order not to change composts composition over the experiments. However, the storage conditions caused changes in composts, especially in MSW compost, which make more difficult to study the influence of the aeration and temperature on compost tea production.

Sampling and sample preparation

Three representative samples of each sieved compost (each of 200 g) were taken using a riffle-type sample splitter. These samples were used for chemical analysis. A subsample (each of 20 g) of each compost sample was taken using the same method. These were dried at 65°C for 24 h, homogenised in a ball mill, then manually ground in an agate mortar, and subsequently sieved to 0.2 mm for the purpose of FTIR and thermal analysis.

As regards the compost teas, three sample aliquots of each produced extract (each of 250 ml) were drawn out through the lower valve of the reactor at the end of the extraction period. These samples were freeze-dried and kept at 4°C until all the extracts had been produced (approximately 3 months), subsequently performing FTIR and thermal analysis.

Chemical analytical methods

The values for pH and electrical conductivity (EC) of the composts were measured in a 1:25 (w/v) suspension of compost and distilled water (MAPA 1994). Ash content was determined by combustion in a muffle furnace at 550°C for 6 h. Total carbon and total nitrogen contents were analysed by combustion in a CHN-600 LECO analyser in accordance with the ASTM D-5373 standard. Oxidizable carbon was determined by the Walkley-Black method (Walkley and Black 1932). Ammonium concentration was estimated in a KCl extract by a selective electrode method (APHA et al. 1992). Compost stability was measured as the respiration rate using an OxiTop® system which evaluates respiration based on the fall in pressure in the interior of a closed vessel over a period of 96 h (Adani et al. 2006; Veeken et al. 2003). The respiration rate was expressed as millimoles of oxygen per kilogram of volatile solids per hour (mmol O_2/kg VS/h).

FTIR spectroscopy

Two milligrams of each sample (subsamples of milled and dried compost or freeze-dried compost extract), together with 200 mg KBr (FTIR grade), were first homogenized in an agate mortar. Infrared (FTIR) spectra were recorded using KBr pellets pressed under vacuum, using a FTIR Perkin-Elmer

2000 spectrophotometer over the 4,000–400 cm^{-1} range at a rate of 0.5 cm/s. Fifty scans were recorded, averaged for each spectrum and corrected against ambient air as background. Three samples of each compost and each compost tea were analysed and mean values were estimated. To highlight the emerging bands, spectra were smoothed with a 30-point smoothing filter. Spectra were baseline corrected using three reference points: 4,000, 2,300 and 860 cm^{-1}, as zero absorbance points (Chefetz et al. 1998; Hsu and Lo 1999). Moreover, relative absorbances were calculated for spectra comparison. Five peaks were selected separately for composts, M extracts and MSW extracts, and the relative absorbance (rA) was calculated by dividing the absorbance by the sum of the absorbance of the five selected bands in each case and multiplying by 100 (Haberhauer et al. 1998). The spectra were plotted using the same scale on the relative absorbance axis for all the composts and teas (0–50% of rA). The mean coefficient of variation between the three replicates of each compost or compost tea ranged between 0.6% and 3.1%.

Thermal analysis

Thermal analysis was performed using a TA Instruments SDT 2960 thermobalance registering TG and DTA measurements simultaneously. The heating rate applied to the samples was 10°C per minute from 20 to 950°C with a flow rate of 100 ml/min of synthetic air (composition 21 ± 1% O_2 and 79 ± 1% N_2; purity $\geq$99.9994%). The manometric pressure was maintained at 101 kPa and the sample weights were approximately 10 mg. Each sample was analysed and mean values of the three replicates were estimated for each compost and each lyophilized extract.

Results and discussion

Compost analysis

Chemical analysis

Table 2 shows the results of the chemical analysis of both composts. The pH values of MSW compost were low, a feature of materials at an early stage of the composting process (Sharma et al. 1997). Furthermore, MSW compost recorded a higher oxidizable carbon content, even though the total carbon concentration of M compost was higher. M compost was richer in nitrogen. However, the concentration of nitrogen as ammonium in MSW compost was higher than in M compost.

In addition, M compost may be considered as stable on the basis of the criteria established by Veeken et al. (2003), according to which compost is stable if its respiration rate is lower than 15 mmol O_2/kg VS/h.

In contrast, MSW compost recorded a respiration rate of 95.4 mmol O_2/kg VS/h, which would correspond to very unstable compost according to Veeken's criteria. The stability of both composts was measured again 3 months later, when the compost tea production trials had ended. The respiration rate of M compost had hardly changed, while for MSW compost it had decreased to 30.2 mmol O_2/kg VS/h. The stability of MSW compost had therefore increased over the course of the three months that the study lasted. However, MSW compost was still unstable according to the criteria put forward by Veeken et al. (2003).

FTIR analysis

Figure 2 shows FTIR spectra for M (Fig. 2b) and MSW (Fig. 2c) composts carried out before the compost tea production experiments had begun.

The FTIR spectra of both composts exhibited similar areas of absorbance, comparable to the findings of other authors. Interpretation of the compost spectra is based on numerous studies, notably García et al. (1992), Outmane et al. (2000), Chen (2003), Jouraiphy et al. (2005), Smidt et al. (2005), and Smidt and Meissl (2007). The main absorbance bands noted were as described below. There was a broad band between 3,360 and 3,392 cm^{-1} (H-bonded OH groups), peaks between 2,960 and 2,850 cm^{-1} (C–H stretch of aliphatic structures), a peak between 1,620 and 1,660 cm^{-1} which may encompass the C=O vibration of bonded conjugated ketones, quinones, carboxylic acids and esters, and the C=C vibration of aromatic components. Another broad band was noted between 1,430 and 1,455 cm^{-1}, arising from the O–H in-plane bend of carboxylic acids, the CO_2 stretch of carboxylates and the aliphatic CH_2 group of alkanes, and also the C–O

Table 2 Values for pH, electrical conductivity (EC), ash content, total carbon, nitrogen (total and ammonium), oxidizable carbon and respiration rate of M and MSW compost

Compost	pH	EC mS/cm	Ash % d.m.	Total C % d.m.[a]	Oxidizable C % d.m.[a]	Total N % d.m.[a]	N–NH$_4$ mg/kg d.m.[a]	Respiration rate mmol O$_2$/kg VS/h
M	9.70 (0.03)	4.16 (0.12)	39.4 (0.5)	34.3 (0.9)	23.4 (1.3)	3.4 (0.7)	13.3 (3.1)	9.6 (0.9)
MSW	6.72 (0.06)	2.82 (0.03)	52.5 (0.4)	30.1 (1.5)	26.3 (0.9)	1.9 (0.3)	130.7 (4.5)	95.4 (1.2)

Means and standard deviations of three replicates are shown

[a] d.m., dry matter

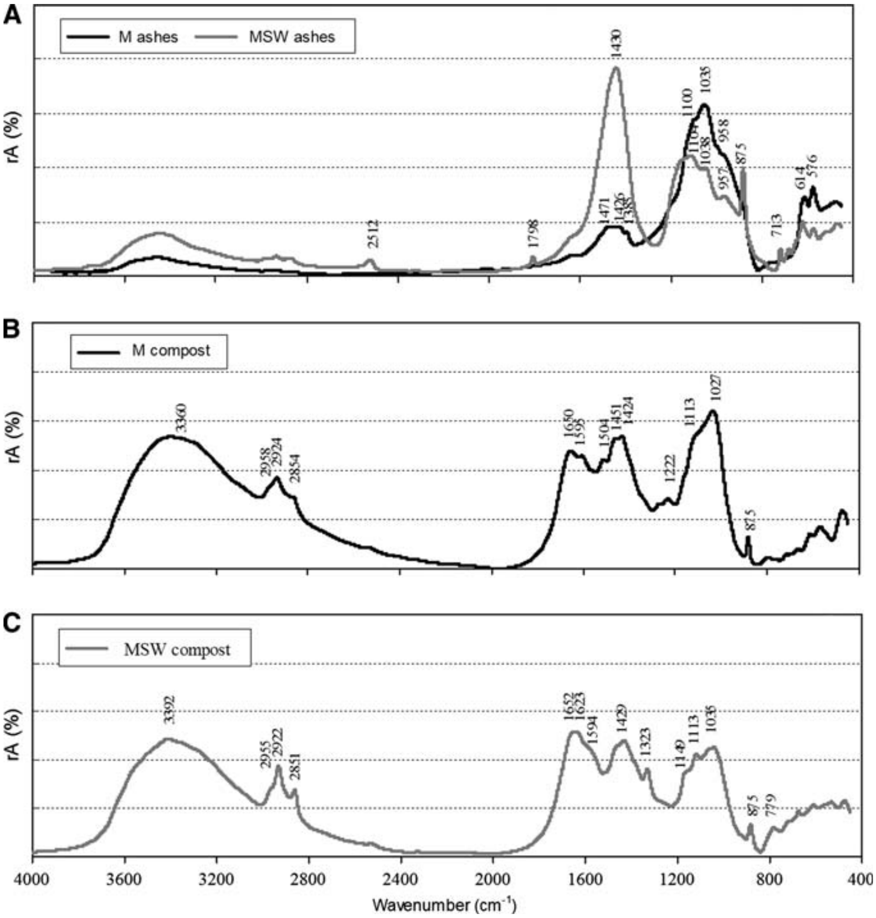

Fig. 2 FTIR Spectra. (**a**) Ashes in M and MSW composts; (**b**) M compost; and (**c**) MSW compost

stretch vibration of carbonates, a very broad peak between 1,150 and 1,030 cm^{-1} that can be attributed to polysaccharides, although clay minerals are also characterized by a huge band around 1,030 cm^{-1}. Finally, the sharp band noted at 875 cm^{-1} may be assigned to the C–O out-of-plane bend of carbonates.

When the M and MSW spectra were compared, a weak peak around 1,504 cm^{-1} was visible for the M compost spectra, attributed to lignocellulose. M compost was produced from manure and straw, the latter feedstock being rich in lignin. Another typical band of lignin was identified for M compost around 1,595 cm^{-1}, caused by the vibration of the aromatic skeleton. These bands were also found by other authors for manure composts (Inbar et al. 1989; Zmora-Nahum et al. 2007). However, these peaks were not clear in spectra for MSW compost. A peak around 1,323 cm^{-1} is distinguished in MSW compost spectra, which can be attributed to aromatic primary and secondary amines.

To verify whether the peaks observed in the spectra were related to organic matter or to mineral forms, FTIR spectra of residual ash were also recorded (Fig. 2a). Clear differences between the ash spectra of the two composts were found, indicating a different composition of the inorganic fraction. The spectra of M ashes exhibited a broad band between 900 and 1,100 cm^{-1}, with a similar shape to the same band of M compost spectra. This band can be attributed to Si–O stretch of clay minerals and Si–O–Si vibration of silica. The absorption of different inorganic components of phosphorus or sulphur, which could be interesting as nutrients, also contributes to this band. This way, sharp bands around 600 cm^{-1} and a small peak around 2,500 cm^{-1} confirmed the contribution of sulphur inorganic compounds to the broad band between 900 and 1,100 cm^{-1}. In contrast, the spectra of MSW ash were dominated by a sharp peak at 875 cm^{-1} and by the band around 1,430 cm^{-1}, both corresponding to carbonates. This latter band was less noticeable for M ash spectra, which allowed distinguishing a slight peak at 1,385 cm^{-1} attributed to N–O stretch of nitrates.

Given the high relative absorbance of the band between 900 and 1,100 cm^{-1} in the spectra of MSW compost, and the lower relative absorbance of this band for MSW ashes, it was evident that some organic compound had to have contributed to this band. Polysaccharides shows an absorbance band in this region, therefore this fact could indicate that MSW compost showed a high concentration of polysaccharides (readily-oxidizable organic matter).

Thermal analysis

Figure 3 shows the results of thermal analysis (DTG and DTA) for the two composts (M and MSW). Four steps may be distinguished in the compost thermograms. DTG curves showed a slight peak within the temperature range 70–160°C, which was mainly caused by the loss of residual water (Gómez et al. 2005, 2007; Smidt and Lechner 2005; Melis and Castaldi 2004; Dell'Abate et al. 2000). Two prominent peaks between 200 and 350°C and between 400 and 550°C, respectively, indicated the main losses of organic matter. According to the kinetics of thermal oxidative decomposition, this behaviour indicated a two-stage process. The peak between 200 and 350°C (Peak 1) may be attributed to aliphatic structures and the second, between 400 and 550°C (Peak 2), to the thermal breakdown of more aromatic and stable moieties, such as lignin (Dell'Abate et al. 2000; López-Capel et al. 2005). Both peaks were exothermic, as is shown in the DTA profiles in Fig. 3. Finally, the weight loss at temperatures higher than 550°C was associated with endothermic oxidation of refractory C as well as with the decomposition of both mineral and biogenic salts (Baffi et al. 2007).

As regards the differences between the organic fraction of the two composts, MSW compost showed lower values of weight loss than M compost in the two main peaks (Peak 1 and Peak 2), probably caused by the higher ash content of the former (Table 2). When the weight losses associated with both peaks were compared, MSW compost showed similar values for both peaks (19% for Peak 1 and 18% for Peak 2). In contrast, M compost presented a lower value of weight loss between 200 and 350°C (21%) than between 400 and 550°C (26%). The organic fraction of M compost was hence richer in complex forms, which burn primarily within the range between 400 and 550°C, while MSW compost showed a high content in readily oxidizable organic forms. This latter pattern is typical of non-stabilized compost; as compost becomes more stable, products that burn within the range of temperatures 200–350°C disappear (Smidt and Lechner 2005).

Finally, M and MSW composts differed in the composition of their mineral fraction. M compost exhibited a broad peak between 800 and 900°C, while MSW compost showed a peak around 650°C. These

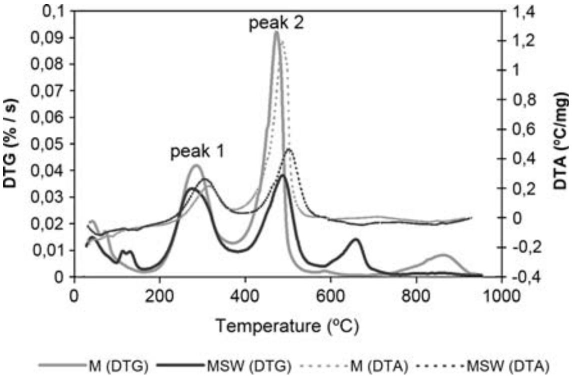

Fig. 3 DTG and DTA profiles for M and MSW composts

different patterns were caused by the different composition of both compost, and these results agreed with the results of FT-IR ashes spectra, since MSW ashes were richer in carbonates which were decomposed around 650°C, while M ashes were mainly composed by inorganic nutrients (N, P or S) which decomposed at higher temperature.

Tea analysis

Infrared analysis

The interpretations of the spectra of the extracts were based on numerous studies in which FTIR spectroscopy was applied to freeze-dried samples (Chen et al. 2002; Jouraiphy et al. 2005; Fakharedine et al. 2006; Smidt and Meissl 2007).

The spectra of the M extracts produced under differing conditions of aeration and temperature (Fig. 4) were very similar. According to these results, temperature and aeration therefore had hardly any influence on the composition of the different M extracts, which can be owing to the high stability of M compost.

Some differences were found between compost and extracts spectra. However, these differences should be cautiously interpreted, since it is necessary to take into account that the quantitative differences between the compost and the extracts spectra may be due to the different sample preparation since freeze-drying of extracts caused concentration of the soluble ingredients.

The band between 1,000 and 1,050 cm^{-1} was dominant in the M compost spectra (Fig. 2b); in contrast, its contribution to the M extract spectra was lower. As this band was attributed to polysaccharides and different mineral compounds, the decrease could be caused both by the low solubility of some mineral component or by the preferential degradation of polysaccharides by the microorganisms which grew in compost teas during the extraction process.

The band between 1,620 and 1,675 cm^{-1} (aromatic and C=O vibrations) was dominant for all M extract spectra. Furthermore, the peak at 1,450 cm^{-1}, which was clearly recognized in compost spectra (Fig. 2b), appeared as a shoulder in M extracts. Given the low carbonate content of M compost, this peak was attributed to carboxylic acids, carboxylates or alkanes.

The changes in the band between 1,350 and 1,450 cm^{-1} for the extracts with respect to the compost allowed a new peak to be distinguished around 1,400cm^{-1}, which could be attributed to the absorbance of the nitrates in freeze-dried samples (Smidt and Meissl 2007).

Three peaks appeared in the extracts at around 837, 704 and 620 cm^{-1}, which correspond respectively to primary amine groups (NH_2 out-of-plane), secondary amine groups (N–H wag) and inorganic sulphates (S–O bend). A broad band at around 2,590 cm^{-1}, which was attributed by Smidt and Meissl (2007) to the S–H stretch of thiol groups in freeze-dried leachates, was also common to all the M extracts.

Figure 5 shows the spectra of the compost extracts produced from MSW compost. Differences among the extracts of MSW compost were more noticeable than those among M compost extracts. However, it is necessary to be cautious interpreting these results, because the differences between MSW extracts spectra could be caused not only by the different conditions of temperature and aeration, but also by the different degree of stability of MSW compost when each extract was produced. It means that MSW compost suffered transformations during the three months that the production of the different extracts lasted, and these changes could affect to the extracts composition.

The band between 1,570 and 1,650 cm^{-1} was dominant in most of MSW extract spectra; this band was also important in MSW compost spectra. However, while this band was centred between 1,620 and 1,650cm^{-1} for MSW compost, it showed a maximum around 1,560–1,590 cm^{-1} for MSW extracts, possibly caused by the contribution of secondary amides as well as aromatic C=C to this band.

The most significant differences among MSW extracts were found in the band between 1,030 and 1,200 cm^{-1}. The intensity of this band was higher for aerated than for non-aerated extracts, the difference between the two aeration systems being greater as the temperature increased. The influence of temperature depended on the aeration system. As temperature increased, the rA of this band decreased for non-aerated extracts, while the effect of temperature on this band was less intense for aerated teas. Given the low solubility of clay minerals, this band could be mainly attributed to carbohydrates and polyols (900–

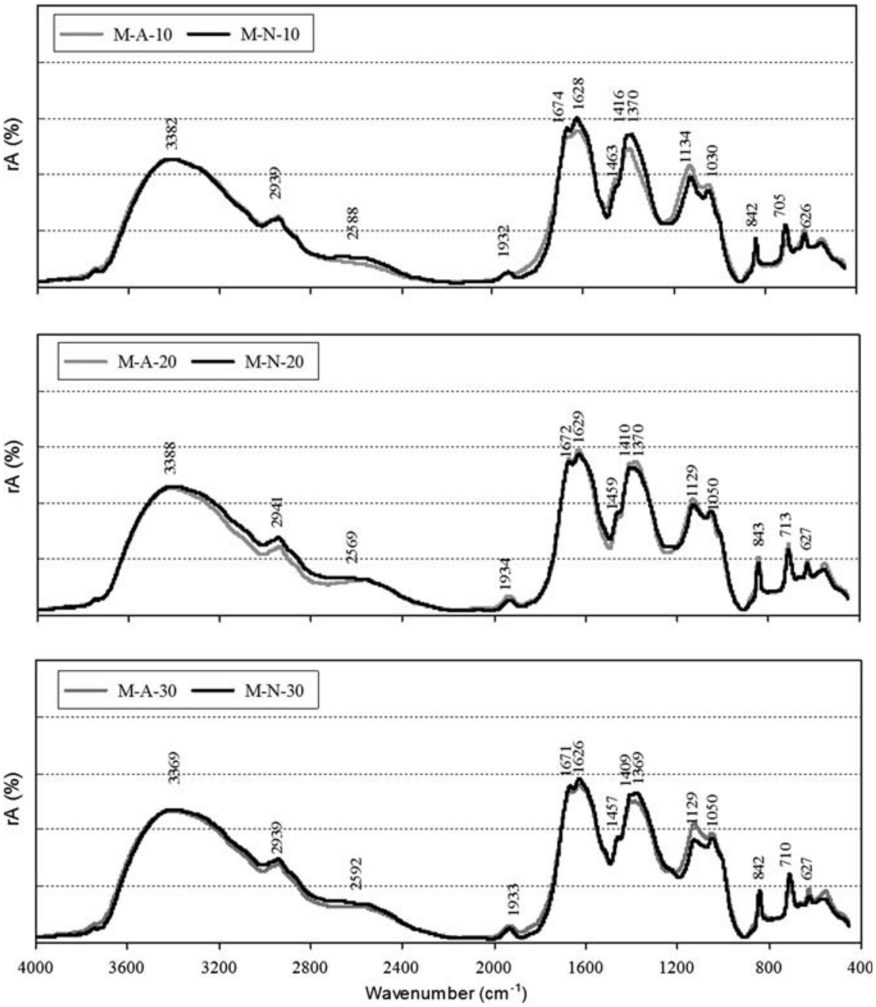

Fig. 4 FTIR spectra of M compost extracts produced under differing conditions of aeration and temperature

1,250 cm^{-1}). The longer duration of the production process of non-aerated teas can explain this finding, since the degradation of polysaccharides by microorganisms would be greater and therefore the intensity of this band would be lower. With respect to the effect of temperature, high temperatures seem to favour microbial activity; therefore degradation of easily oxidizable organic matter would be more intense. On the other hand, aerated teas showed slightly lower rA for 1,423–1,427 cm^{-1} (carboxylic acids and carbonates) than non-aerated extracts. Once more, the difference between both seems to increase at high temperatures. It is likely that this band was more intense for non-aerated teas due to the increase in the concentration of low molecular weight carboxylic acids, which are typically produced when organic matter is degraded under anaerobic conditions. Moreover, these anaerobic processes are favoured by high temperatures. Finally, significant differences were also found between aerated and non-aerated extracts produced at 30°C for the band around 1,570 cm^{-1} (aromatic C=C and secondary amides), being higher for non-aerated teas and indicating that aromatic compounds were probably produced during non-aerated extractions at high temperatures or that these compounds were concentrated mainly as a result of the degradation of polysaccharides.

Thermal analysis

DTG profiles of the compost teas (Fig. 6) exhibited a larger number of peaks than the profiles of the composts from which they were produced. Moreover, peaks were narrower than those of the composts, thus

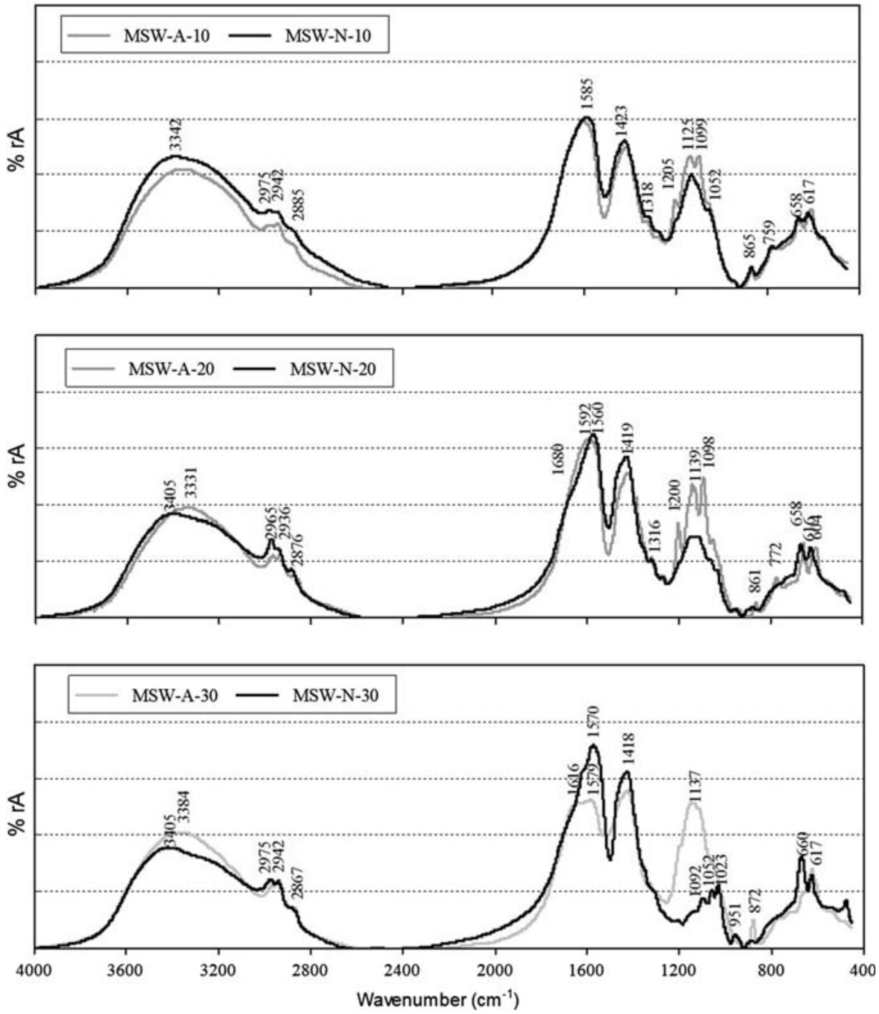

Fig. 5 FTIR spectra of MSW compost extracts produced under differing conditions of aeration and temperature

indicating that the extracts were composed of a smaller number of clearly defined chemical groups than the complex highly heterogenic organic matter of the composts.

Five regions of weight loss were distinguished in the DTG profiles of the compost extracts (Fig. 6). The first region (I), between 20 and 200°C, corresponded to the loss of residual water. Between 200 and 400°C, two peaks (region II and III) appeared, these being attributed to the combustion of carbohydrates and of the less condensed structures of the lignin molecules. Region IV, corresponding to the region between 400 and 550°C, was associated with the thermal degradation of resistant aromatic structures and polynuclear systems of higher molecular weight. Finally, peaks at temperatures above 550°C (region V) indicated oxidation of refractory C as well as the decomposition of both mineral and biogenic salts, such as carbonates. DTA curves (Fig. 7) showed that the temperature range with T < 200°C recorded endothermic peaks resulting from dehydration reactions, the range between 200 and 550°C corresponded to the exothermic oxidation of organic material, while the decomposition of mineral fraction at temperatures above 550°C produced an endothermic region. The greatest energy release in the DTA signal in every extract was linked to Thermal Effect IV, at around 400–550°C.

The main differences in DTG curves for M and MSW extracts affected Region IV (400–550°C), where the combustion of complex organic moieties took place, and Region V (550–950°C), where breakdown reactions affecting the inorganic fraction occurred.

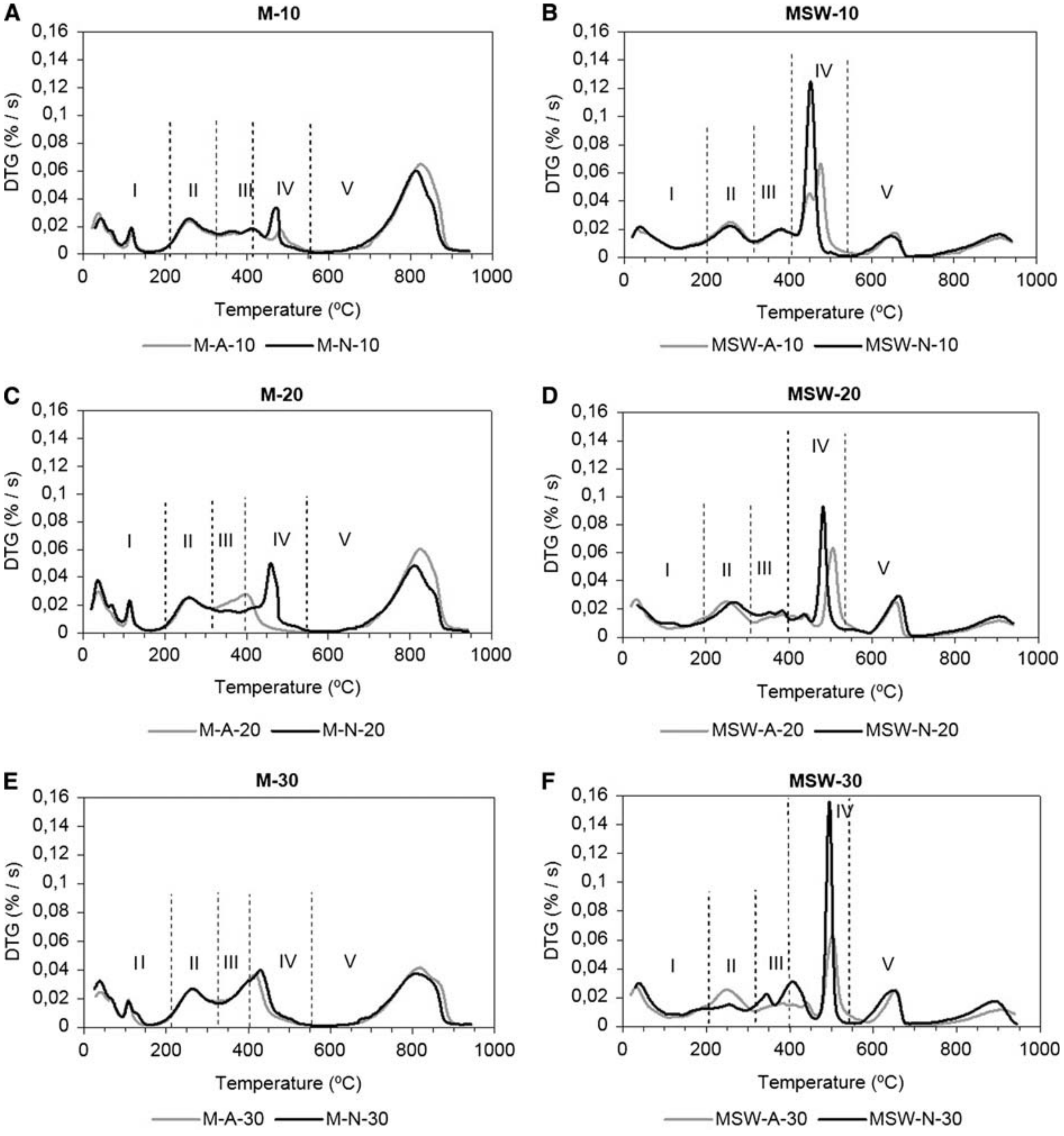

Fig. 6 DTG profiles for extracts produced with different composts under varying conditions. **a**, **c** and **e** correspond to extracts made from M compost at 10, 20 and 30°C, respectively; **b**, **d** and **f** correspond to extracts made from MSW compost at 10, 20 and 30°C, respectively

As regards Region IV, the extracts produced from MSW compost showed a loss of weight in this range (Table 3) of between 18% and 23%, while M extracts recorded lower values (7–17%). M compost, on the other hand, recorded a higher weight loss than MSW compost in this region. Thus, MSW extracts were richer in resistant aromatic structures than M extracts. Given the very low solubility of resistant organic matter, this could arise because the process of producing the extracts accelerated the degradation

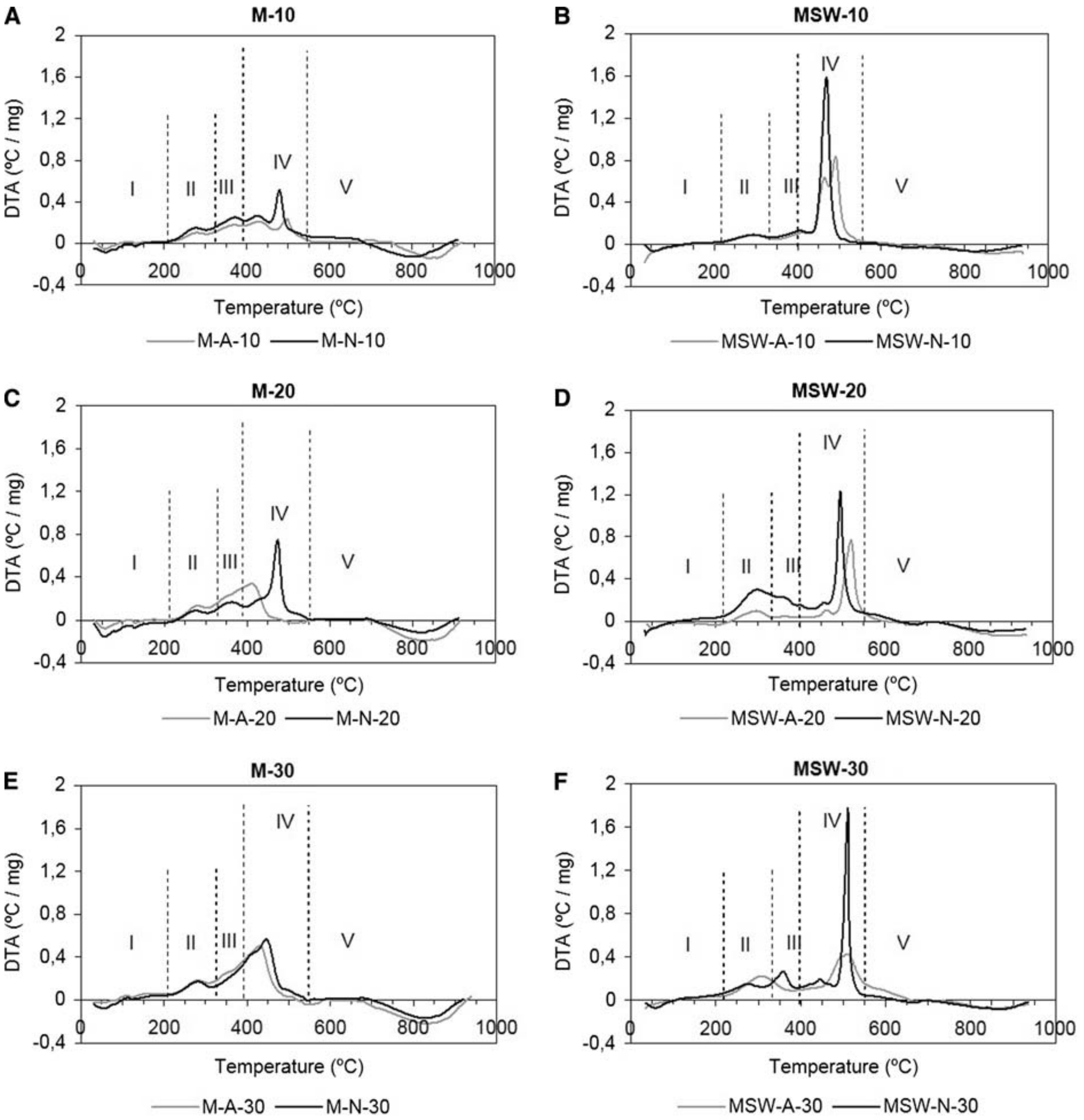

Fig. 7 DTA profiles for extracts produced with different composts under varying conditions. **a**, **c** and **e** correspond to extracts made from M compost at 10, 20 and 30°C, respectively; **b**, **d** and **f** correspond to extracts made from MSW compost at 10, 20 and 30°C, respectively

of labile organic matter, which, given the low stability of MSW compost, was more abundant in MSW than in M compost, the decrease in the concentration of this organic matter thus leading to the concentration of more complex forms. This pattern was also observed in the DTA graph (Fig. 7), where the area of the exothermic peak with a maximum between 400 and 550°C was higher for MSW than for M extracts.

With respect to Region V (550–950°C), a much higher weight loss was noted in the extracts (Table 3) than in the composts from which they had been produced (Table 2). For M extracts, this weight loss reached values of between 31% and 47%. For MSW extracts, it ranged between 16% and 22%, while it was less than 10% for both composts. This difference between the compost and its extracts indicated a concentration of inorganic forms in the extracts respect to the compost. The difference between MSW and M extracts were caused by the different composition of both composts. M extracts reached higher values of weight loss for region V because of the higher concentration of inorganic soluble nutrients in M compost, which easily lixiviated from the compost; in contrast inorganic fraction of MSW compost was less soluble.

Additionally, M and MSW extract profiles differed in the temperatures at which maximum weight loss occurred in Region V (Fig. 6). M extracts showed a broad peak around 800°C, whereas MSW extracts showed two peaks in this region, one around 650°C and another, broader peak at 950°C. The latter appeared as a very slight peak in the DTG profile of MSW compost. Taking into account the results of FTIR analysis, the peak at around 650°C could be attributed to carbonates. However, this peak was not distinguished in M extract DTG curves because of the lower content in carbonates of M compost. Given the low solubility of clay minerals, the peak around 800°C of M compost was probably caused by the solubilization of various nutrients, in which M compost was richer than MSW compost. The preferential solubilization of inorganic nutrients, such as nitrates, phosphates, sulphates, etc., caused the enrichment of M extracts in inorganic forms and explained the high weight loss associated with Region V in M extracts. The peak at 950°C of MSW extracts could be attributed to more thermally resistant inorganic forms than carbonates.

Similarly to the results of FTIR spectroscopy for M extracts, hardly any difference was appreciated among M extracts produced under varying conditions of aeration and temperature. However, the weight loss associated with Region IV for non-aerated teas was slightly higher than for aerated teas. In contrast, however, differences were more evident for MSW extracts. Region IV showed similar values of weight loss for both aeration systems, although non-aerated extracts showed a narrower, higher peak in this region than aerated extracts. A higher weight loss for Region IV in non-aerated extracts may be caused by the longer extraction time used in the production of these extracts, which caused a more intense degradation of easily oxidizable organic forms, and therefore a concentration of more complex forms.

Table 3 Weight losses (percentage of total sample weight) for the main regions shown in the thermograms (Fig. 6) for composts and compost extracts

	Weight losses (%)					Material remaining at 950°C (%)
	Region I T < 200°C	Region II 200–325°C	Region III 325–400°C	Region IV 400–550°C	Region V 550–950°C	
Compost M	9.8	18.1	7.1	28.3	8.2	28.5
Compost MSW	8.6	16.1	6.2	18.2	9.0	41.9
M-N-10	11.5	12.3	7.0	11.9	41.8	15.5
M-N-20	15.0	13.1	7.2	15.2	34.8	14.7
M-N-30	15.2	13.3	9.1	16.6	31.6	14.2
M-A-10	11.7	11.6	7.0	11.5	46.5	11.7
M-A-20	13.1	12.5	9.8	7.7	42.6	14.3
M-A-30	12.5	13.0	9.4	13.4	34.1	17.6
MSW-N-10	13.2	12.4	7.3	22.7	18.0	26.4
MSW-N-20	13.7	14.2	7.7	18.5	21.4	24.5
MSW-N-30	15.9	9.7	8.4	22.9	22.2	20.9
MSW-A-10	13.2	13.6	7.4	22.9	16.1	26.8
MSW-A-20	14.2	14.0	6.3	19.5	16.8	29.2
MSW-A-30	14.1	12.6	6.7	20.3	18.4	27.9

In addition, the two extracts produced at 20°C showed lower values of weight loss for this region, though higher values for Region II. As MSW extracts produced at 20°C were the first extracts produced with MSW compost, the evolution of the stability of MSW compost over the three months that the compost tea production experiments lasted seems to influence the composition of the extracts. Thus, given the low stability of MSW compost when the two extracts were produced, these extracts presented a higher concentration of readily degradable organic matter.

Conclusions

In this study, FTIR spectroscopy and thermal analysis were used to characterize liquid extracts of compost (compost teas) and compare their composition with that of the compost used in their production. The use of these techniques applied to compost extracts provided information about the chemical composition of the extracts. It enabled identification of which components had been preferentially extracted and/or which biological and chemical transformations had taken place.

The effect of temperature and aeration on compost extract composition is difficult to determine, since an uncontrolled factor affected to the extracts composition: the degree of stability of the composts. M compost showed a high degree of stability; in contrast MSW compost was unstable and underwent transformations over the three months that the experiments lasted. This way, hardly any difference was found among M extracts produced under differing conditions. In contrast, differences were more significant for MSW extracts. The different behaviour of the extracts produced from each compost was mainly caused by the different degree of stability of M and MSW composts.

Compost with a low degree of stability had a high content of easily oxidizable organic matter and a lower content of aromatic forms. These characteristics were shown by MSW-A-20 and MSW-N-20, which were produced with less stabilized MSW compost.

Independently of compost stability, organic matter composition suffered some changes throughout the extraction process; simpler forms such as polysaccharides and aliphatic forms were degraded by the microorganisms which grew in the extracts, causing a concentration of more complex forms such as resistant aromatic structures. These transformations, given the higher concentration of easily oxidizable organic matter, were more intense for MSW extracts, and the effect of temperature and aeration on the composition was more noticeable for these extracts.

Temperature had hardly any influence on the composition of M extracts. In contrast, temperature favoured microorganism activity in MSW extracts: the higher temperature, the more intense the degradation of carbohydrates and aliphatic forms.

Non-aerated teas showed a higher content in more complex forms according to thermal analysis, probably caused by the longer extraction time, which allowed microorganisms to degrade organic matter to a higher extent, leading to concentration of more complex forms.

Finally, the solubility of the inorganic forms present in the composts affected the composition of the extracts; the concentration of inorganic soluble nutrients increased in the extracts with respect to compost. This issue is interesting with a view to using compost tea as a fertilizer.

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