Waste Management 178 (2024) 231–238

Contents lists available at ScienceDirect

Waste Management

journal homepage: www.elsevier.com/locate/wasman

Research Paper

Addressing the gaseous and odour emissions gap in decentralised biowaste community composting

Daniel González [a], Raquel Barrena [a], Javier Moral-Vico [a], Ignacio Irigoyen [b], Antoni Sánchez [a,*]

[a] Composting Research Group (GICOM) Dept. of Chemical, Biological and Environmental Engineering, Universitat Autònoma de Barcelona, 08193-Bellaterra, Barcelona, Spain
[b] Department of Agronomy, Biotechnology and Food, Public University of Navarre, 31006 Pamplona-Iruña, Navarra, Spain

ARTICLE INFO

Keywords:
Ammonia
Community composting
Gaseous emissions
GHG
Odours
VOC

ABSTRACT

Composting has demonstrated to be an effective and sustainable technology to valorise organic waste in the framework of circular economy, especially for biowaste. Composting can be performed in various technological options, from full-scale plants to community or even individual composters. However, there is scarce scientific information about the potential impact of community composting referred to gaseous emissions. This work examines the emissions of methane and nitrous oxide as main GHG, ammonia, VOC and odours from different active community composting sites placed in Spain, treating kitchen, leftovers and household biowaste. Expectedly, the gaseous emissions have an evident relation with the composting progress, represented mainly by its decrease as temperature or biological activity decreases. GHG and odour emission rates ranged from 5.3 to 815.2 mg CO_{2eq} d^{-1} kg^{-1}VS and from 69.8 to 1088.5 ou d^{-1} kg^{-1}VS, respectively, generally being lower than those find in open-air full-scale composting. VOC characterization from the community composting gaseous emissions showed a higher VOC families' distribution in the emissions from initial composting phases, even though terpenes such as limonene, α-pinene and β-pinene were the most abundant VOC along the composting process occurring in the different sites studied. The results presented in this study can be the basis to evaluate systematically and scientifically the numerous current projects for a worldwide community composting implementation in decentralised biowaste management schemes.

1. Introduction

Composting is a well-known technology for the treatment and valorisation of biowaste. Biowaste composting presents several challenges as the potential presence of impurities or pollutants, but probably the main problem concerning their massive implementation is the emission of some gases with several negative effects (Cerda et al., 2018). Among them, the presence of ammonia, greenhouse gases (GHG, specifically methane and nitrous oxide, with a strong global warming potential), volatile organic compounds (VOC, some of which can be toxic) and unpleasant odours is critical to determine the suitability of the biowaste composting in a specific location and to develop measures for their abatement (Colón et al., 2009, 2012; González et al., 2019). It is of special relevance that most of the published studies on this topic are focused on one or two types of emission, which makes difficult to have a general picture of the overall environmental impact attributed to gaseous emissions derived from composting.

In large-scale composting plants or, in general, in waste treatment facilities, gaseous emissions have been largely studied (Colón et al., 2017; González et al., 2022a). The abatement of these emissions is today well developed with the inclusion of chemical or biological units or the combination of them. Specifically, biofilters have demonstrated to be a good option for the abatement of ammonia, VOC and odours (Pagans et al., 2006; Rolewicz-Kalinska et al., 2021). In general, with a good characterisation of gaseous emissions, there are several treatments that can reduce the impact of composting to a minimum (Wei et al., 2017).

However, in community or individual home composting, gaseous emissions are often directly released to the atmosphere, fact that could cause some environmental and social problems. On one hand, the most evident is the release of pollutants to atmosphere with negative effects in air quality, global warming or human health. Besides, as these composters are generally very close to citizens, the nuisance caused by some gases, especially malodorant compounds such as sulphur- and nitrogen-based VOC. In any case, it is important to have quantitative results on

---

* Corresponding author.
E-mail address: antoni.sanchez@uab.cat (A. Sánchez).

https://doi.org/10.1016/j.wasman.2024.02.042
Received 14 December 2023; Received in revised form 19 February 2024; Accepted 23 February 2024

the emission rates and emission factors of all these gases. This is an issue that has been partially treated in home composting, small-scale systems that are generally used to treat the household biowaste generated by a family unit (Barrena and Sánchez, 2022), but rarely in community composting, which are bigger systems devoted to treat higher biowaste income from bigger communities such as neighbourhoods, schools or hospitals in urban, suburban or rural areas (García-Prats et al., 2023). In fact, in home composting there is a considerable number of studies reporting data on gaseous emissions and related environmental impact (Andersen et al., 2010; Cheng et al., 2022). As general conclusion, it can be stated that home composting emissions per kg of volatile solid treated are normally lower than those found in industrial facilities (Cheng et al., 2022; Sánchez, 2022), even though the latter are always treated prior to their release into the atmosphere (Colón et al., 2009).

Nevertheless, this is not the case of community composting. Several scientific and dissemination publications explaining initiatives of community composting in markets, universities, schools, hospitals, etc., around Central Europe, the Mediterranean area and some Spanish locations are available, which are evaluated in economic and social terms (Marcello et al., 2021; Sánchez, 2022; Torrijos et al., 2021); however, to our knowledge, there is a lack of publications related to the performance of the process and, specifically, in the field of atmospheric gaseous emissions. Few studies addressing the environmental impact of community composting experiences are available, mainly applying default emission factors provided by the Intergovernmental Panel on Climate Change (IPCC) in the 2006 Guidelines for National Greenhouse Gas Inventories (IPCC, 2006) to estimate GHG emissions for further Life Cycle Assessment (Hibino et al., 2023). However, these default emission factors have been proved to vary depending on the composting conditions and scale (Ermolaev et al., 2015; Thomas et al., 2020), pointing out the need to specifically study the related CH_4 and N_2O emissions per mass unit of biowaste treated in community composting systems.

Therefore, the main objective of this paper is to fill this gap and to report novel data on gaseous emissions from biowaste community composting units. Specifically, these gaseous emissions covered the main gaseous pollutants emitted from composting: (i) ammonia, responsible for atmospheric and odour pollution causing the loss of nitrogen in compost; (ii) methane and nitrous oxide as powerful GHG; (iii) volatile organic compounds with different effects on atmosphere, superficial water and soil and (iv) odours, one of the main societal concerns when implementing composting strategies. Several active and consolidated composting sites, which have been under continuous operations for at least 5 years, were studied in different locations of Spain during spring 2022. In these systems (which contemplate different scales and locations), ammonia, methane, nitrous oxide, VOC (total and chemical families) as well as odours determined by dynamic olfactometry were measured and correlated with the composting stage (active composting, middle stage and maturation). To our knowledge, this is the first paper where these data are presented. Although this study is only focused on Spanish community composting systems, the climate conditions and the food habits in Spain are similar to all the European Mediterranean area, making the results here presented representative enough for a larger territory than that of the studied composting sites.

2. Materials and methods

2.1. Community composting sites

Four community composting sites were studied (Sites 1–4) during spring 2022. They were located in different municipalities in the North of Spain, from the Atlantic coast to the Mediterranean area, specifically in Barcelona (Catalonia), Pamplona (Navarre) and Pontevedra (Galicia) as shown in Fig. S1 of the Supplementary Information. All of them were active systems, with a long-lasting operation of at least 5 years and processed biowaste of different sources. According to Zero Waste Europe Guide (Europe, 2019), Sites 1, 3 and 4, were modular slatted composters with three 1 m^3 modules each where organic kitchen waste, leftovers and household organic waste composed mainly by vegetables, fruits, meat and fish coming from a university restaurant, a civic centre kitchen and private houses, respectively, were treated. First module was appointed to receive the biowaste input by the user (input module or module 1). Once filled, material was transferred to a second thermophilic module (module 2), and finally was transferred again to a third one where compost was cured (output module or module 3). Remaining time in each module depended on filling rate and ranged between 2 and 4 weeks. Site 2 was a single independent 800 L rod composter where organic kitchen waste and leftovers mainly containing vegetables, fruits, meat and fish and collected from a little university canteen were entirely composted in the same module. Biowaste was added from the top and compost was extracted from the bottom like in home composting. The main characteristics of the studied sites are compiled in Table 1.

Sites 1, 3 and 4 were visited once in spring 2022 due to distance restrictions. The different modules conforming the community composting systems were sampled and analysed to obtain a complete and representative characterization of each of the systems performance and their related gaseous emissions. On the other hand, it was possible to monitor in a weekly basis the evolution of Site 2 during the whole composting process thanks to its proximity.

2.2. Solids and gaseous emissions sampling procedures

2.2.1. Solids sampling

Random representative solid samples (between 2 and 5 kg) were obtained directly from different points of the community composter units. After collection, samples were ground to 15–20 mm size to obtain more representative samples. Samples were frozen and conserved at −18 °C. Before analysis, the samples were thawed at room temperature (25 °C) during no more than 24 h.

2.2.2. Gas sampling procedure

Gas sampling campaigns were carried out during spring 2022. Gas samples were collected from each of the units under study (Table 1) for the determination of VOC, ammonia, GHG (methane and nitrous oxide) and odours, as detailed in subsequent sections.

Regarding sampling, all the emission sources in this study were defined as passive area emission sources. As reported by different authors, the determination of emission rates from area sources requires the use of sampling devices such as flux chambers or wind tunnels to simulate environmental conditions related to gas emission sources (Capelli et al., 2009). In this case, a semi-spherical stainless-steel flux chamber (FC) was used to collect gas samples for the subsequent measurement of odour, ammonia, hydrogen sulphide, methane and nitrous oxide concentrations and total and specific VOC characterization. High purity nitrogen was pumped into the FC at a flow rate of 4.5 L min^{-1} for 30 min, which represented about 3 FC residence times, to ensure

Table 1
Characteristics of community composting sites. All the systems are fed in a daily basis.

Composting site	Number of Modules	Module capacity (L)	Biowaste Origin
Site 1 - University campus in Pamplona	3	1,000	Several university kitchens – kitchen waste and leftovers
Site 2 - University canteen in Barcelona	1	800	University canteen kitchen – kitchen waste and leftovers
Site 3 - Civic centre in Pontevedra	3	1,000	Community kitchen of the civic centre – kitchen waste and leftovers
Site 4 - Neighbourhood in Pontevedra	3	1,000	Private houses – household kitchen waste

reaching constant gas concentrations inside the FC before sampling. To avoid cross-contamination, Nalophan® sampling bags were placed inside a hermetic sampling drum and a vacuum pump was used to obtain the gaseous samples. A schematic of the sampling train is shown in the Supplementary Information (Fig. S2).

Stainless steel sorbent tubes packed with two different hydrophobic sorbents (Tenax® TA and Carbograph™ 1TD, Markes International, Inc., Gold River, CA, USA) were used to retain gaseous samples for VOC characterization as detailed by the USEPA TO-17 method (USEPA, 1999) and reported elsewhere (González et al., 2019). Two different sorbents were used to maximise the retention of a wider range of VOC. All the sorbent tubes were sealed with Swagelok end caps fitted with PTFE ferrules after sampling and stored at 4 °C until the moment of analysis, which should be before the following 7 days to preserve sample's stability (Ribes et al., 2007).

Several images of the gas sampling procedure are compiled in the Supplementary Information (Fig. S5 and S6).

2.3. Physical and chemical analyses

2.3.1. Composting and compost analytical procedures

2.3.1.1. Composting temperature and interstitial oxygen. Temperature and interstitial oxygen within the composting matrix were measured using a portable thermometer (HD2307.0, Delta Ohm, Italy) and an oxygen probe connected to a manual air pump (ClipSense O_2, Sensotran, Spain), respectively. Temperature and interstitial oxygen measures were done at three different points from the centre to the composter wall at the same time to obtain an integrated measurement of each parameter.

2.3.1.2. Routine analytical methods. Solid materials were characterized in terms of moisture content (MC), organic matter (OM), pH and electrical conductivity (EC) according to standard procedures (Thompson et al., 2001).

2.3.1.3. Dynamic respiration index. Dynamic respiration index (DRI) was used to assess the biological activity of the composting solid samples, calculated as the average oxygen uptake rate reached during the 24 h of maximum activity (Ponsá et al., 2010). All measurements were conducted in triplicates.

2.3.2. Gaseous emissions measurement

2.3.2.1. Ammonia, total VOC and hydrogen sulphide analysis. Total VOC and ammonia concentration of the gas samples were measured with a MiniRAE 3000 portable analyser (RAE Systems, San José, CA, USA), equipped with a 10.6 eV PID lamp for VOC measurement (detection range 0–15,000 ppm_v with 0.1 ppm_v increments) and an iBrid™ MX6 multi-gas monitor (Industrial Scientific Co., Pittsburgh, PA, USA) equipped with an electrochemical sensor for ammonia (detection range 0–100 ppm_v with 1 ppm_v increments), respectively. Hydrogen sulphide was also analysed with an iBrid™ MX6 multi-gas monitor supplied with a hydrogen sulphide electrochemical sensor (detection range 0–500 ppm_v, with 0.1 ppm_v increments).

2.3.2.2. Greenhouse gases analysis. Methane and nitrous oxide analysis were performed by gas chromatography (GC). For methane analysis, an Agilent 6890 N GC equipped with a flame ionization detector (FID) and a HP-PLOT Q semi-capillary column was used. Besides, an Agilent 8860 GC equipped with an electron capture detector (ECD) was used for nitrous oxide analysis, using the same type of chromatographic column.

2.3.2.3. VOC characterization. VOC characterization in the form of different VOC species in the gaseous samples was based on a previous methodology developed by González et al. (2019a), using a UNITY-2 thermal desorber (Markes International, Inc.) to desorb the VOC retained in the sorbent tubes and an Agilent 7820 GC coupled to an Agilent 5975 Mass Spectrometer (MS) for the separation and analysis of the different VOC species present in each gaseous sample. The chromatographic column used was an Agilent DB-624 capillary column. The Agilent 5975 MS acquired data in scan mode with m/z interval ranging from 35 to 355 amu. Wiley275 mass spectra library was used to identify the different VOC by matching their mass spectra, with a minimum match quality of a 90 %.

2.3.2.4. Odour analysis. Odour analysis of the gaseous samples was performed using a Scentroid SM-100 portable field olfactometer (IDES Canada, Inc., Whitchurch-Stouffville, ON, Canada), previously described elsewhere (González et al., 2019). This specific portable olfactometer is factory-calibrated, with a calibration range from 3.5 to 11,355 $OU \cdot m^{-3}$. All samples were analysed in duplicates by the same panellist in a clean, closed, and well-ventilated lab within the next 24 h after sample collection.

2.3.2.5. Estimation of emission rates. To determine the different emission rates, the methodology used was based on the measured pollutant concentration, the nitrogen flow introduced in the FC as inert gas and normalized by a representative variable of the treatment process according to Capelli et al. (2009) and González et al. (2022b).

To objectively compare the emission rates from different sites or systems, which can be affected by different treatment capacities and biowaste dry matter and volatile solids content, the emission rates can be normalized by the mass treated in volatile solids (VS), as shown by Eq. (1):

$$ER_{VS,i} = ER_i \cdot m_{VS} \tag{1}$$

being $ER_{VS,i}$ the emission rate of the pollutant i per mass of VS in the composter (mg d^{-1} kg^{-1}VS or ou d^{-1} kg^{-1}VS), ER_i the emission rate of the pollutant i (mg d^{-1} or ou d^{-1}) and m_{VS} the mass of VS in the composter (kg of VS).

3. Results and discussion

3.1. Composting performance

Several parameters were measured as indicators of the composting performance. In particular, moisture, organic matter content, pH and electrical conductivity of the initial composting mixtures (Table S1) were similar to those found in biowaste composting at industrial and home scale (Lleó et al., 2013).

Temperature showed two different patterns according to the composting site. On one hand, Sites 1, 3 and 4, where different modules were used for the different stages of the material, presented a gradual decrease in temperature according to the content of biodegradable organic matter, as expected. Thus, the first module, which contains raw biowaste showed values of temperature in the thermophilic range, within 60–70 °C. The second module, which contains partially degraded biowaste (age of 2–3 weeks) presented considerably lower temperatures in the range of 35–45 °C, whereas the third module, containing composted material of an age up to two–three months, was close to ambient temperature. On the other hand, Site 2, where all the process take place in the same composter, temperature evolution was similar to those found in full-scale composting although the thermophilic period was shorter (around 30 days) than those corresponding to larger composting mass, which can last over 50 days (Barrena et al., 2006b). The temperature evolution of Sites 1 and 2 is shown in Supplementary Information (Fig. S3).

Regarding interstitial oxygen, and although it was only occasionally measured, all the values obtained were higher than 8 % at the beginning of the composting processes, which are suitable for the prevalence of aerobic conditions. This was due to a proper porosity of the initial mixture, which was achieved by including pruning wastes, in a volumetric ratio of 1 vol of biowaste and 1 vol of pruning waste (Ruggieri et al., 2009). As expected, interstitial oxygen in composted biowaste where close to ambient air (higher than 19 %).

Stability is a useful parameter to measure the efficiency of the composting process and to monitor the composting process along time (Colón et al., 2012). In this study, the values of DRI measured in the final compost of Sites 3 and 4 (selected as examples) were 1.4 and 1.3 g O_2 kg^{-1} dry matter h^{-1}, respectively. These values are similar to those found in full-scale mechanical–biological treatment plants for final stabilised compost (1.5 g O_2 kg^{-1} dry matter h^{-1}, Barrena et al., 2014). Considering that the DRI of raw biowaste from municipal source-selected collection systems is around 5–7 g O_2 kg^{-1} dry matter h^{-1} (Barrena et al., 2014), it can be concluded that a proper stabilisation occurred in the studied community composting sites.

3.2. Ammonia emissions and total VOC

The emission trend observed for ammonia, hydrogen sulphide and total VOC for the composting community Site 1 is presented in Fig. 1, used as example.

Sites 3 and 4 are also presented in Supplementary Information (Fig. S4), showing similar trends. In Site 1 (Fig. 1), ammonia concentrations were between 0 and 62.5 ppm_v, with concentrations in module 1 (after turning the material) being higher than those found in home composting studies, which have been reported to be around 5 to 6 ppm_v on average (Lleó et al., 2013; Neugebauer and Sołowiej, 2017). This situation is most likely due to the presence of raw materials with a high protein content such as meat or fish, in the range of 5 to 15 % (w/w) (Storino et al., 2016). Generally, ammonia emissions during biowaste composting are relatively low, as the composting material has a C/N ratio close to the optimum values for a biological process (around 25:1, Pagans et al., 2006). Regarding hydrogen sulphide, emission was only observed in module 1, especially after turning the material, reaching values of 19 mg H_2S d^{-1} kg^{-1}VS. In reference to the total VOC, high emission fluxes and concentrations were observed in the first module before turning (17 mg C-VOC d^{-1} kg^{-1}VS and 52 ppm_v, respectively). This fact could be related to the layer of bulking agent that is placed on the top of the biowaste to be composted since, as previously reported, the vegetable fraction used as bulking agent can cause the volatilization and emission of certain VOC families such as terpenes (Schiavon et al., 2017).

In Sites 3 and 4, ammonia and total VOC emissions follow, to a certain extent, the same pre- and post-turning emission dynamics observed for other emission flows (such as odours, as explained in section 3.5). Notwithstanding this, it should be noted that a correlation has not been reported between the content of ammonia or total VOC with the concentration of odour, when this concentration is measured through dynamic olfactometry (González et al., 2019). This is basically related to the high diversity of VOC in the composting gaseous emissions, whose presence can affect the perception of odour and, therefore, the concentration of odour perceived, as previously reported by Hanajima et al. (2010). In Sites 3 and 4 (data not shown), the ammonia concentrations were between 1 and 389 ppm_v and between 0 and 3 ppm_v respectively, which are something in between those found in home composting (Lleó et al., 2013). The differences in NH_3 concentration are probably related to a different biodegradability of the starting material (Colón et al., 2012), an issue that is inherent of the OFMSW (Barrena et al., 2011). Regarding total VOC, high emission flows and concentrations were observed in the first and second modules of Sites 3 and 4, 5.9 – 39.4 ppm_v and 0.3 – 120.9 ppm_v, respectively. In this sense, it is important to note that Site 4 has a higher amount of the rejected materials from plants used as bulking agent, as seen in the VOC characterization presented in section 3.4.

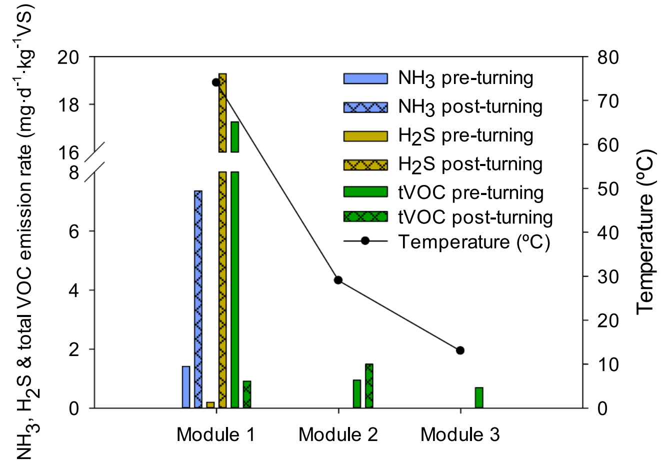

Fig. 1. Fluxes of ammonia, hydrogen sulphide and total VOC in Site 1.

3.3. GHG emissions

Discarding carbon dioxide, which is considered to come from biogenic sources in the biological process of composting (International Energy Agency, 2022), the main contributors to global warming from composting are methane and nitrous oxide (Forster et al., 2021). They come from anoxic and anaerobic spots in the composting mass (Ermolaev et al., 2014). These gases can be individually analysed or expressed as carbon dioxide equivalents, especially when used for global warming measurements in Life Cycle Assessment (LCA) studies (Colón et al., 2012).

In the studied sites, the profile observed for methane and nitrous

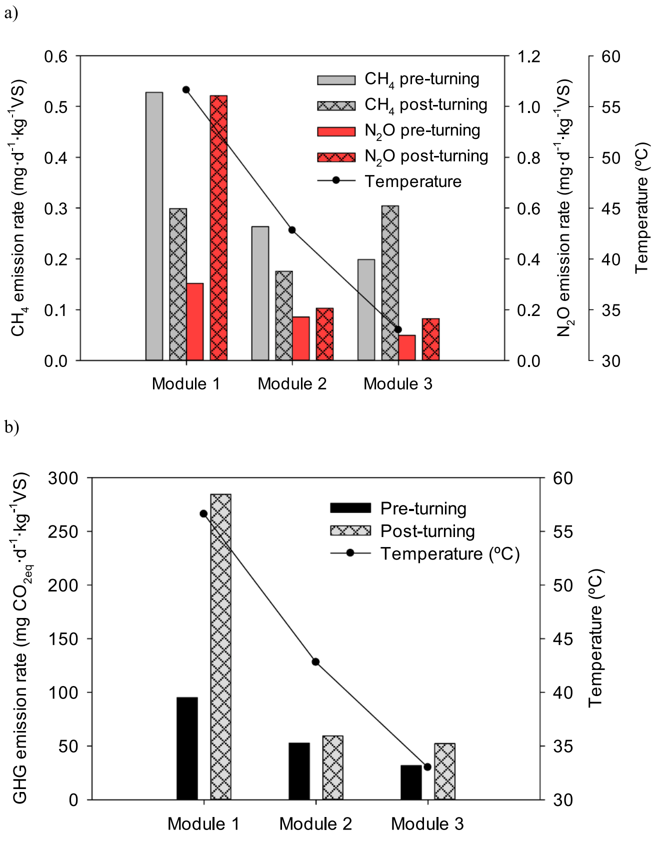

Fig. 2. a) Fluxes of methane and nitrous oxide emissions in Site 4; b) Flux of carbon dioxide equivalent emission in Site 4.

oxide followed a decreasing evolution according to the stage of the organic material (Fig. 2, Site 4).

However, increases and decreases of emissions according to turning were found, which theoretically should favour the prevalence of aerobic conditions and, in consequence, the reduction of methane and nitrous oxide. A possible explanation of these specific findings can be due to an incomplete manual mixing of the entire composting mass, which in community composting is a laborious and complicated operation (some pictures of the manual mixing are shown in the Supplementary Information, Fig. S6). Another possible explanation to this specific situation can be that methane and/or nitrous oxide retained in anoxic or anaerobic spots within the composting mass can easily flow through during and just after the mixing of the material, coinciding with the "post-turning" sampling event and punctually increasing the emission rates (Dietrich et al., 2021).

GHG have been extensively studied in other composting systems, especially in full-scale composting plants (Colón et al., 2012) but also in home composting (Colón et al., 2010), which would be more similar to community composting. In this latter case, there is a clear dependence between the temperature of the material and the GHG emissions generated during the process. Temperature and turning are the factors on which GHG emissions depend in low-scale composting (Ermolaev et al., 2014). In the case of industrial composting, GHG emissions can be an effect of compaction or insufficient aeration. Table 2 shows a comparison of the specific emission rates and concentrations determined in this study with values obtained in other composting studies to illustrate these differences among the GHG of the composting at different scales.

As observed in Table 2, it is evident that the GHG emissions are highly variable, and strongly dependant on the composting conditions. As a general rule, emissions from low-scale systems are lower than those of full-scale systems. However, most of these industrial systems have specific units for air cleaning, which diminishes the impact of GHG and odour-like emissions. The results obtained in this work represents a first step into the future determination of GHG emission factors corresponding to community composting systems. At the moment, IPCC Guidelines for National GHG Inventories (IPCC, 2006) sets default emission factor values for CH_4 and N_2O composting emissions addressing full-scale facilities, but do not represent the reality in GHG emissions from smaller scale facilities such as community composting systems, as it can be observed by comparing GHG emission rates shown in Table 2.

3.4. VOC characterization

Table 3
Complete characterisation of VOC detected in Site 1 (ppb$_v$ units, symbol - means not measured). DMS: Dimethyl sulphide, DMDS: Dimethyl disulphide.

VOC	Input module	Second module	Output module
DMS	3.2	0.0	0.0
Hexane	6.6	0.0	0.0
1-butanol	3,535.6	60.9	0.0
DMDS	4,028.1	32.1	14.6
Pyridine	98.1	0.0	0.0
Ethyl butyrate	73.5	0.0	0.0
1-hexanol	33.9	0.0	0.0
Styrene	6.8	0.0	0.0
α-pinene	672.5	6.3	2.5
2-butoxyethanol	2.8	0.0	0.0
Cyclohexanone	6.8	0.0	0.0
Decane	27.9	13.1	14.4
β-pinene	1,620.4	25.3	12.6
Benzaldehyde	13.1	0.0	0.0
Limonene	7,969.7	1,149.0	933.1
p-cymene	155.3	9.7	3.1
Phenol	7.7	0.0	0.0
Decanal	0.0	0.0	5.3
Total	18,261.8	1,296.4	985.6

Table 3 shows the characterization of the main VOC detected in Site 1 before turning for the three modules. This site was selected as example, although relatively similar results were found in other sites (Sites 3 and 4, Supplementary Information, Table S2).

In general, some differences can be observed during VOC characterization depending on the different gas samples analysed. First, it should be noted that the quantified compounds represent between 35 and 98 % of the total VOC measured according to each sample, and that the variability of the observed compounds was high. This is somewhat expected in a composting process of a heterogeneous waste as biowaste. In gas emissions from Site 1, the compound with the highest concentration found was limonene, a compound from the terpene family with a characteristic smell of citrus, followed by dimethyl disulphide (DMDS, with a very low olfactory detection threshold of about 3 ppb$_v$), and by 1-butanol (alcohol that also has a low olfactory detection threshold of about 38 ppb$_v$) (Nagata, 2003). This could be related to the fact that approximately 5 % of the biowaste from Site 1 was composed by orange peel from the juice machine in the canteen on the university campus. Apart from these, there were also other different terpenes such as α and β-pinene and p-cymene, which have been previously referenced as compounds released during the biological degradation of lignocellulosic and plant-like material such as the one used as a bulking agent during composting (Schiavon et al., 2017).

Table 2
Emission rates and concentrations of GHG determined in this study and values from other composting studies.

Reference	Composting process information		CH_4 (mg CH_4 d^{-1} kg^{-1} VS)	N_2O (mg N_2O d^{-1} kg^{-1} VS)	GHG (mg CO_{2eq} d^{-1} kg^{-1}VS)	CH_4 (ppm$_v$)	N_2O (ppm$_v$)
Site 1	Community composting. Natural convection aeration.	Min	0.1	0.0	5.3	0.7	0.0
		Max	0.2	0.1	32.6	2.2	0.4
Site 2	Community composting. Natural convection aeration.	Min	0.0	0.0	0.0	0.9	0.0
		Max	0.5	0.2	55.1	2.1	0.4
Site 3	Community composting. Natural convection aeration.	Min	0.3	0.0	7.1	0.9	0.0
		Max	12.1	1.8	815.2	61.0	3.3
Site 4	Community composting. Natural convection aeration.	Min	0.2	0.1	31.8	0.5	0.1
		Max	0.5	1.0	284.5	1.9	1.3
Adhikari et al. (2013)	Home composting. Natural convection aeration. 65 °C Max temperature reached.	Min	–	1.0	–	2.0	0.0
		Max	–	74.1	–	11.0	250.0
Andersen et al. (2010)	Home composting. Natural convection aeration. 30 °C Max temperature reached.	Min	4.5	3.3	1,022.4	–	–
		Max	34.4	6.1	2,594.1	–	–
Lleó et al. (2013)	Home composting. Natural convection aeration. 55 °C Max temperature reached.	Min	–	–	–	1.8	0.3
		Max	–	–	–	7.8	3.2
Amlinger et al. (2008)	Full-scale composting. Forced aeration. > 70 °C Max temperature reached.	Min	16.8	1.9	972.3	–	–
		Max	55.5	31.5	10.1E3	–	–
Beck-Friis et al. (2000)	Full-scale composting. Natural convection aeration. > 70 °C Max temperature reached.	Min	–	–	–	0.0	1.0
		Max	–	–	–	4.7E5	3,421.0

Together with the VOC quantification, the gas samples were also qualitatively analysed to obtain a clear picture of the distribution of the different VOC families generated throughout the composting process. Fig. 3 shows the evolution and distribution of the different families present in the gaseous emissions from Site 1. The qualitative analysis of VOC corresponding to Sites 2, 3 and 4 can be found in Fig. S7 in the Supplementary Information.

As it can be observed in Fig. 3, and evidenced by the results shown in Table 3, the most abundant VOC family found in the gas emissions is terpenes (76 to 92 %), being limonene the most abundant individual VOC. In module 1, other types of VOC such as alcohols, ketones or sulphur-based compounds (mainly DMDS) were also present in a range of 3 to 4 %, which are normally generated and emitted during the first steps of biowaste composting (Maulini-Duran et al., 2013). Then, VOC emitted by middle-aged and final material (modules 2 and 3, respectively) were characterised by presenting traces of other VOC such as aromatic hydrocarbons and aldehydes, apart from the ones mentioned before (Reboredo-Rodríguez et al., 2015). These results are in accordance with other works targeting the characterization of VOC generated at bench and full-scale composting plants treating organic fraction of municipal solid waste (OFMSW), in which terpenes such as limonene and alcohols such as 1-butanol were found to be the most abundant VOC present in the gaseous emissions (Dorado et al., 2014, Schiavon et al., 2017).

Regarding the results obtained in Sites 1, 3 and 4 (Supplementary Information, Table S2), some slight differences appeared. Specifically, the quantified compounds represented between 18 and 63 % of the total VOC measured depending on each sample being the variability of the observed compounds higher. In Site 3, the compound with the highest concentration was dimethyl disulphide, followed by 1-butanol and limonene. In Site 4, it was observed that the highest contribution was given by different terpenes such as limonene, α and β-pinene and p-cymene, all of them previously referenced as emitted compounds during the biodegradation of plant material, as previously commented.

Apart from the composition trends observed, two other general tendencies are observed, which have been showed with other composting emissions: on one hand, the age of the material has a dramatic effect on the decrease of emissions of practically all the VOC analysed, except for the case of limonene, related to the decomposition of plant-like and lignocellulosic biomass, which is more recalcitrant to biodegradation (Maulini-Duran et al., 2014); on the other hand, turning does not have the same effect in the emissions of VOC studied, and it is also related to the material age. Thus, at the early stages of composting, there is a clear trend of increasing VOC emissions after turning the material, which is the expected behaviour (Duan et al., 2022). However, in the composted material, this trend is not clear for all the compounds analysed. Unfortunately, to our knowledge, there are no scientific publications regarding this aspect at this scale of composting, although it has been presented in industrial composting (Dorado et al., 2014). In general, the number of publications where VOC families emitted during composting are presented and quantified is relatively scarce.

3.5. Odours

Odours were followed in some samples of the community composting sites 1, 3 and 4. It is important to note that the number of publications with odour data determined by dynamic olfactometry in waste treatment plants is very scarce and, to our knowledge, inexistent in community composting. However, the importance of odours in the acceptance of community composting is a critical issue (González et al., 2022a).

In the study of the community composting sites, the first thing to point out is the clear relation between the decrease of odours emissions and the age of material and hence, its biological stability degree. As example, the flux of odour emissions in Site 4 is shown in Fig. 4. The trends observed in the other sites are similar and are shown in Fig S8 in

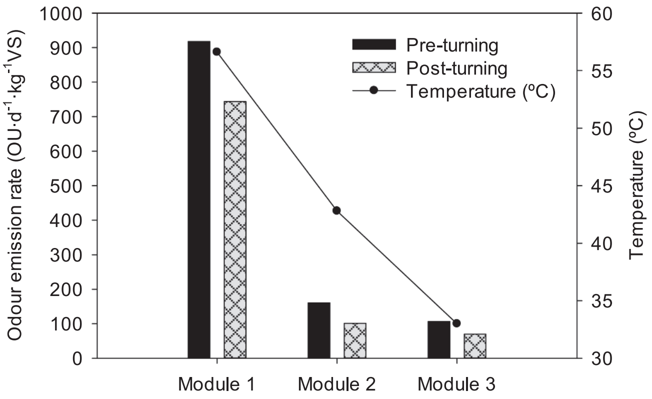

Fig. 4. Flux of odour emissions in Site 4.

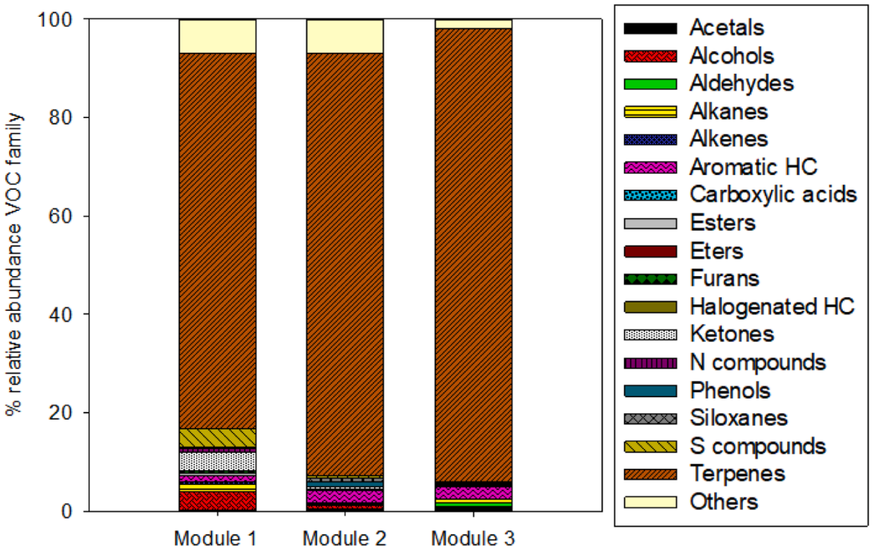

Fig. 3. Relative abundance of VOC families in gaseous emissions from Site 1.

the Supplementary Information.

In Fig. 4, a decreasing trend in the odour emission rates is observed as the composting process progresses, as previously described and correlated in various composting processes where, as biological stability of the material -expressed as DRI- increased, odour emissions decreased (Gutiérrez et al., 2015; González et al., 2019; Scaglia et al., 2011). These odour emissions depend on the current emission of volatile odorants such as NH_3 and the many different VOC, the contribution of their respective concentration and the odour detection threshold of each odorant compound present in the different gas samples, from which it is possible to determine the individual contribution to odour of each odorant present in the gaseous samples (Schiavon et al., 2017). However, it should be considered that the sum of these individual contributions to odour does not represent the final odour of a complex gas sample due to the synergistic and antagonistic effects between single odorants (Hanajima et al., 2010). The odour concentrations determined are from 187 to 4,208 ou m^{-3} (Site 3), from < 100 to 1,910 ou m^{-3} (Site 4) and from 195 to 2,834 ou m^{-3} (Site 1), which cannot be contrasted with results from similar composting studies due to a lack of references. However, these values are significantly lower than those reported in studies of OFMSW industrial composting plants, which were from 2,256 to 11,000 ou m^{-3} according to Sironi et al. (2006) and Gutiérrez et al. (2015). Obviously, this fact is of special relevance when implementing new community composting sites in populated locations. However, it seems evident that more data is necessary to know the odour impact in community composting sites (Sánchez et al, 2022).

The results presented in this study can be a consistent starting point to build specific databases on community composting gaseous emissions for further feeding of Life Cycle Inventories and to be used by policy makers to promote the development of this kind of waste management programs. It is evident that, as a future trend for the massive implementation of community composting, i) there is a need on developing continuous monitoring of the gaseous emissions, and specially of the GHG and odour emissions, from biowaste community composting systems to confidently define reliable specific emission factors for this kind of biowaste treatment strategy and ii) the use of measures that significantly reduce gaseous emissions and odours such as simple biofilters or geotextile covers, or even more novel techniques such as the use of biochar, can be an attractive option to enhance communities and neighbourhoods' acceptance and participation (Harrison et al., 2022).

4. Conclusions

Results indicated a proper performance of the four community composting sites examined, along with the possibility of systematically analyse the gaseous and odour emissions generated by them. GHG and odour emissions were lower than those corresponding to full-scale composting, even though both types of system present similar emission trends, as a clear relationship between the gaseous and odour emissions and the material's age is observed. Besides, terpenes were found to be the predominant VOC in the community composting gaseous emissions, being limonene, α-pinene and β-pinene the terpenes measured at higher concentrations. This information can be relevant enough for the safe implementation of these decentralised biowaste treatment initiatives to consolidate them in future waste management programs, which would entail an increasing use of composting by making the process more accessible. However, more data from well-stablished and operating community composting systems treating biowaste is needed to define specific emission factors for this technology as a previous step to assess the related environmental and socio-economic impacts.

CRediT authorship contribution statement

Daniel González: Supervision, Investigation, Data curation. **Raquel Barrena:** Validation, Investigation, Data curation, Conceptualization. **Javier Moral-Vico:** Writing – review & editing, Formal analysis, Data curation. **Ignacio Irigoyen:** Writing – review & editing, Validation, Supervision, Investigation, Data curation, Conceptualization. **Antoni Sánchez:** Writing – review & editing, Supervision, Resources, Project administration, Investigation, Funding acquisition, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

This study has been financially supported by the Pandèmies Call from *Agència de Gestió d'Ajuts Universitaris i de Recerca* of Generalitat de Catalunya (Project Ref. 2020PANDE00021).

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.wasman.2024.02.042.

References

Adhikari, B.K., Trémier, A., Barrington, S., Martinez, J., Daumoin, M., 2013. Gas emissions as influenced by home composting system configuration. J. Environ. Manage. 116, 163–171. https://doi.org/10.1016/j.jenvman.2012.12.008.

Amlinger, F., Peyr, S., Cuhls, C., 2008. Greenhouse gas emissions from composting and mechanical biological treatment. Waste Manage. Res. 26, 47–60. https://doi.org/10.1177/0734242X07088432.

Andersen, J.K., Boldrin, A., Christensen, T.H., Scheutz, C., 2010. Greenhouse gas emissions from home composting of organic household waste. Waste Manage. 30, 2475–2482. https://doi.org/10.1016/j.wasman.2010.07.004.

Barrena, R., Cánovas, C., Sánchez, A., 2006. Prediction of temperature and thermal inertia effect in the maturation stage and stockpiling of a large composting mass. Waste Manage. 26, 953–959. https://doi.org/10.1016/j.wasman.2005.07.023.

Barrena, R., Font, X., Gabarrell, X., Sánchez, A., 2014. Home composting versus industrial composting: influence of composting system on compost quality with focus on compost stability. Waste Manage. 34, 1109–1116. https://doi.org/10.1016/j.wasman.2014.02.008.

Barrena, R., Sánchez, A., 2022. Home composting: a review of scientific advances. Eng. Proc. 19 (1), 35. https://doi.org/10.3390/ECP2022-12625.

Beck-Friis, B., Pell, M., Sonesson, U., Jönsson, H., Kirchmann, H., 2000. Formation and emission of N_2O and CH_4 from compost heaps of organic household waste. Environ. Monit. Assess. 62, 317–331. https://doi.org/10.1023/A:1006245227491.

Capelli, L., Sironi, S., del Rosso, R., Céntola, P., 2009. Predicting odour emissions from wastewater treatment plants by means of odour emission factors. Water Res. 43, 1977–1985. https://doi.org/10.1016/j.watres.2009.01.022.

Cerda, A., Artola, A., Font, X., Barrena, R., Gea, T., Sánchez, A., 2018. Composting of food wastes: Status and challenges. Bioresource Technol. 248, Part A, 57-67. https://doi.org/10.1016/j.biortech.2017.06.133.

Cheng, J., Yin, R., Luo, W., Li, Y., Wang, L., Chang, R., 2022. Home composting for onsite treatment of household organic solid waste: a review. Current Pollution Reports. 8, 395–408. https://doi.org/10.1007/s40726-022-00233-8.

Colón, J., Martínez-Blanco, J., Gabarrell, X., Rieradevall, J., Font, X., Artola, A., Sánchez, A., 2009. Performance of an industrial biofilter from a composting plant in the removal of ammonia and VOCs after material replacement. J. Chem. Technol. Biotechnol. 8411, 1111–1117. https://doi.org/10.1002/jctb.2139.

Colón, J., Martínez-Blanco, J., Gabarrell, X., Artola, A., Sánchez, A., Rieradevall, J., Font, X., 2010. Environmental assessment of home composting. Resources, Conservation and Recycling. 54, 893–904. https://doi.org/10.1016/j.resconrec.2010.01.008.

Colón, J., Cadena, E., Pognani, M., Barrena, R., Sánchez, A., Font, X., Artola, A., 2012. Determination of the energy and environmental burdens associated to the biological treatment of source-separated municipal solid wastes. Energy Environ. Sci. 5, 5731–5741. https://doi.org/10.1039/C2EE01085B.

Colón, J., Álvarez, C., Vinot, M., Lafuente, F., Ponsá, S., Sánchez, A., Gabriel, D., 2017. Characterization of odorous compounds and odor load in indoor air of modern complex MBT facilities. Chem. Eng. J. 313, 1311–1319. https://doi.org/10.1016/j.cej.2016.11.026.

Dietrich, M., Fongen, M., Foereid, B., 2021. Anaerobic digestion affecting nitrous oxide and methane emissions from the composting process. Bioresource Technol. Reports. 15, 100752 https://doi.org/10.1016/j.biteb.2021.100752.

Dorado, D., Husni, S., Pascual, G., Puigdellivol, C., Gabriel, D., 2014. Inventory and treatment of compost maturation emissions in a municipal solid waste treatment facility. Waste Manage. 34, 344–351. https://doi.org/10.1016/j.wasman.2013.10.044.

Duan, Z., Lu, W., Mustafa, M.F., Du, J., Wen, Y., 2022. Odorous gas emissions from sewage sludge composting windrows affected by the turning operation and associated health risks. Sci. Total Environ. 839 (15), 155996 https://doi.org/10.1016/j.scitotenv.2022.155996.

Ermolaev, E., Sundberg, C., Pell, M., Jönsson, H., 2014. Greenhouse gas emissions from home composting in practice. Bioresource Technol. 151, 174–182. https://doi.org/10.1016/j.biortech.2013.10.049.

Ermolaev, E., Jarvis, A., Sundberg, C., Smars, S., Pell, M., Jönsson, H., 2015. Nitrous oxide and methane emissions from food waste composting at different temperatures. Waste Manage. 46, 113–119. https://doi.org/10.1016/j.wasman.2015.08.021.

Zero Waste Europe. 2019. Community Composting. A Practical Guide for Local Management of Biowaste. Zero Waste Europe Guides/01. URL: https://zerowasteeurope.eu/wp-content/uploads/2019/04/zero_waste_europe_fertile_auro_guide_community-composting_en.pdf (accessed September 2023).

Forster, P., Storelvmo, T., Armour, K., Collins, W., Dufresne, J.-L., Frame, D., Lunt, D.J., Mauritsen, T., Palmer, M.D., Watanabe, M., Wild, M., Zhang, H., 2021. The Earth's Energy Budget, Climate Feedbacks, and Climate Sensitivity. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 923–1054, doi: 10.1017/9781009157896.009.

García-Prats, M., González, D., Moral-Vico, J., Madrid-López, C., Sánchez, A., 2023. Implementing community composting in primary schools: first experiences at universitat autònoma de Barcelona. Spain. Eng. Proc. 37 (1), 37. https://doi.org/10.3390/ECP2023-14730.

González, D., Colón, J., Sánchez, A., Gabriel, D., 2019. A systematic study on the VOCs characterization and odour emissions in a full-scale sewage sludge composting plant. J. Hazard. Mat. 373, 733–740. https://doi.org/10.1016/j.jhazmat.2019.03.131.

González, D., Gabriel, D., Sánchez, A., 2022. Odors emitted from biological waste and wastewater treatment plants: a mini-review. Atmosphere. 13, 798. https://doi.org/10.3390/atmos13050798.

González, D., Colón, J., Sánchez, A., Gabriel, D., 2022. Multipoint characterization of the emission of odour, volatile organic compounds and greenhouse gases from a full-scale membrane-based municipal WWTP. Journal of Environmental Management. 313, 115002 https://doi.org/10.1016/j.jenvman.2022.115002.

Gutiérrez, M.C., Martín, M.A., Serrano, A., Chica, A.F., 2015. Monitoring of pile composting process of OFMSW at full scale and evaluation of odour emission impact. J. Environ. Manage. 151, 531–539. https://doi.org/10.1016/j.jenvman.2014.12.034.

Hanajima, D., Kuroda, K., Morishita, K., Fujita, J., Maeda, K., Morioka, R., 2010. Key odor components responsible for the impact on olfactory sense during swine feces composting. Bioresource Technol. 101, 2306–2310. https://doi.org/10.1016/j.biortech.2009.11.026.

Harrison, B.P., Gao, S., Gonzales, M., Thao, T., Bischak, E., Ghezzehei, T.A., Berhe, A.A., Diaz, G., Ryals, R.A., 2022. Dairy manure co-composting with wood biochar plays a critical role in meeting global methane goals. Environ. Sci. Technol. 56, 10987–10996. https://doi.org/10.1021/acs.est.2c03467.

Hibino, K., Takakura, K., Nugroho, S.B., Nakano, R., Ismaria, R., Haryati, T., Yulianti, D., Zusman, E., Fujino, J., Akagi, J., 2023. Performance of takakura composting method in the decentralised composting Centre and its comparative study on environmental and economic impacts in Bandung city. Indonesia. Int. J. Recyc. Org. Wast. Agricult. 12, 1–23. https://doi.org/10.30486/ijrowa.2022.1945234.1379.

International Energy Agency. 2022. Fossil vs biogenic CO_2 emissions. URL: https://www.ieabioenergy.com/iea-publications/faq/woodybiomass/biogenic-co2/# (accessed September 2023).

IPCC. 2006. IPCC Guidelines for National Greenhouse Gas Inventories. Volume 5: Waste. Chapter 4: Biological Treatment of Solid Waste. URL: https://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/5_Volume5/V5_4_Ch4_Bio_Treat.pdf.

Lleó, T., Albacete, E., Barrena, R., Font, X., Artola, A., Sánchez, A., 2013. Home and vermicomposting as sustainable options for biowaste management. J. Cleaner Prod. 47, 70–76. https://doi.org/10.1016/j.jclepro.2012.08.011.

Marcello, B., Di Gennaro, V., Ferrini, S., 2021. Let the citizens speak: an empirical economic analysis of domestic organic waste for community composting in Tuscany. J. Cleaner Prod. 306, 127263 https://doi.org/10.1016/j.jclepro.2021.127263.

Maulini-Duran, C., Puyuelo, B., Artola, A., Font, X., Sánchez, A., Gea, T., 2013. VOC emissions from the composting of the organic fraction of municipal solid waste using standard and advanced aeration strategies. J. Chem. Technol. Biotechnol. 89, 579–586. https://doi.org/10.1002/jctb.4160.

Maulini-Duran, C., Artola, A., Font, X., Sánchez, A., 2014. Gaseous emissions in municipal wastes composting: effect of the bulking agent. Bioresource Technol. 172, 260–268. https://doi.org/10.1016/j.biortech.2014.09.041.

Nagata, Y., 2003. Odor measurement review, Measurement of odor threshold by triangle odor bag method. Ministry of Environmental Government of Japan 122–123. URL: https://www.env.go.jp/en/air/odor/measure/02_3_2.pdf (accessed September 2023).

Neugebauer, M., Sołowiej, P., 2017. The use of green waste to overcome the difficulty in small-scale composting of organic household waste. J. Cleaner Prod. 156, 865–875. https://doi.org/10.1016/j.jclepro.2017.04.095.

Pagans, E., Font, X., Sánchez, A., 2006. Emission of volatile organic compounds from composting of different solid wastes: abatement by biofiltration. J. Hazard. Mat. 131, 179–186. https://doi.org/10.1016/j.jhazmat.2005.09.017.

Ponsá, S., Gea, T., Sánchez, A., 2010. Different indices to express biodegradability in organic solid wastes. J. Environ. Qual. 39, 706–712. https://doi.org/10.2134/jeq2009.0294.

Ribes, A., Carrera, G., Gallego, E., Roca, X., Berenguer, M.J., Guardino, X., 2007. Development and validation of a method for air-quality and nuisance odors monitoring of volatile organic compounds using multi-sorbent adsorption and gas chromatography/mass spectrometry thermal desorption system. J. Chromatogr. a. 1140, 44–55. https://doi.org/10.1016/j.chroma.2006.11.062.

Rolewicz-Kalinska, A., Lelicinska-Serafin, K., Manczarski, P., 2021. Volatile orgànic compounds, ammonia and hydrogen sulphide removal using a two-stage membrane biofiltration process. Chemical Engineering Research and Design. 165, 69–80. https://doi.org/10.1016/j.cherd.2020.10.017.

Ruggieri, L., Gea, T., Artola, A., Sánchez, A., 2009. Air filled porosity measurements by air pycnometry in the composting process: a review and a correlation analysis. Bioresource Technol. 100, 2655–2666. https://doi.org/10.1016/j.biortech.2008.12.049.

Sánchez, A., 2022. Decentralized composting of food waste: a perspective on scientific knowledge. Front. Chem. Eng. 4, 850308 https://doi.org/10.3389/fceng.2022.850308.

Scaglia, B., Orzi, V., Artola, A., Font, X., Davoli, E., Sánchez, A., Adani, F., 2011. Odours and volatile organic compounds emitted from municipal solid waste at different stage of decomposition and relationship with biological stability. Bioresource Technol. 102, 4638–4645. https://doi.org/10.1016/j.biortech.2011.01.016.

Schiavon, M., Martini, L.M., Corrà, C., Scapinello, M., Coller, G., Tosi, P., Ragazzi, M., 2017. Characterization of volatile organic compounds (VOCs) released by the composting of different waste matrices. Environ. Pollut. 231, 845–853. https://doi.org/10.1016/j.envpol.2017.08.096.

Sironi, S., Capelli, L., Céntola, P., del Rosso, R., il Grande, M.,, 2006. Odour emission factors for the prediction of odour emissions from plants for the mechanical and biological treatment of MSW. Atmos. Environ. 40, 7632–7643. https://doi.org/10.1016/j.atmosenv.2006.06.052.

Storino, F., Arizmendiarreta, J.S., Irigoyen, I., Muro, J., Aparicio-Tejo, P.M., 2016. Meat waste as feedstock for home composting: effects on the process and quality of compost. Waste Manage. 56, 53–62. https://doi.org/10.1016/j.wasman.2016.07.004.

Thomas, A.R., Arulraj, P.R., Kranert, M., Philip, L., 2020. Investigation on greenhouse gas emissions and compost dynamics during in-vessel co-composting of septage and mixed organic wastes. Int. J. Environ. Sci. Technol. 17, 1675–1690. https://doi.org/10.1007/s13762-019-02450-z.

Thompson, W.H., Leege, P.B., Millner, P.D., Watson, M.E., 2001. The Test Method for the Examination of Composting and Compost (TMECC). United States Composting Council. URL: https://www.compostingcouncil.org/page/tmecc (accessed September 2023).

Torrijos, V., Calvo Dopico, D., Soto, M., 2021. Integration of food waste composting and vegetable gardens in a university campus. J. Cleaner Prod. 315, 128175 https://doi.org/10.1016/j.jclepro.2021.128175.

Usepa, 1999. Compendium method TO-17 – determination of volatile organic compounds in ambient air using active sampling onto sorbent tubes. compendium of methods for the determination of toxic organic compounds in ambient air, 2nd Edition. United States Environmental Protection Agency, OH, USA.

Wei, Y., Li, J., Shi, D., Liu, G., Zhao, Y., Shimaoka, T., 2017. Environmental challenges impeding the composting of biodegradable municipal solid waste: a critical review. Resour. Conserv Recycl. 122, 51–65. https://doi.org/10.1016/j.resconrec.2017.01.024.