

Chapter 2

Greenhouse Gas from Organic Waste

Composting: Emissions and Measurement

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Abstract There is actually common consensus to use biological technologies for the treatment of organic wastes. For instance composting involving the aerobic biological stabilization of organic wastes is gaining popularity. The amount of materials and the variety of wastes composted is increasing fast. However

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composting is a process emitting gases some of which being greenhouse gases (GHG) that favour global warming. In particular carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) are responsible for the global warming potential of composting. A part of these gases can be abated by low-cost biological technologies such as biofiltration. This review compiles all the points related to the emission of GHG from composting processes, from detection and measurement to minimization and abatement. We focus on measurements of GHG to obtain reliable emission factors for designing composting technologies. This will help to compare waste treatment options based on integrated tools such as Life Cycle Assessment (LCA). A chapter discusses C and N dynamics in the compost, and implications on emitted C and N gases. Finally we review the best available practices to minimize the GHG emissions from composting. We also present the final treatment of composting gases.

Keywords Composting · Anaerobic digestion · Greenhouse gas (GHG) · Environmental impact · Life cycle assessment (LCA) · Carbon dioxide · Methane · Nitrous oxide · Volatile organic compounds (VOCs) · Biofiltration

2.1 Introduction

The sustainable use of resources and wastes, including waste minimisation and valorisation, is a common objective of the plans, directives and rules published in the last few decades. One example is the Sixth Programme of Community Action in the field of Environment (“Environment 2010: the future is in our hands”) published by the European Union for the period 2001–2012 (European Union 2008a). The Sixth Program of Action includes the implementation of seven thematic strategies and, among them, specifically waste prevention and recycling, with the objective to reduce the negative environmental impacts during the whole life cycle of wastes, from their production to their elimination, including their recycling. One of the results of all these legislation efforts was the publication of the Waste Framework Directive in 2008. This Directive considers waste not only as a potential source of pollution, but also as a resource that can be used. Specifically, in the case of biodegradable wastes, the Directive 1999/31/CE on landfilling of wastes encourages the diversion of these wastes to other treatment technologies involving the recycling and energy recovery from wastes, where composting will have a great importance (European Union 2008b; Commission of the European Communities 2008). Nevertheless, the environmental impact assessment during the whole life cycle of wastes lacks of data obtained directly at full-scale waste treatment facilities operating in different locations, thus limiting the quality and reliability of these analyses necessary for the decision-making process.

A direct consequence of the above mentioned plans and directives has been the proliferation of a large number of new waste treatment plants installed in Europe

and all over the world in the last years, as well as the modification and adaptation of the existing ones. In particular, composting and anaerobic digestion are the more widely accepted processes for organic waste treatment. Composting plants are typically operated either in piles or tunnels, whereas anaerobic digestion can take place either in wet or dry digesters, typically followed by composting of the digested sludge with the aim of ensuring its sanitation and stabilization (Ponsá et al. 2008). The anaerobic decomposition process that is carried out in anaerobic digestion facilities allows energy recovery from wastes in the form of biogas. All these treatments also allow the valorisation of wastes by their use in agriculture or as soil organic amendments.

Waste treatment facilities can be the origin of public complaints, most of them associated to annoyances caused by odour emissions generated during the process. Biological treatment plants are a clear example of this problem. Odours generated from this type of treatment plants are mainly associated to the emissions of volatile organic compounds (terpenes, alcohols, ketones, sulphur compounds, amines, etc.) and ammonia (Goldstein 2002; Komilis et al. 2004). Some of the annoyances caused by these emissions are often magnified because of the lack of real data from operating plants that would contribute to have an objective and scientific base to analyse these problems. Such lack of data also represents a problem for the design of mitigation measures such as the use of biofilters. In addition to this, greenhouse gases (GHG) emission inventories evidence the increase in the amount of these compounds that are emitted from waste treatment facilities. Emission of CO_2 , CH_4 and N_2O are the main responsible of this increase (Colón et al. 2012).

Emissions generated in waste treatment plants, in particular those based on biological treatments, are related to the type of technology, the type of wastes treated and the operational conditions of the plant. For this reason, it is very important to relate the emissions to the performance of the biological treatment plants and also to the wastes being treated, since each treatment technology and waste will give rise to different end products quality and organic matter stabilisation degrees. The use of respirometric indices to monitor the stability of the organic matter has been one of the main research topics in the last years (Barrena et al. 2005; Barrena et al. 2006; Barrena et al. 2009a; Barrena et al. 2009b; Ponsá et al. 2008).

Although ammonia is not considered a GHG, its emissions during composting are usually studied because it causes acid rain and from the point of view of the conservation of nitrogen in the end-product because of the potential use of compost in agriculture as organic fertiliser, as well as for the determination of the efficiency of the systems for gas emission treatment, such as scrubbers and biofilters. Ammonia emissions are affected by the C/N ratio of the initial composting mixture, by the temperature reached during the process and by the aeration (Pagans et al. 2006b; Raviv et al. 2002; Sánchez-Monedero et al. 2001). Biofilters have shown to be an efficient equipment for the reduction of ammonia emissions in enclosed waste treatment plants (Hong and Park 2004; Pagans et al. 2006b), although for long periods ammonia tends to reduce the efficiency of this technology (Baquerizo et al. 2005).

An important part of the published literature in the field of gaseous emissions is related to odours, mainly by means of dynamic olfactometry, in both composting plants and mechanical-biological treatment plants (MBT). As already mentioned, a number of laboratory-scale experiments have been performed with the aim of determining the compounds that more significantly contribute to odour pollution. Thus, Goldstein (2002) identified terpenes, alcohols, aldehydes, fatty acids, ammonia and a range of sulphur compounds as the main responsible of odour emissions at composting plants. Other authors have studied the effect of some operational conditions, such as ventilation and turning, in these emissions (Szanto et al. 2007). Gage (2003) proposed a number of managing practices aimed at reducing the annoyances generated by odour emissions; for instance, preparation of an optimal initial mixture and the maintenance of high levels of porosity to assure aerobic conditions in the pile (Ruggieri et al. 2009). Enclosing the composting operations and the use of biofilters are among the main mitigation strategies for both odours and GHG.

The importance of GHG emissions generated during the biological treatment of wastes has been also stated by several authors. CO₂ emissions coming from biological process are not considered to contribute to global warming since this carbon has a biogenic origin, i.e., this carbon has been previously fixed biologically. Regarding other gases, He et al. (2001) measured the emissions of N₂O and CH₄ during the composting of food wastes under laboratory conditions in a closed system with forced aeration. Although generated in small amounts, N₂O and CH₄ have a great contribution to global warming since they have a warming potential 25 (CH₄) and 296 (N₂O) times higher than that of CO₂.

There are some scientific publications that provide gaseous emissions data generated during the biological treatment of organic wastes, mainly for manures and sewage sludge. However, the number of published papers dealing with municipal solid wastes is scarce (Colón et al. 2012). The works carried out by Eitzer (1995) and Staley et al. (2006) are very important for the characterization of the emissions generated during the biological treatment of wastes and the identification of specific compounds. In 1995, Eitzer performed a comprehensive characterisation of the volatile organic compounds (VOC) generated in composting plants treating municipal solid wastes and its possible relation to the process performance. On the other hand, Staley et al. (2006) studied the VOC emissions originated during the aerobic treatment of wastes and also during the anaerobic biodegradation process. These works highlighted the importance that forced aeration, used in the biological processes, had on the total emissions (Delgado-Rodríguez et al. 2012). Terpenes and ketones are shown to be the most abundant compounds. These experimental works were performed under laboratory conditions, which would limit their extrapolation to full-scale plants. Pagans et al. (2006a) also evaluated the effect of the type of waste (industrial and municipal solid waste) on VOC emissions under laboratory conditions. Komilis et al. (2004) identified the main VOC emitted during composting of pruning residues (mainly terpenes, alkyl benzenes, ketones and

alkanes) and also during composting of food wastes (sulphides, organic acids and alcohols), as well as the stages of the process that generated the highest emissions (thermophilic phase).

The determination of emission factors for different wastes and different treatment technologies will be a useful tool for the calculation of global emissions at facilities operating with a technology already studied in other treatment plants. Emission factors for VOC, NH₃ or GHG are usually expressed per ton of treated waste or per amount of obtained compost (Amlinger et al. 2008).

Sampling and measurement protocols for the determination of emissions have been also studied (Sironi and Botta 2001). Even though there are several published papers about this topic (Sommer et al. 2004), there is a lack of information on the measurement of emissions from surface sources, in both non-aerated (composting piles with natural aeration by convection) and those with a common source that will be later spread in an outlet surface (biofilters).

The main factors controlling a composting process are those characteristics of an aerobic biological process such as oxygen concentration, temperature, moisture, pH and C/N ratio. The optimum values for the C/N ratio range from 15 to 30, even though it is possible that composting takes place in a wider range of values (Haug 1993). For this reason, adjusting the optimum C/N ratio of the starting mixture is recommended. The use of different organic wastes or some selected additives could also be satisfactory (Charest and Beauchamp 2002). Nevertheless, the amounts of carbon and nitrogen used for the calculations should be referred to the amounts that are ready available for the microorganisms when considering the C/N ratio as a parameter to be optimised (Puyuelo et al. 2011). This specific point is very important for the potential practical implications in the preparation of starting composting mixtures. In relation to pH, recent studies have demonstrated its effect on the emissions of odours (Sundberg et al. 2013).

In this context, respirometric methodologies have been shown to be suitable and reliable for the determination of the amount of biodegradable organic matter in wastes of different origin and characteristics. There are two types of respirometric analysis for this purpose: dynamic and static determinations, being the dynamic methods the most widely accepted and recommended (Adani et al. 2004; Barrena et al. 2006; Gea et al. 2004). The measurement of the CO₂ produced during the respirometric test is also used as a measurement of the biodegradability of the organic matter (Cooper 2004) and, consequently, of the biodegradable organic C.

Other researchers have worked on the emissions generated during the composting process of agricultural wastes (Komilis et al. 2004; Cayuela et al. 2006; Mondini et al. 2006; Mondini et al. 2007; Sánchez-Monedero et al. 2008; Szanto et al. 2007). In the USA, other studies are focused on VOC and NH₃ emissions during the composting of biowaste (Büyüksönmez and Evans 2007).

This review is a compilation of the different works dealing with the measurement, detection, minimization and treatment of the GHG emitted during the composting process of a wide variety of organic wastes.

2.2 Composting

2.2.1 *The Specific Role of Composting in Greenhouse Gas (GHG) Emissions*

Composting is an environmentally friendly waste treatment process where organic matter is biologically degraded. Although the benefits of composting are evident, GHG can be generated and emitted to the atmosphere during this process contributing to global warming.

In this context, composting of organic waste contributes (composting process) and avoids (compost application) at the same time to GHG emissions. GHG are released from composting facilities due to degradation of organic matter and the use of electricity and fuels in management waste operations. The use of compost in agriculture has a positive effect in GHG emissions since its application as an organic amendment provokes that carbon stays bound to soil, although the content of other nutrients (N, P, etc.) is typically low. GHG emissions from composting processes depend on the waste type and composition, the technology systems used (static and dynamic process, open and closed systems, presence or not of gas treatment units) and the final use of compost.

Benefits of compost application have to be assessed together with a real knowledge about the amount of GHG such as N_2O and CH_4 generated during the composting process. The relation of GHG with some operational conditions and the technology used must be also considered. Data on GHG emissions from full-scale composting facilities are necessary to improve the knowledge about the contribution to the composting in GHG emissions. In the last years, there has been an increase in the number of scientific publications studying GHG emissions during composting (Amlinger et al. 2008; Boldrin et al. 2009; Sánchez-Monedero et al. 2010; Cayuela et al. 2012; Colón et al. 2012; Deportes 2012).

GHG emissions from composting processes are highly dependent on the waste type and composition. The composition and characteristics of the feedstock are key parameters for the design and operation of the composting facilities and for the final quality of the compost (Haug 1993).

Wastes with a low C/N ratio and high water content have a great potential for generating GHG emissions both during the storage and the composting process. In fact, wastes lacking of nutrients, porosity and structure, or presenting low biodegradability can hamper the correct evolution of the process, increasing the GHG emission. In order to minimize these emissions, optimal conditions for the initial mixture are required.

For some wastes, pretreatment operations before composting are required. This is the case of municipal solid wastes, especially when a source-separation system is not implemented. The production of high-quality compost from MSW may require a lot of energy because of the use of heavy machinery that makes GHG emissions unavoidable (Lou and Nair 2009). Other materials, such biosolids or manure, have a poor structure and an excess of water content and require the use of a bulking agent.

Grinding and mixing this bulking agent are operations that require energy that again contribute to GHG emissions.

Composting technologies can be open and closed systems. In open systems, composting is performed in facilities where, in general, gaseous emissions are neither collected nor treated. However, when the composting process takes place in an enclosed system usually the exhaust gases are treated. As expected, concentrations of GHG reported in facilities when the gas treatment systems are well-implemented were lower (Colón et al. 2012) than those of open systems. Effects of forced aeration and turning in GHG emissions have been also studied. Szanto et al. (2007) observed lower N_2O and CH_4 emissions in turned piles than in static systems. They related these emissions to the prevalence of anaerobic regions in the static systems, as other similar studies (Parkinson et al. 2004). Amlinger et al. (2008) proposed that high aeration and effective stripping of NH_3 during the early stages of composting can reduce N_2O formation. Ermolaev et al. (2012) studied the effects of different aeration and temperature settings on the emission of CH_4 , N_2O and CO_2 during windrow composting with forced aeration following three different control strategies. However, they found that the emissions of CH_4 and NO_2 were low regardless the amount of ventilation. The oxygen concentration, temperature profile and moisture content are factors controlling GHG emissions. Nowadays, in the composting field, the technology that allows the control of these parameters is available.

Regarding CO_2 , its emissions in composting derived from the organic matter biodegradation are not taken into account in their contribution to global warming since this carbon has a biogenic origin. The CO_2 that contributes to GHG emissions is generated by composting facilities as a result of operational activities. In composting, the main GHG that can contribute to global warming are CH_4 and N_2O . Both are related to a lack of oxygen during the composing process and consequently they depend on the management of the composting process (Cayuela et al. 2012; Colón et al. 2012). These gases, although they are generated in small amounts, have a great contribution to global warming since they have a warming potential of 25 (CH_4) and 296 (N_2O) times higher than that of CO_2 .

Several authors reported that even in well-aerated process CH_4 was emitted (He et al. 2000; Clemens and Cuhls 2003) while Beck-Friis et al. (2000) observed a rapid decrease when the oxygen supply was increased. The production of N_2O can be due to an incomplete ammonium oxidation or incomplete denitrification (Beck-Friis et al. 2000). Emissions of N_2O have been reported at different stages of the process. Some authors reported high emissions at the beginning of composting (He et al. 2000; Parkinson et al. 2004). Other studies reported the production of N_2O during the mesophilic and maturation phases (Beck-Friis et al. 2000; Hao et al. 2004) when the readily available carbon sources has been depleted (He et al. 2000). According to Cayuela et al. (2012), N_2O formation will be hampered if there are conditions to inhibit nitrification (such as low available NH_4^+ in the pile or high pH). Beck-Friis et al. (2000) and Fukumoto et al. (2003) related N_2O emissions to the temperature of the process and CH_4 emissions to the size of the pile (both works were performed at full-scale, using windrows and forced aeration systems, respectively), the structure

of the material and the time of the process. Higher emissions were measured in larger piles, with a poor structure and longer composting times. Monitoring of CH_4 emissions showed a large experimental fluctuation in all works.

Several authors have reported the GHG emissions generated during the biological treatment of several typologies of wastes. Most of them were calculated from laboratory and pilot scale processes, although interesting data at industrial scale have been also reported (Boldrin et al. 2009; Colón et al. 2012; Ermolaev et al. 2012). There are an important number of studies that quantify CH_4 and N_2O emissions from animal manures (Fukumoto et al. 2003; Hao et al. 2004; Szanto et al. 2007). However, less published works dealing with municipal solid wastes can be found, and even less works studying the GHG emissions of different composting systems have been published.

Colón et al. (2012) evaluated four different full-scale facilities treating the source-separated organic fraction of municipal solid wastes (OFMSW). They reported a range of CH_4 and N_2O emissions between 0.34 and 4.37 kg CH_4 Mg OFMSW⁻¹ and 0.035 and 0.251 kg CH_4 Mg OFMSW⁻¹, respectively. Regarding CH_4 , the highest values were found in facilities without gas treatment units. Also, Boldrin et al. (2009) presented a study where several technologies for municipal solid waste treatment were evaluated. They reported CH_4 and N_2O emissions ranging from 0.02 to 1.8 kg CH_4 Mg OFMSW⁻¹ and 0.0075 and 0.252 kg CH_4 Mg OFMSW⁻¹.

As previously commented, although ammonia is not considered a GHG, its emission during composting plays an important role. Ammonia emissions are affected by the C/N ratio of the initial composting mixture, by the temperature reached during the process and the aeration (Pagans et al. 2006b). High loads of ammonia can reduce the optimal use of the biofilter system in enclosed facilities (Amlinger et al. 2008). Moreover the conservation of nitrogen in the end-product improves compost use in agriculture as organic fertiliser. Consequently, from a global warming point of view, less use of chemical fertilizers will be required (Favoino and Hogg 2008).

In the role played by composting in GHG emissions it is important to bear in mind the role of compost as an end-product. The use of compost as an organic amendment can contribute to mitigate GHG in several forms.

Compost utilization can reduce the need of chemical fertilisers and pesticides, which implies the reduction of GHG emissions associated with their production and application. Also, a positive effect in soil structure is produced with compost application by improving tillage and workability. Improved structure of soils associated with the application of organic matter can help to reduce requirements for water irrigation in periods of drought and to increase the potential of soils to retain moisture (Favoino and Hogg 2008).

One of the aspects associated with compost utilization that more attention has received in the last years is the potential for sequestration of carbon in agricultural soils (Mondini et al. 2007; Favoino and Hogg 2008). By applying compost, biogenic carbon is held in soils for a period of time before carbon is released, increasing carbon uptake and storage within the plant and removing CO_2 from the atmosphere.

2.2.2 GHG Emitted During Composting and Their Relationship to C and N Dynamics

Microbial transformations involved in the formation of CH_4 and N_2O in composting piles are similar to those taking place in other environments such as soil, water bodies, wastewater treatment plants, etc. However, the microbial gas production and the final emission to the atmosphere will be affected by the particular environmental conditions of composting piles (such as temperatures up to 70°C , high organic matter content, easily available organic compounds, rich and active microbial population and limited amount of oxygen, etc.) and composting management operations (turning, watering, pile size and geometry, etc.). All these variables represent a characteristic environment affecting not only the microbial gas production in the pile, but also its transport within the pile and the final emission to the atmosphere. In the following sections the impact of the C and N dynamics on GHG emissions during composting will be also discussed.

2.2.2.1 Carbon Dioxide (CO_2)

As previously mentioned, there are two main sources of CO_2 emissions from composting facilities, biogenic and non-biogenic CO_2 . Biogenic CO_2 emissions derive from the biological degradation of the organic matter, mostly as a consequence of aerobic decomposition and, to a lesser extent, from anaerobic processes or the oxidation of CH_4 by aerobic methanotrophic bacteria. This emission accounts for the highest amount of gas generated during the process, since between 40 and 70% of the original organic matter can be degraded during composting (Haug 1993). However, the global warming potential of these emissions are not taken into account in the environmental impact of composting operations since this biological CO_2 is considered to be carbon neutral (IPCC 2006). The exclusion from the inventories has reduced the number of papers studying CO_2 emissions and this gas is only studied from the point of view of establishing mass balances of composting operations (Boldrin et al. 2009) or as an index of the overall microbial activity of the pile, reflecting the progress of the process (Hobson et al. 2005; Sánchez-Monedero et al. 2010) and the evaluation of the stability of the end-product (Barrena et al. 2006).

Non-biogenic CO_2 from composting includes the emissions associated to energy and fuel consumption in the composting facility. These emissions are dependent on the technology of the plant and the machinery used such as shredders, front-loaders, turning equipment, screenings, and other processing activities. These emissions are beyond the scope of this review, but updated information can be found elsewhere (Boldrin et al. 2009; Scheutz et al. 2009; Lou and Nair 2009; Brown et al. 2008).

2.2.2.2 Methane (CH₄)

Methane emissions derived from organic waste composting have attracted the attention of researchers as a considerable contributor to global warming since this greenhouse gas has a global warming potential 25 times greater than carbon dioxide over a time horizon of 100 years (IPCC 2006).

The optimum growing conditions for methanogenic bacteria are a lack of oxygen (strict anaerobic microorganisms), a redox potential below -200 mV, neutral pH and the presence of nutrients and substrates rich in organic matter (Kebreab et al. 2006). These conditions can be temporally found at the early stages of the composting process, where large amounts of nutrients and available sources of organic compounds stimulate microbial growth, depleting the oxygen levels in the pile. Accordingly, most of CH₄ emissions have been recorded during the initial weeks of the process, at the beginning of the thermophilic phase (Beck-Friis et al. 2000; Sánchez-Monedero et al. 2010). The high temperatures reached at the beginning of the process reduce oxygen solubility (Pel et al. 1997), facilitating the creation of anaerobic spots within the pile. However, there are other variables such as high concentration of ammonia, which may inhibit the activity of methanogens at pH > 9 (Kebreab et al. 2006), or the presence of electron acceptors such as sulphates, which reduce their activity by competition with sulphate reducing bacteria (Hao et al. 2005). Sánchez-Monedero et al. (2010) reported that the high ammonia levels generated by the hydrolysis of urea, used as nitrogen source, inhibited the production of CH₄ in olive mill waste composting piles.

The emission of CH₄ from composting piles is governed by the biological activity of the pile (Hao et al. 2001) and also by other factors affecting gas transport from the anaerobic spots to the pile surface, such as gas diffusion within the pile and the presence of methanotrophic bacteria. Methanotrophs are aerobic microorganisms colonising the surroundings of anaerobic zones and pile surface, which are able to oxidise between 46 and 98% of the CH₄ generated in the pile (Jäckel et al. 2005). Methanotrophic bacteria also play an important role in the production and consumption of other relevant GHG emitted during composting, such as N₂O and CO (Topp and Hanson 1991). Sánchez-Monedero et al. (2011) performed a 4-year interannual evaluation of the GHG emissions from a composting plant treating olive mill wastes and found a reduction of CH₄ emissions associated to the improvement of the management of the composting plants (watering and turning frequencies).

Kebreab et al. (2006) and Brown et al. (2008) reviewed the topic of GHG emissions from livestock and composting operations and they highlighted the importance of the composting feedstock, the height and shape of the pile, the control of moisture content and turning frequency as the main factors governing CH₄ emissions during the process, since these variables will affect both the oxygen availability and gas diffusion in the composting pile. The presence of manure can also increase the methane emissions due to the incorporation of anaerobic microorganisms, as



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