

Gaseous emissions from management of solid waste: a systematic review

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Abstract

The establishment of sustainable soil waste management practices implies minimizing their environmental losses associated with climate change (greenhouse gases: GHGs) and ecosystems acidification (ammonia: NH₃). Although a number of management strategies for solid waste management have been investigated to quantify nitrogen (N) and carbon (C) losses in relation to varied environmental and operational conditions, their overall effect is still uncertain. In this context, we have analyzed the current scientific information through a systematic review. We quantified the response of GHG emissions, NH₃ emissions, and total N losses to different solid waste management strategies (conventional solid storage, turned composting, forced aerated composting, covering, compaction, addition/substitution of bulking agents and the use of additives). Our study is based on a meta-analysis of 50 research articles involving 304 observations. Our results indicated that improving the structure of the pile (waste or manure heap) via addition or substitution of certain bulking agents significantly reduced nitrous oxide (N₂O) and methane (CH₄) emissions by 53% and 71%, respectively. Turned composting systems, unlike forced aerated composted systems, showed potential for reducing GHGs (N₂O: 50% and CH₄: 71%). Bulking agents and both composting systems involved a certain degree of pollution swapping as they significantly promoted NH₃ emissions by 35%, 54%, and 121% for bulking agents, turned and forced aerated composting, respectively. Strategies based on the restriction of O₂ supply, such as covering or compaction, did not show significant effects on reducing GHGs but substantially decreased NH₃ emissions by 61% and 54% for covering and compaction, respectively. The use of specific additives significantly reduced NH₃ losses by 69%. Our meta-analysis suggested that there is enough evidence to refine future Intergovernmental Panel on Climate Change (IPCC) methodologies from solid waste, especially for solid waste composting practices. More holistic and integrated approaches are therefore required to develop more sustainable solid waste management systems.

Keywords: ammonia, composting, emissions, GHGs, manure, meta-analysis, methane, nitrous oxide

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Introduction

Management of organic waste has been identified as a major source of anthropogenic emissions contributing to regional (eutrophication, acidification) and global-scale (climate change) environmental issues (Tamminga, 2003; Naylor *et al.*, 2005; Steinfeld *et al.*, 2006). The main waste flows are associated with urban, industry, and livestock production systems and in some cases they are managed in solid form, which facilitates handling and transport across the entire management system.

Organic waste is generated directly by households mainly in the forms of kitchen and garden waste, and indirectly as sewage sludge from wastewater treatment facilities. Industrial plants, particularly those related with food processing activities, also produce important amounts of organic residues surrounding urban areas.

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In livestock systems, solid waste is produced when straw, or other absorbent material is added for bedding purposes during animal housing, or after mechanical solid–liquid separation of raw slurry, resulting in a stackable residue that can be stored or composted outdoors. In the last two decades, scientific knowledge on management of organic solid waste, and specifically on composting, has notably increased and, despite several of the insight mechanisms which drive such a complex process are not deeply understood, the technology to treat and stabilize organic matter is well founded (Haug, 1993; Szanto, 2009). The production of certain amounts of methane (CH₄) and nitrous oxide (N₂O) seems to be unavoidable due to the heterogeneous nature of waste piles; however, the selection of management conditions plays a key role determining the magnitude of these emissions (Chadwick *et al.*, 2011).

Different types of composting methods have been proposed, being mechanically turned system and

forced aerated composting the most common technologies. An adequate adjustment of the structure (e.g., C/N ratio) via bulking agents addition/substitution (Raviv *et al.*, 2004; Yamulki, 2006; Maeda *et al.*, 2013) together with the monitoring of the main process parameters (e.g., moisture, temperature) has the potential to reduce GHG emissions at the same time that it allows an improved control over nitrogen (N) losses, to obtain a higher N retention in the final product (i.e., compost). Other management strategies, such as covering or compaction, have also been explored with contrasting results in terms of CH₄ and N₂O (Chadwick, 2005). In addition, the use of additives has also been investigated as a potential strategy to minimize gaseous losses from solid waste management (Delaune *et al.*, 2004; Fukumoto *et al.*, 2011).

Methane and N₂O are well-known GHGs usually associated with the agricultural sector, and N₂O is now the most significant ozone-depleting emission to the atmosphere (Oenema *et al.*, 2014). According to the Intergovernmental Panel on Climate Change (IPCC) Guidelines (IPCC, 2006), the global warming potential (GWP) for 100 years' time horizon is about 25 times for CH₄ and 298 times for N₂O compared with that of CO₂ on a weight basis. Methane is mainly produced in strictly anaerobic environments, through the microbial decomposition of easily degradable organic compounds, such as lipids, carbohydrates, organic acids, and proteins present in the organic waste (Husted, 1994; Khan *et al.*, 1997). Nitrous oxide is usually associated with regions of the waste heap where an oxygen (O₂) gradient occurs (Beck-Friis *et al.*, 2000) as a result of nitrification–denitrification processes.

Ammonia (NH₃) emission has been identified as the main pathway of N loss during this process, and it is of major concern because by subsequent deposition it can disturb natural ecosystems through soil acidification and eutrophication of water courses. Besides, it has an indirect contribution to global warming because N deposited on soils and surface waters enhances N₂O formation (Mosier *et al.*, 1998).

In terms of GHGs, the Kyoto Protocol (UNFCCC, 1997) regulates emissions at national level, requiring all Annex I countries to report annual emissions according to the IPCC Guidelines for National GHG Inventories (IPCC, 2006). Under this framework, emissions of CH₄ and N₂O from biological treatment of solid waste (e.g., composting) or manure management are calculated with an emission factor (EF) approach, accounting for the influence of environmental factors and different handling strategies. Likewise, a number of international initiatives have been developed with the aim to reduce NH₃ emissions [UNECE Gothenburg Protocol, EC

Integrated Pollution Prevention and Control (IPPC) Directive].

Further study of waste handling practices was encouraged by the IPCC through the Fourth Assessment Report (IPCC, 2007). As then, a number of individual experiments have been conducted at commercial and pilot scale to examine the gaseous emissions associated with a range of management strategies. Furthermore, some authors have reviewed this subject through different approaches (Brown *et al.*, 2002; Zeman *et al.*, 2002; Boldrin *et al.*, 2009; Chadwick *et al.*, 2011), although drawing general conclusions has often been difficult due to the variability of the selected studies in terms of waste type, system applied, analyzed variables, or environmental factors involved. In this context, the present work is an attempt to summarize and analyze the currently available scientific information associated with gaseous emissions from the treatment of organic solid waste.

The main objective was to investigate those strategies that have the potential to reduce GHG emissions and N losses from solid waste management and to quantify the mitigation potential of each strategy. To do so, we conducted a quantitative review using a meta-analysis (MA) methodology, involving a range of management practices (conventional solid storage, turned composting, forced aerated composting, covering, compacting, addition/substitution of a bulking agent, and specific additives). Furthermore, we intended to address the following specific research questions: (i) Do composting systems reduce GHG emissions in comparison with conventional solid storage management? (ii) Do they involve an increase in N losses and to which extent? and (iii) Which are the potential options for mitigating GHG emissions and environmental trade-offs during solid waste management?

Materials and methods

Literature search and study selection

We gathered the available peer-reviewed literature published before November 2013 concerning gaseous emissions during composting and/or storage of organic solid waste. Articles were searched on the ISI Web of Knowledge (<http://apps.webofknowledge.com>) and Google Scholar database (Google Inc., Mountain View, CA, USA) by combining specific keywords related to treatment (*composting, storage*), type of waste (*organic waste, manure, household waste, green waste, sewage sludge*), and emissions (*gaseous emissions, methane, ammonia, nitrous oxide*). The search was complemented by examining the literature cited in the articles found to collect additional studies which may contain relevant data for this review.

First, studies describing data of CH₄, N₂O, or NH₃ fluxes (at least one of them) over a reported measurement period were

collected. We decided to analyze gaseous losses in terms of cumulative emissions, as a proportion of initial carbon (C) or N content in the waste material (%CH₄-C, %NH₃-N, %N₂O-N). Thus, to harmonize the data included in our dataset, in some cases, it was necessary to transform the reported data into values referred to an element mass basis. Those studies not describing results as cumulative emissions or not reporting enough details to perform this conversion were excluded from the analysis. Additionally, we decided to include articles which expressed results just in terms of total N losses, based on a N mass balance, because this approach can add valuable information with regard to the general influence of different treatments and conditions in the overall N conservation through solid waste management. This parameter involves the already mentioned N gaseous emissions (NH₃, N₂O) but also any other kind of N losses via gas or liquid, such as dinitrogen (N₂) or nitrate (NO₃⁻).

Following this selection criteria, a total of 76 different publications were collected involving 712 observations. For each selected study, we gathered a range of metadata related to the details of every experiment, in terms of substrate characteristics (dry matter, total N (TN), total ammoniacal N (TAN), and C/N ratio), operational conditions (treatment system, period, and climate), and methodology applied (scale, gas measurement method). Carbon dioxide (CO₂) emissions were also collected when available. Although CO₂ produced during composting process is of biogenic origin and is therefore not considered a source of GHG (IPCC, 2006), it can provide information about the evolution of the biological process and the potential stability of the final product (i.e., compost). Thereby, this dataset allowed us to investigate the general influence of a range of environmental and management factors on the cumulative emissions (Table 1).

In addition, we further explored the influence of management practices on gaseous losses through a meta-analysis (MA) approach. New selection criteria were applied by discarding from the dataset those studies that did not involve pair comparison results. After this process, a selection of 50 studies involving 304 observations was used in the dataset to perform the meta-analysis (references available in Appendix S1).

Finally, we decided to compare CH₄-C emissions (%) observed in the gathered experiments with the correspondent values obtained following the IPCC methodology (IPCC, 2006). Studies involving commercial-scale experiments were selected, and CH₄-C estimation was conducted taking into account the parameters in relation to the management system applied, environmental factors, and waste type and composition.

Definition of categories

In the first approach, we studied the influence of a range of factors on the cumulative emissions using a general dataset with the results of all the publications gathered in our preliminary selection (Table 1). We explored the effect of 6 variables: waste type, management system, treatment duration, climatic conditions (temperature, rain), and experiment scale.

Table 1 Variables and categories selected in the preliminary analysis to study their influence on gaseous emissions during solid waste management

Variable	Category
Waste type	Cattle manure (CtM)
	Dairy manure (DrM)
	Pig manure (PgM)
	Poultry manure (PIM)
	Food waste (FW)
	Green waste (GW)
	Sewage sludge (SS)
Treatment type	Storage (ST)
	Turned (TU)
	Forced aeration (FA)
	F. aeration + Turned (F + T)
	Covered (COV)
	Compacted (COM)
Temperature	Cool temperate
	Warm temperate
Annual rainfall rate	Dry
	Moist
	Wet
Duration	<1 month
	1–3 months
	>3 months
Scale	Commercial
	Pilot

Waste type was classified into 7 categories according to the source and general characteristics of the organic material (cattle manure, dairy manure, pig manure, poultry manure, food waste, green waste, and sewage sludge). *Treatment type* was grouped in 6 levels, reflecting the practices and management system applied: (i) Storage involves stacking the materials in unconfined piles during several weeks or months until weather and time allow land application; (ii) Turning refers to composting in windrows with controlled mixing (at least monthly) of the materials for aeration; (iii) Forced aeration involves composting in static piles using a blower to supply air to the materials; (iv) Forced aeration + Turning include experiments treated under both techniques; (v) Covered refers to covering the pile with a plastic sheet; and (vi) Compaction involves an increase of density to reduce the free air space within the waste material.

Potential effects due to the climatic conditions were also explored. Based on the IPCC climate zones classification (IPCC, 2006), two factors were defined: *temperature*, which involved two categories (i) warm temperate and (ii) cool temperate; and *annual rainfall rate*, including (i) dry, (ii) moist, and (iii) wet conditions (see Appendix S2 for detailed ranges). Additionally, the influence of other operational conditions was also studied. Thus, the *scale* of the trial was grouped in 2 levels: (i) pilot scale, including those studies conducted in vessel for research purposes with a limited amount of waste (<1 m³); and (ii) commercial scale, involving trials of windrows and piles of large scale (>1 m³) that simulate realistic

conditions. Finally, the *duration* of the treatment was analyzed by classifying the experiments in three levels: (i) <1 month, (ii) 1–3 months, and (iii) >3 months; according to the total period in which the trial was conducted.

In a second approach, we focused on exploring the data through meta-analysis. This statistical method provides a procedure to compare and integrate the results of multiple studies, allowing to draw general patterns. The influence of a range of management systems and practices on gaseous losses was explored meta-analytically, among them: (i) *turning*, (ii) *forced aeration*, (iii) *covering*, (iv) *compaction*, (v) addition/substitution of *bulking agents*, and the use of specific (vi) *additives*. To do so, the dataset was further narrowed down by restricting the data used to pairwise comparisons of emissions from treated and untreated (control) waste management trials. In most of the cases, conventional static storage of organic waste was taken as the control experiment. Nevertheless, in those studies analyzing the effects of different intensities of forced aeration through pilot-scale trials, the lower level of aeration was considered as the control treatment, assuming that these minimum aeration conditions can be assimilated to those obtained by natural convection in untreated systems.

Bulking agents are materials which are mixed with the organic waste to enhance the composting process. They help to adjust the moisture content and provide structural support which allows the aeration of the pile (Haug, 1993). Influence of bulking agent addition has been explored through two main approaches in the literature reviewed. Some works examine a change in the amount of bulking agent added with respect to the residue, whereas other studies compare different types of bulking material, aiming at increasing C/N and lignin contents that may improve the structure of the waste material. In the first case, trials with none or lower content of straw were considered as the control; while in the second approach, experiments involving straw or sawdust were taken as the control for comparison purposes, because they are the most common materials used for bedding purposes, and the alternative bulking agents explored involve higher levels of lignin content. Finally, for those studies evaluating the effect of specific additives (e.g., phosphogypsum) on the emissions from composting process, results were compared with the respective control treatments, which refer to those trials with no amendment addition to the waste material.

Statistical analysis

As already mentioned, we applied meta-analysis to study the influence of different factors on cumulative gaseous emissions from the composting process, using studies comparing treated (experimental) groups with a control group. The response ratio (RR) was chosen as the effect size unit for all comparisons. We employed natural log-transformed RR (L) for the analyses to work with more normal sampling distributions in small samples (Hedges *et al.*, 1999). The results were unlogged and presented as percent of change.

Many studies compared multiple treatments with a single control group. This nonindependent information can lead to overestimation of the precision of the calculated mean effect

size (Borenstein *et al.*, 2009). To account for this, we calculated all possible combinations between treatments and control. Subsequently, one aggregated mean effect size was computed for each independent study. This reduced the total number of comparisons used in the meta-analysis from 464 simple datasets to 305 composite datasets. Information on variance and sample size was not provided in many of the studies selected for the meta-analysis. Therefore, the only criterion used for weighting was the number of aggregated independent treatments contained in our composite datasets. We accounted for this information following the procedure described in Aguilera *et al.* (2013). Weighted mean effect sizes of each category were calculated, with bias-corrected 95% confidence intervals (CIs) generated by a bootstrapping procedure (10 000 iterations) (Adams *et al.*, 1997), using METAWIN software (Rosenberg *et al.*, 2000). Mean effects of treatments were considered different from the control at the 0.05 significance level when the 95% confidence interval did not overlap zero.

Results and discussion

Description of the database

As displayed in Fig. 1, the number of studies assessing gaseous emissions from solid waste management processes has notably grown in the last decade. This could be associated with the increased awareness of pollution potential (e.g., as GHG and NH₃) from these emission sources and the corresponding progress of International Accounting Protocols. Following our selection criteria, a total of 712 observations (involving CH₄, N₂O, NH₃, and TN losses) were collected from 76 different publications, representing an average of 9.4 observations per study (Appendix S1). Most of the datasets were gathered from peer-reviewed literature, involving 93% of selected studies, while the rest were from official reports (4%), and conference communications (3%) that met our quality requirements.

Among all the studies (76), 72% reported data on total N losses, 66% included data on NH₃ losses and 58% on N₂O emissions. For C losses, 42% of the studies involved measurements on CH₄ emissions and 59% detailed also losses in the form of CO₂. The duration of the selected experiments ranged from 29 to 420 days, with an average of 108 days. Climatically speaking, most observations were collected from studies under cool temperate conditions (57%), followed by warm temperate (34%) and tropical (9%) conditions. According to annual rainfall rate, studies could be grouped in three categories: moist (78%), dry (18%), and wet (4%) conditions. Scalewise, most studies comprised large-scale (mean = 10.5 m³) commercial trials (57%) and the rest (43%) were carried out at the pilot scale in vessel under controlled parameters. In large-scale studies, gaseous emissions were sampled across the entire or a

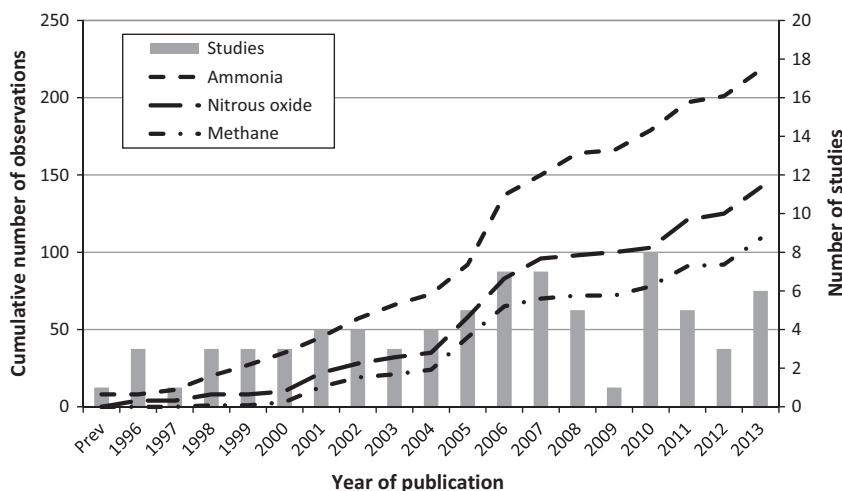


Fig. 1 Number of studies and cumulative number of observations per year of publication.

portion of the waste heap, using static chambers, open dynamic chambers, or emission hoods (wind tunnels). Details about the studies included in the database are provided in the Supporting information (Appendix S1).

General influence of management and environmental factors on gaseous emissions

General results evaluating the influence of a range of factors on the cumulative gaseous emissions are shown in Table 2. Due to the high degree of variability among the waste characteristics, treatments and conditions of the studies included in this analysis, most of the results obtained at this stage involved wide variability, particularly for CH_4 and N_2O emissions, which hinders finding statistical significant differences among the variables studied. A few general trends could be observed though. For waste type, the main differences were in relation to $\text{NH}_3\text{-N}$ emissions and total N losses. Sewage sludge showed the highest mean $\text{NH}_3\text{-N}$ losses (approximately 27%), followed by food waste, poultry and pig manure (Fig. S2). Generally, NH_3 losses seem to be inversely related to their C/N ratio and directly related to their TN (g N kg DM^{-1}) and TAN ($\text{g N-NH}_4^+ \text{ kg DM}^{-1}$) content (Fig. S1). For $\text{CO}_2\text{-C}$ (% of total C), green waste, food waste and pig manure showed the highest losses, whereas sewage sludge tended to show the smallest $\text{CO}_2\text{-C}$ loss in proportion to its initial C content (Fig. S2). This difference can be associated with their different biodegradability. In fact, whereas green and food waste may include an important fraction of easily decomposable compounds, sewage sludge, as a consequence of a previous biological treatment, contains more recalcitrant materials.

The influence of treatment type on gaseous losses could also be observed in some cases. Emissions levels

of $\text{CO}_2\text{-C}$ and $\text{NH}_3\text{-N}$ in systems that enhance aerobic conditions (i.e., turned, forced aeration) were slightly higher than those from untreated storage of solid waste (Fig. S3). In contrast, management practices which tend to limit O_2 diffusivity and concentration, such as covering and compaction, showed lower emissions of $\text{CO}_2\text{-C}$ and $\text{NH}_3\text{-N}$ compared with aerobic treatments, probably as a consequence of a decrease in the overall biological activity and temperature within the organic material.

Results suggest that climate conditions can have an effect on the gaseous emission losses during the waste management process. For example, mean emissions observed in warm temperate climates, as expected, were higher than those from cool temperate areas, particularly in terms of $\text{NH}_3\text{-N}$ and $\text{CH}_4\text{-C}$ emissions (Fig. S4). Furthermore, rain could also have an influence on N losses. Despite $\text{NH}_3\text{-N}$ emissions under dry conditions tend to be higher than under other conditions, overall N losses seem to be greater under moist and wet conditions, which can be associated with higher N losses through leaching pathways (Fig. S5).

No statistical differences were observed with regard to the duration and scale of the experiment, with the exception of N_2O emissions measured in pilot-scale experiments, which were considerably higher than those observed under commercial-scale trials (Fig. S6). We may suggest two reasons for this. On one hand, pilot-scale devices specifically designed for research purposes may collect more precisely total cumulative emissions produced during decomposition of organic material, accounting for some losses that otherwise would be difficult to detect in large-scale trials. On the other hand, the specific conditions of pilot-scale experiments, involving small amounts of waste under controlled temperature and aeration conditions, may

Table 2 Number of observations (N), mean and standard deviation (SD) of cumulative gaseous emissions for some of the factors with a potential influence on C and N losses from management of solid waste

	CO ₂ -C (%)			CH ₄ -C (%)			N ₂ O-N (%)			NH ₃ -N (%)			Total N (%)		
	N	Mean (%)	SD (%)	N	Mean (%)	SD (%)	N	Mean (%)	SD (%)	N	Mean (%)	SD (%)	N	Mean (%)	SD (%)
Waste type															
Cattle manure	27	40.0	14.3	23	3.2	2.7	29	1.3	1.5	40	11.6	14.6	38	27.4	15.7
Dairy manure	19	34.8	14.4	26	0.9	0.9	29	0.6	0.8	20	9.4	7.7	16	23.9	14.3
Pig manure	69	48.0	15.6	48	1.5	2.3	60	2.7	2.2	81	17.1	12.5	94	39.4	17.6
Poultry manure	18	42.3	12.6	4	0.1	0.1	13	1.3	2.3	38	16.7	14.3	37	35.8	21.9
Food waste	37	47.0	22.0	4	2.7	4.9	6	2.2	2.5	15	21.0	21.9	29	45.4	17.1
Green waste	6	55.7	17.4	2	1.4	0.4	2	1.0	0.7	6	11.2	9.4	2	36.3	40.0
Sewage sludge	8	23.1	4.5	0	–	–	0	–	–	8	27.2	18.5	8	42.7	20.8
Treatment type															
Storage	40	40.9	12.9	37	1.1	1.9	51	1.5	1.8	70	12.5	12.4	73	35.7	18.4
Turned	56	51.4	15.9	36	1.9	2.1	39	1.2	1.3	44	21.0	16.6	57	44.6	17.6
Forced aeration	36	50.0	21.4	6	0.3	0.4	7	1.2	0.8	38	18.8	18.1	31	39.7	19.9
F. aeration + Turned	41	36.3	12.4	17	3.2	3.1	28	3.8	2.3	40	16.6	9.0	44	33.3	17.9
Covered	4	25.0	15.8	7	0.9	1.4	7	1.5	1.4	9	5.9	7.1	14	16.7	9.2
Compacted	7	24.5	10.7	4	3.0	4.5	7	0.6	0.7	7	6.4	7.1	5	20.4	12.1
Temperature															
Cool temperate	33	37.4	15.0	46	0.7	1.1	59	1.3	1.4	87	12.4	12.3	57	26.4	18.8
Warm temperate	137	44.1	16.9	54	2.4	2.8	73	2.3	2.3	109	16.5	13.9	144	37.8	17.2
Annual rainfall rate															
Dry	46	44.4	11.3	39	2.7	2.8	39	2.0	2.1	36	21.2	10.6	46	26.6	13.3
Moist	128	45.4	18.7	65	1.2	1.9	106	1.8	2.1	181	14.3	14.4	177	36.7	19.5
Wet	12	22.0	2.0	0	–	–	0	–	–	0	–	–	12	55.3	12.5
Duration															
<1 month	31	38.5	21.9	7	1.6	3.7	6	2.1	2.5	43	14.0	11.0	48	38.2	20.1
1–3 months	85	42.3	14.4	45	1.7	2.4	66	2.0	1.9	75	18.4	14.2	84	32.5	16.2
>3 months	70	47.6	17.9	57	1.7	2.1	73	1.7	2.2	99	13.9	14.9	103	37.1	20.5
Scale															
Commercial	92	42.2	15.2	75	1.6	2.2	96	1.3	1.7	124	14.8	14.6	127	34.7	19.0
Pilot	92	45.6	19.3	32	2.0	2.7	43	2.9	2.2	84	17.1	13.8	97	38.8	18.7

enhance the production of higher levels of N₂O-N emissions than those generated under commercial and therefore more realistic, scale studies.

Meta-analysis of the effect of solid waste management practices on gaseous emissions

Composting systems: turning and forced aeration. Mechanical turning and forced aeration with a ventilation device (e.g., centrifugal blower) are both efficient composting methods that involve active aeration, thereby ensuring the O₂ supply to the microorganisms and promoting microbial breakdown of organic materials. This is consistent with the results displayed in Fig. 2a, which indicates a statistically significant effect of these composting methods on increasing CO₂-C emissions in comparison with conventional static storage. Furthermore, both composting methods led to increasing NH₃-N losses (50–100%) (Fig. 3b). This effect can be

attributed to the important role that temperature plays on the NH₄⁺-NH₃ (gas) equilibrium. Aeration stimulates biological oxidation of C to CO₂, which is an exothermic reaction releasing a considerable amount of heat (Haug, 1993). Through this mechanism, different management practices have the potential to affect the pile temperature, thereby increasing or decreasing NH₃ volatilization rates. As can be observed in Fig. 4, composting systems reached temperatures in the thermophilic range (>40 °C), where NH₃-N emissions are likely to be above 10%. In contrast, conventional storage, covering, and compaction often led to temperatures within mesophilic range (20–40 °C), which tends to prevent NH₃-N volatilization.

For GHGs, according to this meta-analysis, periodical turning is the only composting method that reduces CH₄ emissions in comparison with conventional static storage of solid waste (Fig. 2b). Similarly, although statistical significance could not be found within the

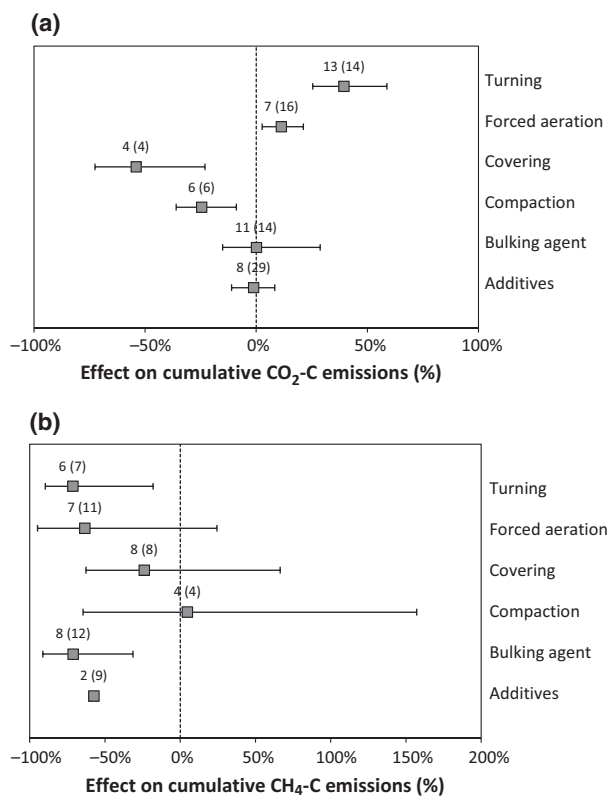


Fig. 2 Effect of different management strategies of solid waste on cumulative CO₂-C emissions (a) and cumulative CH₄-C emissions (b) in relation to conventional management (solid storage). Turning: turned composting; forced aeration: forced aerated composting; covering: covering the pile with a plastic sheet; compaction: increasing density; bulking agent: addition/substitution of bulking agent; additives: addition of specific additives to minimize emissions. Mean effect values and 95% confidence intervals are shown. Numbers above indicate studies and aggregated pair comparisons (in parentheses).

confidence level (95%) of the study, periodical turning showed a tendency toward decreasing N₂O emissions (Fig. 3a).

Differences between the two composting methods may be associated with the additional homogenization of mechanical composting via periodical turning. This avoids stratification, thus preventing the formation of anaerobic pockets and oxygen gradients between aerobic and anaerobic areas where N₂O is produced from both nitrification and denitrification processes (Hassouna *et al.*, 2008; Jiang *et al.*, 2013). However, in static systems, even with regulated ventilation, preferential flow paths can be easily formed, especially if the density and porosity of the initial mixture are not well adjusted with an adequate amount of bulking agent. In this situation, while aerobic conditions may predominate in most of the parts of the pile, anaerobic pockets are likely to appear, where the formation of CH₄ and

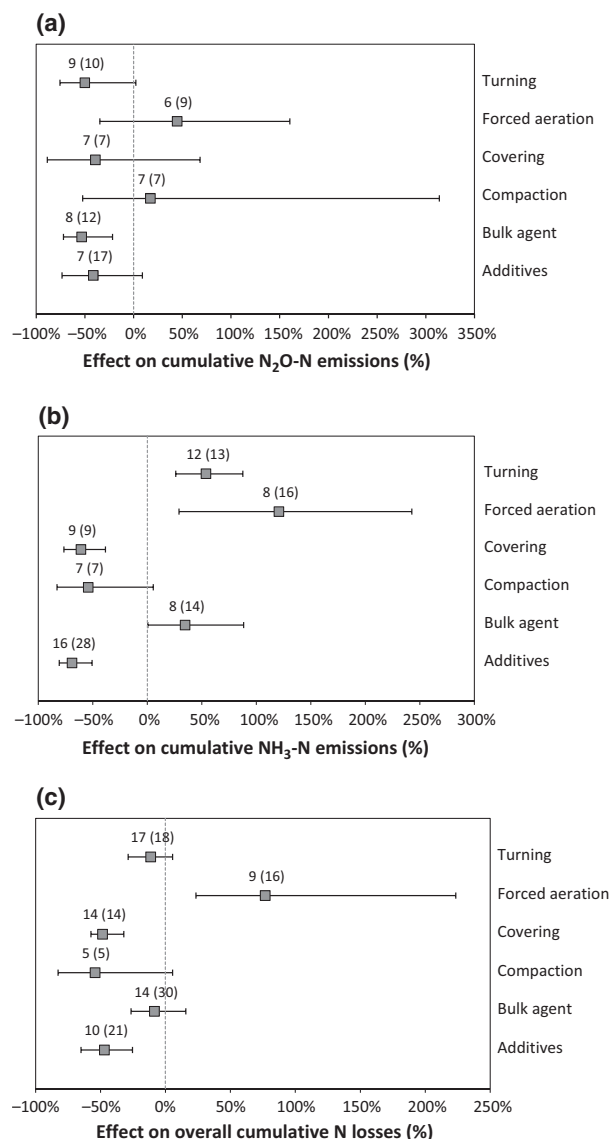


Fig. 3 Effect of different management strategies of solid waste on cumulative N₂O-N emissions (a), cumulative NH₃-N emissions (b), and overall N losses (c) in relation to conventional management (solid storage). Turning: turned composting; forced aeration: forced aerated composting; covering: covering the pile with a plastic sheet; compaction: increasing density; bulking agent: addition/substitution of bulking agent; additives: addition of specific additives to minimize emissions. Mean effect values and 95% confidence intervals are shown. Numbers above indicate studies and aggregated pair comparisons (in parentheses).

N₂O via denitrification is favored. Furthermore, whereas in turning systems, microorganisms on the surface of the pile have the potential to decompose these gases by oxidation (CH₄) or reduction (N₂O) reactions as a consequence of slow gas diffusion in the interturning periods (Hao *et al.*, 2001; USEPA, 2002;

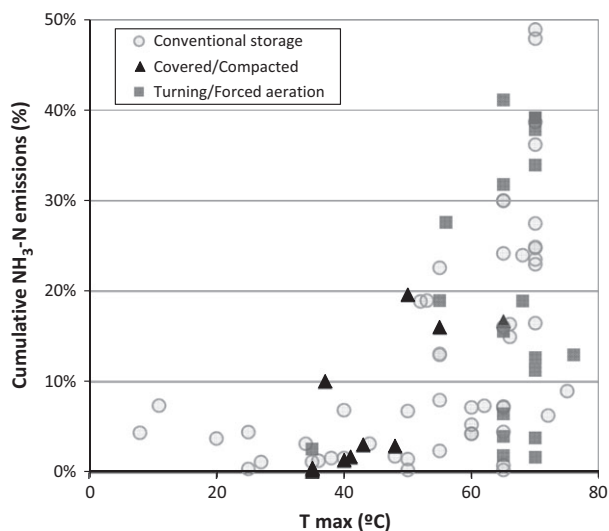


Fig. 4 Relationship between cumulative $\text{NH}_3\text{-N}$ emissions and maximum temperature (T_{max}) reached in the pile according to treatment type (Commercial-scale studies only).

Jiang *et al.*, 2013), forced aeration may enhance the release of GHGs from the pile to the atmosphere.

Nevertheless, turning does not guarantee a complete removal of anaerobic pockets, and therefore, substantial CH_4 emissions may still be produced due to large peaks after the first turning event (Ahn *et al.*, 2011). Production of CH_4 occurs mostly at the early stage of the decomposition process when there is readily available C sources in the raw material, thus promoting high biological activity and warm temperature ranges (Hellmann *et al.*, 1997; Hao *et al.*, 2004). Turning, in fact, could promote the release of confined CH_4 to the atmosphere, thus, preventing CH_4 from potentially being oxidized before reaching the pile's surface (Hao *et al.*, 2001; Ahn *et al.*, 2011).

A different influence on the total loss of TN was also observed for the two composting methods (Fig. 3c). Whereas no significant effect was found for turned systems, static composting with forced aeration led to increasing total N losses compared with conventional storage. As previously mentioned, both methods generally led to higher NH_3 emissions in comparison with conventional storage of solid waste. However, a stronger effect was observed for forced aeration (121%) than for turning (54%). Moreover, both by preventing denitrification conditions and promoting homogenization, turned composting may reduce N emissions in other forms (e.g., N_2O , N_2), thus partly offsetting NH_3 losses (pollution swapping). This improved homogenization, in comparison with forced aeration, also favors a more balanced moisture content, thus preventing N losses through preferential flows (e.g., leaching).

Covering and compacting. Unlike composting methods, covering and compaction are management strategies which involve a restriction in the O_2 supply within the waste material, thus limiting biological activity and preventing temperature increase. According to the meta-analysis results, these practices significantly reduce $\text{CO}_2\text{-C}$ emissions in comparison with conventional solid waste storage (Fig. 2a), with a slightly stronger effect found for covering (-54%) than for compaction (-24%). Although results indicate that both methods have an influence toward reducing $\text{NH}_3\text{-N}$ emissions and total N losses (Fig. 3b), in the case of compaction statistical significance could not be found.

Under restricted O_2 conditions, aerobic microbial decomposition of organic matter is inhibited and temperatures within the pile are kept in the low range, thus reducing N losses via $\text{NH}_3\text{-N}$ volatilization and promoting N conservation. However, these practices may involve constraints for stability and safety of the final product, which may result in agronomic trade-offs. For example, the destruction of weed seeds and pathogens is compromised due to the low temperature achieved. Furthermore, the lack of a strong biological decomposition phase leads to materials containing substantial amounts of decomposable C compounds (Kirchmann & Lundvall, 1993). When these organic amendments are added to the soil, denitrification may be promoted and soil microorganisms can be stimulated to compete for inorganic N, which may eventually affect plant N availability in the soil (Petersen & Sommer, 2011).

For GHGs, no significant effect on CH_4 or N_2O emissions was observed by covering or compacting practices (Figs 2b and 3a), which supports the discrepancies found in the literature. Some authors, for example, have reported low N_2O emissions associated with covering (Hansen *et al.*, 2006; Jiang *et al.*, 2013) and compaction practices (Sommer, 2001; Chadwick, 2005; Abd El Kader *et al.*, 2007). These studies generally attributed these results to a restriction on the air exchange below levels that allow nitrification. However, other studies did not find any significant effect of these practices on the N_2O emissions (DEFRA, 2004) or even a slight N_2O increase (Sommer & Dahl, 1999; Sommer, 2001).

For CH_4 , whereas anaerobic pockets exert a large influence on these losses, temperature inside the pile has also been identified as a key factor controlling the processes leading to CH_4 production (Amon *et al.*, 2001) and efficient covering and compaction practices may have the potential to mitigate it. Mesophilic or thermophilic conditions within the pile are mainly reached as a consequence of aerobic biodegradation activity, so by restricting aerobic conditions, temperature is kept in the cold range which tends to inhibit methanogen activity (Amon *et al.*, 2001). However, the

balance and interactions between aerobic and anaerobic conditions are critical, and must be carefully considered when applying these management practices, otherwise CH_4 emissions could be easily promoted (Webb *et al.*, 2012).

The influence of other factors, such as moisture and C/N on pile anaerobicity and final CH_4 emissions, has been also indicated by several authors (Tamura & Osada, 2006; Yamulki, 2006; Jiang *et al.*, 2011). While water is essential for microbial activity, an excess of moisture can restrict the O_2 supply and consequently provide favorable conditions for anaerobic decomposition. Moisture content in the pile is conditioned by substrate characteristics and environmental conditions. Specifically, these factors can play an important role in noncomposting systems due to the difficulties to remove surplus water. As displayed in Fig. 5, raw materials with high initial moisture, close to 80%, tend to promote CH_4 emissions. This pattern was not so clearly observed in composting systems, probably due to the prevalent effect of active aeration, which enhances the removal of the initial excess of water. The observed fashion is in accordance with the IPCC guidelines, which establish the borderline between 'solid' and 'slurry/liquid' systems at 20% dry-matter content and with the findings of previous studies indicating that handling animal waste in solid form tends to reduce CH_4 emissions (Paustian *et al.*, 2004).

Addition/substitution of bulking agents. Improving the porosity and physical structure of the pile can be achieved by either increasing the ratio of bedding material with respect to manure (e.g., straw) or through the use of a different bulking agent with a high content of

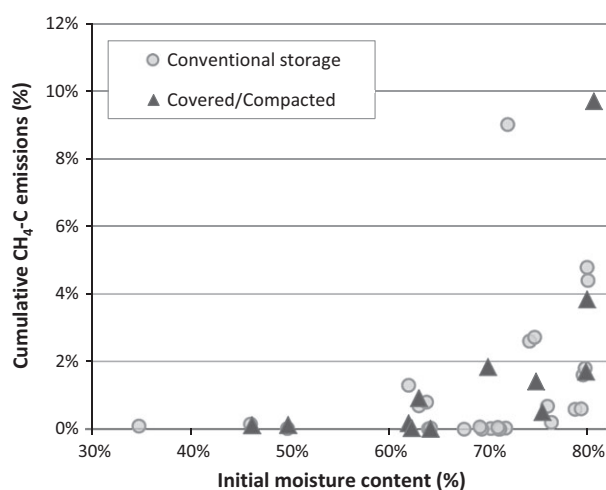


Fig. 5 Relationship between initial moisture content and cumulative CH_4 emissions from commercial-scale studies according to treatment type (Composting systems excluded).

recalcitrant compounds (e.g., wood chips). According to our results, this strategy is an efficient way to reduce both CH_4 (Fig. 2b) and N_2O (Fig. 3a) emissions during solid waste management.

The structure provided by the addition of lignocellulosic materials enhances natural aeration and O_2 supply within the pile, as well as a better regulation of moisture content. This prevents the formation of anaerobic regions consequently suppressing CH_4 production. Although N_2O via nitrification may still be produced (Peigné & Girardin, 2004), these conditions appeared to significantly inhibit denitrification and total N_2O emissions.

The addition of a bulking agent also increased losses of NH_3 -N (Fig. 3b). This is probably a consequence of higher gas diffusion and lower water content which affects the dynamic equilibrium of NH_3 with the ammonium (NH_4^+) in the aqueous solution. In contrast, it did not significantly affect CO_2 emissions (Fig. 2a) and TN losses (Fig. 3c).

Increasing the amount of straw or adding high-fiber bulking agents helps to improve the structure of the pile and to decrease the pile density (higher porosity), thus enhancing O_2 availability. Through a review analysis, Webb *et al.* (2012) examined the relationship between the bulk density of the pile vs. N_2O and NH_3 losses, finding a positive relationship with N_2O emissions and negative with NH_3 emissions. A similar pattern was observed when we applied the same approach to our whole dataset (Fig. 6), which stresses the risk of pollution swapping when trying to mitigate N_2O emissions by manipulating solid waste density.

The incorporation of bedding materials or other bulking agents to the substrate mixture often leads to

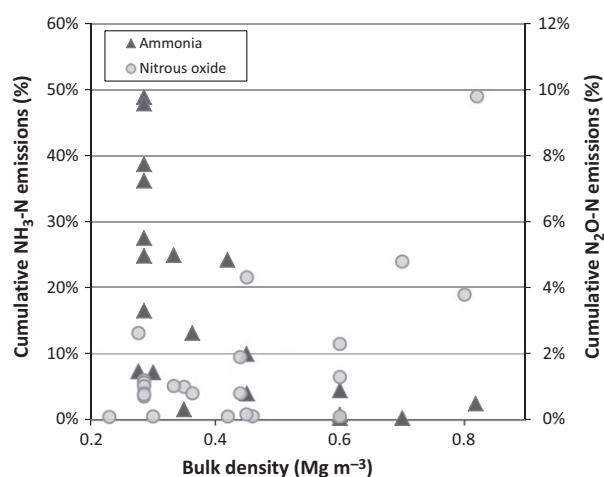


Fig. 6 Relationship between bulk density and cumulative NH_3 and N_2O emissions.

increase the C/N ratio of the initial material. Generally, high values of C/N ratio are likely to promote the immobilization rate of NH_4^+ -N, which leads to reducing NH_3 losses (Rynk *et al.*, 1992; He *et al.*, 2000; Tiquia & Tam, 2000; Raviv *et al.*, 2004). However, bedding materials or bulking agents usually contain recalcitrant C compounds, which are not easily available for microorganisms, as can be suggested by the noninfluence observed on CO_2 emissions in our analysis (Fig. 2a). This effect may have reduced the N immobilization rate and indirectly allowed greater chances for NH_3 losses.

Overall, TN losses were not affected by the addition/substitution of bulking agents, which could be attributed to their moderate effect on NH_3 emissions being offset by other processes such as reduction on N losses through leaching due to a better regulation of moisture content, or N_2O and N_2 emissions via denitrification.

Use of additives to reduce emissions. The addition of additives has been shown to be effective at both mitigating NH_3 emissions during storage or composting of solid waste and enhancing N conservation in the final material (Fig. 3b, c). A number of studies have applied struvite (magnesium ammonium phosphate) precipitation by adding Mg and P salts at the beginning of the process, thus reducing N losses, particularly in the form of NH_3 -N (Ren *et al.*, 2010; Fukumoto *et al.*, 2011; Wang *et al.*, 2013). Other chemical reagents have also been reported to reduce NH_3 emissions when added to the initial mixture in an adequate proportion, for instance ferric chloride (Boucher *et al.*, 1999), phosphogypsum (Luo *et al.*, 2013), aluminum sulfate (Bautista *et al.*, 2010), ferric sulfate, or sodium bisulfate (Li *et al.*, 2008) among others. Furthermore, several authors have demonstrated that materials with physical adsorption features, such as zeolites or attapulgite, are able to decrease NH_3 losses, thus enhancing N conservation (Bautista *et al.*, 2010; Xie *et al.*, 2012). In other cases, studies have evaluated the effect of adding exogenous microorganisms into compost material, resulting in reductions of N losses (Kuroda *et al.*, 2004; Li *et al.*, 2008).

When aiming at reducing N_2O emissions, the application of specific additives has not resulted in consistent effects (Fig. 3a). For example, when the target was to restrict nitrite (NO_2^-) accumulation through the addition of NO_2^- -oxidizing bacteria (NOB) from mature compost (Fukumoto *et al.*, 2006, 2011; Fukumoto & Inubushi, 2009), nitrification (NO_2^- being oxidized to NO_3^-) was promoted and N_2O production was accordingly inhibited. In other cases, using mineral additives such as attapulgite or a nitrification inhibitor called dicyandiamide (DCD) have shown to be successful in reducing N_2O emissions during the solid waste management process. In contrast phosphogypsum, a by-product of

phosphorus fertilizer production, has shown no significant effect on N_2O losses (Hao *et al.*, 2005; Xie *et al.*, 2012; Luo *et al.*, 2013).

The number of studies reporting CH_4 losses from solid waste management applying additives is limited. Our results are based on 9 experiments from only two studies examining the effect of phosphogypsum addition on gaseous emissions. Average values suggest that this strategy tends to reduce CH_4 emissions (mean: -59%). However, more data are still required to confirm this trend.

Our study shows that the use of additives can significantly reduce N losses during solid waste management processes (Fig. 3c). Most of these substances are added with the objective of controlling gaseous N emissions (e.g., NH_3 and N_2O), and therefore, they are also likely to improve N conservation in the final solid waste pile. Furthermore, in several cases, the solid waste amendment, once applied to the soil, acts as a slow release fertilizer, thus reducing environmental issues at other stages of the waste management continuum (Bautista *et al.*, 2010; Ren *et al.*, 2010; Fukumoto *et al.*, 2011).

No significant effect was found in terms of CO_2 emissions (Fig. 2a), which indicates that this strategy has no adverse effect on organic matter degradation in most of the cases.

Implications on GHG EF of manure management systems. As part of the Kyoto Protocol, national GHG inventories are reported according to the methodology described in the IPCC guidelines (IPCC, 2006). Different levels of detail are proposed for the emission estimates, depending on specific characteristics of the country and availability of activity data in every case. For Tier 1 method, emissions of CH_4 and N_2O are calculated through default factors, based on the amount of biowaste processed or manure produced according to the population of different livestock species and management system applied.

For accounting N_2O emissions from manure management, the IPCC guidelines (IPCC, 2006) propose an EF of 0.5% ($0.005 \text{ kg N}_2\text{O-N kg initial N}^{-1}$) for solid storage and in the range from 0.6% to 1% for the composting systems. A higher EF is attributed to turned composting systems in comparison with forced aerated piles, as it is assumed that turning operations influence gas diffusion and enhance the release of N_2O emissions to the atmosphere (Hao *et al.*, 2001). From the studies reviewed in our work, we did not find consistent differences between turned and forced aerated composting systems (Fig. 3a). Unfortunately, we could not investigate this issue in depth because there is a lack of experiments dealing with composting by forced aeration, particularly at commercial scale.

Some differences were observed between turned composting and conventional storage system (solid storage). Despite no statistical effect was found, our meta-analysis results suggest a trend toward obtaining lower N_2O emissions in turned composting systems when compared with solid storage. Furthermore, as displayed in Table 3, when analyzing the whole sample of collected studies, the N_2O emissions observed from both management systems are in the same range, with a slightly lower mean value obtained for turned composting system. Therefore, according to the data examined in this review, we believe that there is no evidence to assume a substantially lower EF for solid storage systems ($0.005 \text{ kg } N_2O-N \text{ kg}^{-1} \text{ N excreted}$) than for turned composting (referred as passive windrow composting in the IPCC methodology) ($0.01 \text{ kg } N_2O-N \text{ kg}^{-1} \text{ N excreted}$) as it is currently assumed in the IPCC methodology (IPCC, 2006).

For CH_4 emissions from manure management, the IPCC Tier 2 proposes an estimation method based on manure characteristics and management system applied. First, depending on the manure source, the maximum amount of CH_4 than can be potentially produced is defined as B_0 . In addition to this, CH_4 conversion factors (MCFs) are used according to different management systems and operational conditions (temperature, retention time), to describe the fraction of B_0 that is converted, thus determining the final amount of volatile solids converted into CH_4 for given conditions.

For comparison purposes, we also estimated cumulative CH_4 -C emissions (as % of total C in the initial pile) for the commercial-scale experiments used in our whole dataset following the IPCC methodology (Fig. 7). The results obtained through the IPCC method are mostly in agreement with the measurements observed in the different studies. However, a general underestimation of CH_4 losses can be observed. Moreover, a lower range of CH_4 emissions from composting systems is estimated in comparison with conventional solid storage, which is consistent with the results of the present work. In the IPCC guidelines, the different

Table 3 N_2O emission factors for solid storage and turned composting in passive windrow according to IPCC methodology and range of results obtained from collected studies in this work

	IPCC	Present study		
	(2006)	Median	Mean	SD
$\text{kg } N_2O-N \text{ kg } N \text{ excreted}^{-1}$	EF			
Solid storage	0.005	0.009	0.017	0.020
Composting – passive windrow	0.010	0.005	0.012	0.013

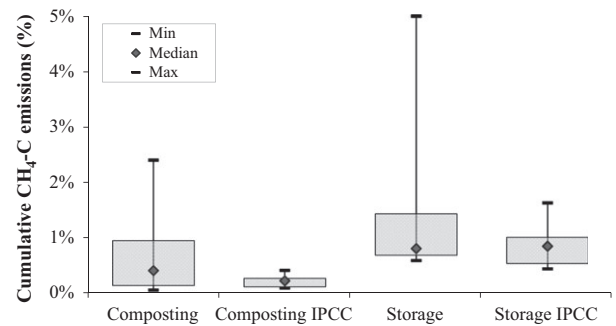


Fig. 7 Range of cumulative CH_4 -C emissions observed in collected studies in this work in comparison with estimations for the same studies according to IPCC methodology.

influence of aerobic and anaerobic conditions enhanced by every solid manure management option is reflected by the MCFs applied, which differs between composting (0.5–1%) and conventional solid storage systems (2–5%).

As discussed in previous sections, there is also scope for reducing GHG emissions through other management practices. For example, increasing the proportion of bedding material or applying a different bulking agent mixed with the solid waste improves the structure of the heap and enhances the O_2 supply within the waste material. This influences the biological process development and the nitrification–denitrification activity, generally resulting in lower CH_4 emissions and N losses via N_2O . Similarly, the use of certain additives applied to solid storage manure has shown to reduce CH_4 and N_2O emissions in several cases. However, the influence of these strategies is not specifically reflected in the IPCC guidelines and would require the development of a Tier 3 approach to be adequately accounted for (IPCC, 2006).

Limitations of the study and information gaps

Meta-analysis is a useful quantitative method that allows integrating results from independent studies with similar characteristics to test the analyzed data for statistical significance. Nevertheless, our conclusions are constrained due to the limitations of the gathered data. Although the number of experiments investigating the influence of management practices on GHG emissions has grown during the last decade, an important restriction of our dataset is that there is still a limited knowledge basis with respect to gaseous losses from solid waste management, particularly for CH_4 and N_2O emissions at commercial scale. In addition to this, the collected results showed large variability, which emphasizes the need to produce additional data through precise and accurate research methods to

obtain robust EF estimates that can help reduce current uncertainties.

Other important issue that restricted our meta-analysis was the lack of detailed information in several studies in relation to the measured emissions and the initial substrate characteristics. Standardization of the literature results implied converting all collected results into an EF form, thus calculating total cumulative emissions as a percentage of the initial content of the respective element (e.g., %N₂O-N). However, in some experiments, only the gas concentration profiles had been determined. In other cases, the gaseous losses were expressed in relation to the emitting surface, or total cumulative emissions were indicated but there was not detailed data about substrate characteristics, so it was not possible to relate results with the initial content of N and C. We were not able to include these data in our meta-analysis, and some observations from additional studies were missing, which otherwise could have provided valuable information. In addition to these limitations, the dataset used in the meta-analysis approach has been constrained due to a lack of comparative experiments. Therefore, it would be interesting, for future studies and comparison purposes, to include a conventional solid storage system as a control treatment. Furthermore, establishing several treatment replicates would facilitate statistical analysis.

The gas measurement method selected during the experiment design stage can also be a significant source of variability. As pointed out by some authors, the use of static chamber technique might not be adequate for commercial-scale experiments because it was designed to measure gasses emitted from soil by diffusion mechanisms, whereas convective flows are usually dominant in solid waste piles (Chadwick *et al.*, 2011). Alternative techniques, as dynamic chamber or wind tunnel systems, are more appropriate for this type of studies.

In a general way, we recommend that future studies should account for gaseous losses as cumulative emissions based on the proportion of initial C or N content, and systematically provide some basic information in terms of (i) initial and final substrate characteristics (physicochemical characterization); (ii) operational conditions (management system, temperature profile, experiment duration, and size); (iii) environmental factors (ambient temperature, precipitation); and (iv) measurement techniques (gas analysis, collection method).

Finally, more detailed information about the C and N transformations during solid waste management is necessary to improve the current knowledge of the involved mechanisms. Many progresses have been made to unveil the relationships and interactions between the biochemical and physical characteristics of the solid waste and the gaseous emissions, which has

been reflected in previous review studies (Chadwick, 2005; Petersen & Sommer, 2011; Webb *et al.*, 2012; Petersen *et al.*, 2013). While systematic review has allowed us to identify some of the factors that regulate this process, we could not analyze the influence of several other factors that may be important due to insufficient number of studies to establish statistical relationships.

Hence, we believe that future studies should consider including parameters accounting for the availability and quality of C and N in the initial feedstock, because this has been identified to have an important effect on the potential C and N emissions (Paillat *et al.*, 2005). Moreover, parameters which may be used as a proxy for pile's aerobicity (e.g., bulk density) should be evaluated and proposed for systematic monitoring. Alternative approaches (e.g., from other research fields) of parameters that incorporate information on chemical and physical properties of the substrate could be explored, like the concept of physically effective fiber (peNDF) used in animal feed research. Specific studies examining the interactions between environmental and management factors and the microbial processes involved in emissions would also be of potential interest.

Furthermore, just a few of our gathered studies reported an analysis of the overall N losses through its different pathways, and even fewer closed the N balance, which in many cases, resulted in substantial unaccounted N losses. Further development of experiments evaluating the different pathways of N losses, considering solid, liquid, and gaseous components (e.g., NO₃⁻, N₂), is needed to disentangle the mechanisms that control these emissions. Direct measurement of both N₂O and N₂ may be difficult though. Therefore, it would be interesting to explore the applicability for solid waste decomposition studies of using specific methods originally developed in soil science that allow partitioning between N₂ and N₂O production (e.g., enzymatic inhibitors, tracer isotopes, or inert gas incubation systems) (Butterbach-Bahl *et al.*, 2013). This will improve the understanding of how N from solid waste transforms and which factors control these processes. Consequently, it will help to understand conditions that allow striking a balance between a low environmental impact and a valuable final product.

Through this work, we have focused on quantifying the influence of a range of practices on the emissions produced during the management of solid waste. Nevertheless, when analyzing the mitigation potential of these strategies, the pollution swapping between different stages of the organic waste management continuum must be accounted; and additional aspects such as economic viability or interactions with the soil-plant system should be considered too. For example, the use of

certain additives at commercial-scale might be constrained due to their cost if it does not compensate the N fertilizer value at the final product. Likewise, increasing the amount of bulking agent may be an adequate strategy for reducing GHG emissions, but it can involve an additional cost, not only linked to the price and availability of the material, but also to its handling and transport. Therefore, for an adequate evaluation of the environmental benefits of management strategies, a more holistic approach would be required, taking into account all the implications and interactions from a life-cycle perspective.

Conclusion remarks

The present study has investigated the influence of six different strategies for reducing GHGs, NH₃, and total N losses during the management of organic solid waste. Improving the structure of the organic waste through the incorporation of a bulking agent is one of the most effective measures, simultaneously reducing CH₄ and N₂O emissions without increasing substantially N losses through NH₃ volatilization. With regard to composting methods, turned systems have shown potential for reducing GHGs emissions, whereas no clear effects were detected for forced aerated system. Nevertheless, the aerobic conditions enhanced in both composting methods involve the risk of pollution swapping due to an increase in NH₃ emissions.

In contrast, strategies based on the restriction of O₂ supply, such as covering or compaction, while providing some advantages in decreasing N losses via NH₃ volatilization, did not show significant effects on reducing either CH₄ or N₂O emissions.

The use of specific additives can be a successful strategy when aiming at reducing gaseous losses during management of solid waste. Nevertheless, their effectiveness varies depending on the substance, dosage, and operational conditions.

According to the data examined in this review, we think that at least there is enough evidence to assume that N₂O emissions from solid storage systems are in the same range as those from turned composting in passive windrow, thereby the respective EFs could be refined in the development of the future IPCC methodology.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Appendix S1. A list of publications and details of studies which were collected for the analysis. MA: publications included in the meta-analysis.

Appendix S2. Ranges of the factors defined in relation with climatic conditions.

Appendix S3. Substrate characteristics according to different waste type.

Appendix S4. Cumulative emissions according to different grouping criteria.

Figure S1. C/N ratio (a), total nitrogen (TN) (b) and total ammoniacal nitrogen (TAN) (c) of solid waste according to waste type.

Figure S2. Cumulative emissions of CO₂-C (a), CH₄-C (b), N₂O-N (c), NH₃-N (d) and total nitrogen (TN) losses (e) from management of solid waste according to waste type.

Figure S3. Cumulative emissions of CO₂-C (a), CH₄-C (b), N₂O-N (c), NH₃-N (d) and total nitrogen (TN) losses (e) from management of solid waste according to treatment type.

Figure S4. Cumulative emissions of CO₂-C (a), CH₄-C (b), N₂O-N (c), NH₃-N (d) and total nitrogen (TN) losses (e) from management of solid waste according to climatic conditions (temperature).

Figure S5. Cumulative emissions of CO₂-C (a), CH₄-C (b), N₂O-N (c), NH₃-N (d) and total nitrogen (TN) losses (e) from management of solid waste according to annual rainfall rate.

Figure S6. Cumulative emissions of CO₂-C (a), CH₄-C (b), N₂O-N (c), NH₃-N (d) and total nitrogen (TN) losses (e) from management of solid waste according to experiment scale.

Figure S7. Cumulative emissions of CO₂-C (a), CH₄-C (b), N₂O-N (c), NH₃-N (d) and total nitrogen (TN) losses (e) from management of solid waste according to duration scale.