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Review

Gaseous Emissions from the Composting Process: Controlling Parameters and Strategies of Mitigation

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Abstract: Organic waste generation, collection, and management have become a crucial problem in modern and developing societies. Among the technologies proposed in a circular economy and sustainability framework, composting has reached a strong relevance in terms of clean technology that permits reintroducing organic matter to the systems. However, composting has also negative environmental impacts, some of them of social concern. This is the case of composting atmospheric emissions, especially in the case of greenhouse gases (GHG) and certain families of volatile organic compounds (VOC). They should be taken into account in any environmental assessment of composting as organic waste management technology. This review presents the relationship between composting operation and composting gaseous emissions, in addition to typical emission values for the main organic wastes that are being composted. Some novel mitigation technologies to reduce gaseous emissions from composting are also presented (use of biochar), although it is evident that a unique solution does not exist, given the variability of exhaust gases from composting.

Keywords: organic wastes; composting; gaseous emissions; mitigation strategies

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1. Introduction

As a result of increasing solid wastes' generation, the implementation of a reliable technology to deal with these wastes is considered as a pillar of sustainable development of any nation [1]. However, the selection of any technology should be compatible with the economic situation within the jurisdiction. Concurrently, the used technology has to satisfy the laws and regulations that fundamentally aim to reduce any environmental and health problems [2]. Among the different technologies used in this field is the composting process, which has been used to deal with solid wastes and mainly for the organic fraction of wastes [3,4]. This process is recognized as an environmentally friendly and cost-effective method, as organic matter is biologically degraded under aerobic conditions [5]. This biodegradation of organic matter contributes to reducing the volume of wastes and producing a stabilized and nutrient-rich final end product, "compost", that could be used in agricultural activities due to its various positive impacts on the physical and chemical properties of the soil, meanwhile reducing utilization of inorganic fertilizers [6–8]. Actually, when the process-controlling parameters are well adjusted, this will lead to different advantages; thereby the process is viewed as a sustainable alternative for landfilling and other treatment options [9]. However, even though composting is a natural biochemical decomposition process, a successful composting operation that produces a valuable end product is normally associated with releasing gaseous emissions including greenhouse gases (GHGs) into the atmosphere (Figure 1). The released GHGs are attributed to energy requirements for composting plants' operation and to the biochemical reactions within the organic waste itself, which produces CO_2, methane (CH_4), and nitrous oxide (N_2O) due to the mineralization and degradation of organic matters [10,11]. According to Hao et al. [12], the majority of organic carbon is converted to CO_2, whereas the methane accounts for less than 6%. Nevertheless, it should be noted that even though CO_2 represents the major part of the emissions, it does not add to global warming due to the biogenic origin of carbon. On the contrary, the other emissions resulting from the process such as CH_4 and N_2O have a direct impact on the global warming, while NH_3, Sulphur compounds, and most of the volatile organic compounds (VOCs) emissions cause undesirable and other odor nuisances [9,13,14]. Indeed, these gases contribute to climate change, global warming, acidification, and eutrophication of ecosystems as a result of NH_3 deposition, which also contributes to the formation of particulate matters in the air [9]. As a matter of fact, these GHGs and ammonia (NH_3) deteriorate the compost quality, besides being a secondary environmental pollution, as mentioned before [15,16].

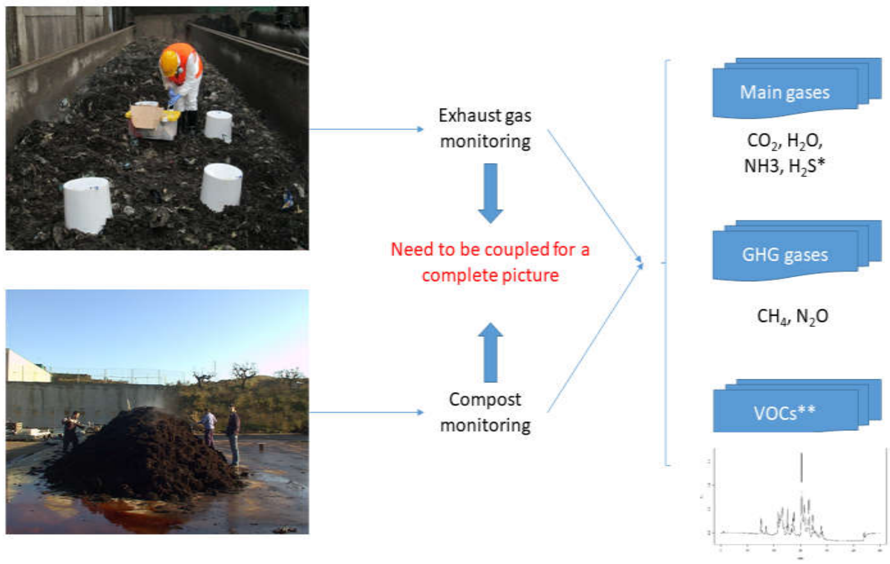

Figure 1. Monitoring exhaust gases from a composting process. * H_2S is only significantly observed when anaerobic conditions prevail in the composting process. ** VOCs: Volatile Organic Compounds, a wide group including families such as alcohols, aldehydes, alkanes, aromatic hydrocarbons, carboxylic acids, ketones, nitrogen compounds, phenols, sulphur compounds, and terpenes, among others.

Emissions are formed due to inadequate aerobic conditions of composting [9]. Generally, the creation of anaerobic zones in compost mixtures results in CH_4 emissions, whereas nitrogen transformation and loss (NH_3 and N_2O) are linked to ammonification, nitrification, and denitrification during the composting process [17–19], but still they are less than GHGs' emissions generated from landfilling and waste-to-energy processes [20–22]. During the composting process, various forms of VOCs are formed, where the rates and specific forms of these emissions highly depend on the feedstock materials and composting phases, taking into account that aeration of the composting mixture has a major role in releasing of these compounds [23,24]. The rate of gaseous emissions is differing based on the applied composting method, whereas the initial content of the carbon and nitrogen is of great importance in the produced amount of gaseous emissions such that low total carbon (C) and nitrogen (N) content can simultaneously reduce CH_4, CO_2, and N_2O emissions [25]. In this regard, it has been reported that manure composting may account for 46% and 67% of the initial N and C content of the original manure, respectively [26]. The losses in nitrogen mass are normally in the form of NH_3 emissions, whereas nitrous oxide emission, which has 265 times the global warming potential of CO_2 [27], accounts for about 0.1–5% of total N losses [28–30]. Noteworthy is the amount of these emissions influenced by the composting technology. In this context, silo composting reduced GHGs' losses by

82.84% compared with turning composting, which resulted in larger carbon and nitrogen losses [25].

Reducing the impact of the resulting emissions from composting has been investigated and practiced using different approaches. For example, biofilters effectively reduced the NH_3 emission with mitigation efficiency (ME) of 97%, whereas adding sawdust or straw reduced CH_4 and N_2O emissions by 66.3% and 44.0%, respectively, as such types of materials enhance the absorption and microbial assimilation of NH_4^+/NH_3 [25]. Providing an optimal initial mixture and maintaining aerobic conditions among other practices have been used to mitigated both odors and GHGs [31]. This research presents a comprehensive overview on the gaseous emissions from composting processes. Factors that influence the production of emissions and the mitigation approaches are highlighted also.

2. Gas Emissions from Composting Process

As a result of microbial activities and putrefaction, gaseous emissions from organic wastes are produced [10]. These emissions, which include CO_2, CH_4, N_2O, Sulphur compounds, and many other volatile organic compounds (VOCs), as shown in Table 1, have been detected during the different phases of the waste management [9,31].

Table 1. Volatile organic compounds (VOCs) detected in the composting of different organic wastes.

Waste	Main VOC Family	Other VOCs	Reference
Poultry litter	Alkanes and alkylated benzenes	Aldehydes, terpenes, and ketones	[32]
Chicken manure and biochar	Ketones, phenols, and organic acids	Aliphatic, aromatic, and terpenes	[33]
Municipal solid waste	Alkylated benzenes, alcohols, and alkanes	-	[14]
Wastewater sludge	Terpenes	Furans and esters	[34]
Digested wastewater sludge	Terpenes	Alcohols and Ketones	[34]
Swine carcass	Sulphur compounds	-	[35]
Municipal solid waste	Terpenes	Alcohols, volatile fatty acids, and aromatic compounds	[36]
Livestock and Poultry Manure	Sulfur compounds, aliphatic hydrocarbons, aromatic hydrocarbons	Chlorinated organic compounds	[37]
Municipal solid waste digestate	Terpenes and oxygenated compounds	Sulphur compounds and methanethiol	[38]
Green waste	Alcohols	Alkenes, aliphatic alkanes, aromatic hydrocarbons, ketones, aldehydes, furans, and esters	[39]
Sewage sludge	Isovaleraldehyde, butyric acid, sulphur compounds, and pinene	Indole, skatole, and phenol	[40]

In the composting process, the amount of emitted gases is highly influenced by the type of treated wastes, composting technology, and operational conditions, mainly aeration, which would have a direct impact in reducing the rate of emissions, mainly N_2O and methane, when it is properly adjusted [9]. According to Goldstein [41], the odors generated from composting plants are attributed to different compounds including terpenes, alcohols, aldehydes, fatty acids, ammonia, and a range of Sulphur compounds. Methane is normally formed during the composting process due to anaerobic condition that could be established in some parts of the composted material such as middle zones of a pile, which suffer from insufficient diffusion of oxygen [12,24]. However, nitrous oxides are produced due to nitrification and denitrification [42], taking into account that other conditions such as temperature, nitrate concentration, and aerobic conditions influence these emissions [43].

For the determination of emissions' rates and their subsequent global impact, emission factor is usually used as a useful tool for VOCs, NH_3, or GHGs. The emission factor is usually expressed per ton of treated waste or per amount of obtained compost [44]. For instance, GHGs' emission factor, in terms of kg $CO_{2eq}.Mg^{-1}$ dry matter of sewage sludge (DM–SS), was found to be 2.30×10^2. On the other hand, the sewage sludge composting odor emission factor (OEF) was 2.68×10^7 ou.Mg^{-1} DM–SS [45]. Different emission factors could be found in the literature, depending on the characteristics of the feedstock or the composting technology [46–49].

Compared with other treatments or management technologies for solid waste, different studies demonstrated that the composting process has less impact on global warming, as it produces lower amounts of GHGs. In this regard, Lou and Nair [50] showed that composting of municipal solid waste produced about 1.29 t CO_2-eq/t-of-waste, which is lower than the amount produced from landfills. Actually, this was concluded and documented by different studies, which emphasized that composting produces lower amounts of emissions (g CO_2-eq/t-of-waste) compared to landfilling and incineration based on emission factor [21,49–51]. However, when composting and vermicomposting were compared, it was found that the vermicomposting process caused 78.19% lesser GHGs' emission as compared to the composting process, which released 80.9 kg CO_2-eq/t-of-waste [52].

3. Factors Affecting the Emissions' Rates

During the initial stages of the composting process, both nitrogen and sulfur are in the organic form [53]. As the process proceeds forward, the mineralization of the organic nitrogen leads to the formation of ammonia (NH_3), which could react with hydrogen ions to form ammonium (NH_4^+). The NH_4^+-to-NH_3 equilibrium is highly affected by the dominant conditions within the composting mixture, mainly the pH value and temperature [54–56]. Thermophilic temperatures and alkaline conditions enhance the loss of nitrogen as ammonia. Additionally, ammonia-oxidizing bacteria or archaea and nitrite-oxidizing bacteria convert part of the nitrogen to nitrate through the nitrification process. This nitrate is used by the microbial community, but it would be converted to N_2O under certain conditions including denitrifications' process, especially under insufficient oxygen levels [54]. Furthermore, the low levels of oxygen lead to the formation of some anaerobic zones within the compositing mixture. These zones play a major role in the sulfur transformation and the production of H_2S through the action of Sulfate-reducing bacteria (anaerobic) during the degradation of the organic matter [57]. Additionally, during the formation of H_2S, other reduced sulfur compounds will also be produced, such as MeSH, Me_2S, Me_2SS, and others [54]. The following are some of the main factors that affect the emissions' rates during the composting process.

3.1. Composting Method

Composting of solid wastes can be carried out using different technologies [4]. As reported in various studies, the used technology has a direct impact on the rate of gaseous emissions [31]. In this regard, turned and windrow technologies showed higher values of CH_4, CO_2, and N_2O compared with other technologies [25,58–60]. Turning of composted materials increases the chances of releasing trapped gasses within the composting materials and exposing them to the air. The frequent turning helps in re-structuring the materials and improving the porosity; thus, more air could be diffused that supports the microbial activities and promotes the biodegradation of the organic matter, which ultimately increases the amount of CO_2 volatilization [25,61,62]. Additionally, N_2O emissions are high in turned piles compared with other technologies. This is attributed to the losses as a result of nitrification near the surface and denitrification by mixing NO_3 /NO_2 accumulated on the surface into the pile [63–65]. Amlinger et al. [44] suggested that high aeration and effective stripping of NH_3 during the early stages of composting can reduce N_2O formation. Additionally, the enzymatic activity is thought to be affected by turning and increases the N_2O emissions. Under anoxic conditions, denitrification enzymes are in an equilibrium state; however, when the material is exposed to oxygen as a result of turning, nitrous oxide reductases that can catalyze the transformation of N_2O to N_2 are clearly more severely inhibited by O_2 than the other reductases, resulting in a stronger N_2O emission [66,67]. Between turned piles and static systems, lower emissions of N_2O and CH_4 were observed in turned piles, attributed to the difference to the anaerobic zones in the static system [68–70]. In silo composting, the N_2O and CH_4 emissions were lower than other methods. This is because a good aeration system resulted in reducing the chances for the denitrification process. Moreover, more NH_3 is emitted from this system, which reduced the substrates for N_2O emissions [25,59,60]. Similar observations regarding the aeration effect on the emissions were noticed by Ermolaev et al. [71], such that lower emissions of CH_4 and NO_2 were observed regardless of the amount of aeration.

3.2. Average Composting Temperature

The temperature evolution during the composting process has a direct impact on the rate of gaseous emissions. It is well documented that a positive correlation is normally observed between temperature and emissions' rate, where a higher rate of emissions was recorded with high temperatures and, more specifically, in the thermophilic ranges (45–70 °C) [9]. This could be attributed to the high rate of organic matter decomposition at higher temperature [25,62,72]. In this regard, Fillingham et al. [59] demonstrated that the highest NH_3 emissions were recorded in silo composting (111.07 g [NH_3-N] kg^{-1} [TN]) compared to windrow composting, and the difference was attributed to high temperatures, which were about 65 °C in silo composting. These conditions enhance the equilibrium between ammonium and NH_3 towards gaseous NH_3, whereas low temperature inhibits microbial ammonization, thus reducing NH_3 emissions [25,63]. Similarly, elevated temperatures result in increasing CH_4 emissions. This could be explained by the high rate of microbial activities that result in increasing the temperatures, and these conditions are associated with high oxygen consumption, which ultimately leads to forming anaerobic conditions and the formation of CH_4 [45,72–74]. The same trend was also observed regarding CO_2 and N_2O emissions that exhibit an increase with increasing temperature [63,75]. In this context, the maximum concentrations measured during sewage sludge composting were 2600 ppmv of NH_3, 66 ppmv of H_2S, and 1650 ppmv of tVOCs, which were observed during the peak of maximum temperature of the reactor [76]. Accordingly, controlling this parameter would help in controlling the emissions' rates [9].

3.3. Initial Moisture Content

Providing an optimum moisture content is crucial for the composting process performance, as it will promote the microbial activities [4]. However, increasing moisture content above the recommended values (40–60%) would result in creating anaerobic zones within the composted materials [25]. This was clear regarding CH_4 emissions that were positively correlated to the moisture content of the compost [28,77], meanwhile a negative correlation with moisture content was recorded regarding the CO_2 emissions [25]. However, for N_2O emissions, the correlation with moisture content is not well established. For instance, Hwang and Hanaki [78] demonstrated that N_2O emissions decreased when the material became very moist because of the inhibition of N_2O nitrification, but Yan et al. [79] showed that the N_2O would increase with water content as aerobic and anaerobic zones would simultaneously exist and also the nitrification and denitrification might be promoted concurrently and N_2O emission flux could become relatively high.

3.4. Initial Total Carbon (TC) and Initial Total Nitrogen (TN) Content

Carbon and nitrogen are essential for the microbial activities during the composting process. Providing an adequate ratio of carbon and nitrogen (normally indicated as C/N ratio, with recommended values between 25:1 to 30:1) is considered as one of the controlling parameters in this process [25,31]. Importantly, these elements also have an impact on the rate of emissions resulting from the process. When the microbial communities biodegrade the organic matter under aerobic condition, most of the carbon is lost as CO_2, such that a linear relation between carbon content and CO_2 emissions would be observed during the process [76]. Furthermore, initial carbon content was found to have a positive correlation with CH_4 emissions [80], considering the nitrogen content, which is a primary source for methanogenic bacteria [11,81]. Similarly, the rate of N_2O emissions is positively correlated with nitrogen content, as both nitrification and denitrification are enhanced by a high content of nitrogen [65,82]. Usually, composting feedstocks with low C/N ratios and high moisture contents provides favorable conditions of producing more greenhouse gas emissions [31]. Ammonia emissions are also affected by the C/N ratio [31,73,83,84].

3.5. Aeration Rate

As an aerobic process, supplying a sufficient amount of oxygen is recognized as an important parameter for maintaining the microbial activity and reducing the gas emission during the composting process [85]. Sufficient aeration through forced aeration or mechanical turning would guarantee the non-formation of anaerobic zones within the composting mixture, thereby reducing odor problems [9,86]. Importantly, and per statistical analysis, it absolutely was clear that aeration rate was the foremost important factor that could significantly affect the NH_3, CH_4, and N_2O emissions [5,87]. Rosenfeld et al. [88] indicated that aeration reduced the concentrations of NH_3, CH_2O_2, and CH_3COOH by 72%, 57%, and 11%, respectively, compared to the windrow. Additionally, Quiros et al. [89] reported a reduction in emissions' rates by five times when frequent turning was employed compared to non-turned treatments. However, it should be taken into account that an adequate aeration rate has to be applied that would maintain the biological activity and reduce the emissions' rates at the same time [5,90–92]. Applying higher aeration rates would reduce some emissions such as CH_4, but others such as NH_3 and N_2O would be promoted. Additionally, higher aeration rates might render temperature evolution, thus decelerating the degradation of the organic matter as a consequence [5]. Results obtained by Chowdhury et al. [90] showed that low aeration rates were more practical in reducing GHGs' emissions. The same observation was reported by Zhang et al. [93] during composting of kitchen waste, where aeration rates of 0.1, 0.2, and 0.3 L (kg DM min)$^{-1}$ were studied and it was found that the lower aeration was more significant than the other two treatments. Additionally, it was indicated that intermittent aeration was better than continuous aeration in mitigating CO_2 emissions [9]. Nevertheless, Ermolaev et al. [71] indicated that aeration reduced the emissions of CH_4 and NO_2 regardless of the rate of aeration. Turning of the composted mixtures has a positive impact on reducing the rate of emissions also. This is because turning gives the chance for air exchange and releasing of different gases, as indicated in different studies [11,17]. The efficiency of aeration and turning in reducing emissions' rates was evaluated by Friedrich and Trois [10] during composting of garden waste. The study revealed that turning resulted in 8.14% higher GHGs than an aerated treatment. These findings prove that aeration is better than other treatments in reducing GHGs' emissions [94,95]. Another important element for maintaining the aerobic conditions is providing an optimal ratio of a bulking agent that provides proper structure and porosity for the composting mixture [31], meanwhile maintaining the heat and biological activity [96,97]. This will be deeply discussed in the following section.

3.6. pH Value

An optimum pH value between 6 and 8 (ideally 7) is recommended for microbial population during successful composting process. However, this parameter fluctuates, especially during the first stages of the process as organic acids are released due to organic matter degradation and, thus, the pH decreases. After that, a gradual increase in alkalinity occurs as a result of the phenolic and carboxyl groups' decomposition [4]. The increase in the pH level promotes ammonia release, by influencing the NH_4^+ to NH_3 equilibrium in spite of its directs influence on biological activity, as indicated [54,55]. However, these conditions are considered suitable for decreasing other emissions such as H_2S, which normally increases under low pH values [56]. These behaviors were documented by Gu et al. [98], where reducing the pH of compost resulted in reducing the cumulative NH_3 emissions and TN losses by 47.80% and 44.23%, while an increase in the emissions of volatile sulfur compounds and total sulfur losses was observed. More information and details about the effect of pH adjustment to mitigate the emission rates are provided in Section 4.4.

4. Mitigation Strategies

4.1. Providing Adequate Bulking Agent

The addition of some materials to organic wastes has proven its efficiency in improving air convection within the composting mixture, thereby reducing the amount of gases' emissions such as CH_4 and N_2O from composting, since most of the degraded carbon would be released as CO_2 [11,28,90]. For instance, sawdust and straw for dairy manure composting resulted in an effective mitigation for CH_4 and NH_3 with ME values of 66.3% and 44.0%, but they may increase CO_2 emission [12,99]. Additionally, Li et al. [94] demonstrated that ammonia emission may well be mitigated by adding a mix of sucrose and straw powder at the start stage of a composting process [95]. Indeed, these materials facilitate the absorption and microbial assimilation of ammonium, which decreases NH_3 emissions [9,25,95].

4.2. Introducing Microorganism for Promoting Nitrification Process and Reducing NH_3 Emissions

This approach stands on the mineralization of organic nitrogen into ammonium nitrogen, which could be transformed into nitrate by nitrification and eventually to N_2 by denitrification, or the ammonium could even be also a fixed microbial protein under the action of fungi [25,90,100–103]. It was found that the introduction of mature compost rich in nitrifying microorganism to food wastes' composting was able to reduce NH_3 volatilization by 36% [104]. Nevertheless, and despite the capability of this approach in reducing NH_3 emission, regulating the denitrification process to reduce N_2 and N_2O still represents a challenge for its successful application [5,103]. Additionally, the introduction of some exogenous microbial communities including CC-E (a complex bacterial community in which *Alcaligenes faecalis* is the main advantageous strain) and EM (Effective Microorganisms, a kind of commercial microbiological agent) for dairy manure composting reduced the potential for NH_3 emissions, with ME of 9.15% [104,105].

4.3. Vermicomposting

This composting approach demonstrated promising results in reducing the amounts of gaseous emissions including nitrous oxide, CH_4, $NH_{3,}$ and others [95,106]. The decrease in emissions' rates is attributed to the reduction of anaerobic denitrification, due to the burrowing action of the earthworms [107]. Furthermore, the large specific surface area and loose texture in vermicomposting contribute to creating a strong adsorption capacity and, at last, reducing production of different emissions, among them the NH_3, where vermicomposting was able to mitigate NH_3 emission with a ME median value of 33.5% [15,25,108]. The loss of texture improves the aerobic conditions and,, therefore, the biodegradation of the organic matter as a consequence. In this regard, it was noticed that CO_2 emissions were increased, whereas a decrease in ammonia emissions and nitrous oxide was noticed as well as a sink of methane in treatments with earthworms [109,110]. Similar results were obtained by Chan et al. [108] and Velasco-Velasco et al. [111]. Combining pre-composting and vermicomposting with additions of reed straw and zeolite resulted also in a significant reduction of ammonia, nitrous oxide, and methane during composting of duck manure [95,111].

4.4. Using Different Additives

The addition of phosphogypsum results in decreasing the pH of the composting mixture. The high sulphide concentrations and acidic conditions due to the use of phosphogypsum could inhibit methanogenesis and the action of N_2O reductase, thus reducing CH_4 and N_2O emissions [12,25,112,113]. Additionally, adjustment of pH has been practiced to reduce the emissions of NH_3. About 55.7% of NH_3 emissions was decreased due to the reduction in volatilization when phosphogypsum was applied [114]. Additionally, the addition of both $K_2HPO_4/MgSO_4$ and $KH_2PO_4/MgSO_4$ as a pH buffer agent's additive contributed to reducing NH_3 emissions [100]. However, health risks due to high hydrogen sulphide concentrations have to be considered when this mitigation method is to be used [25,115]. Manure acidification significantly (up to 93%) decreased the emissions during storage and composting processes [116,117]. Excessive acidification (pH = 5), on the other hand, increased N_2O emissions (18.6%) during composting. When manure was acidified to pH of 6, N_2O (17.6%) and CH_4 (20%) emissions, as well as GHG emissions, represented as global warming potential (GWP) (9.6%) were reduced during composting [118]. The addition of calcium magnesium phosphate fertilizer (CaMgP) also demonstrated its effectiveness in reducing emissions' rates during the composting process [119]. In this regard, Zhang et al. [93] reported that CaMgP could reduce H_2S emissions by 65%. Similar results were obtained when the effect of calcium magnesium phosphate fertilizer (CaMgP), biochar, and spent mushroom substrate (SMS) additives was investigated on compost maturity and gaseous emissions during pig manure composting. Ammonia (NH_3), hydrogen sulfide (H_2S), dimethyl sulfide (Me_2S), and dimethyl disulfide (Me_2SS) emissions could all be reduced using the three additives. However, when it came to reducing NH_3 emissions, the effect of adding CaMgP was the most noticeable (42.90%). CaMgP to H_2S emission reduction was similar to SMS, which was 34.91% and 32.88%, respectively. The three additives had obvious emission reduction effects on Me_2S and Me_2SS, all of which were greater than 50%. Adding SMS, on the other hand, reduced N_2O emissions by 37.08% [120].

Struvite could also be used to reduce emissions as struvite crystallization enhances nitrogen (ammonium) conservation during composting, which thereby reduces NH_3 emissions [47,121]. However, this approach increases the salinity of the produced compost [5,94], but this limitation could be mitigated by using other additives like lime or zeolite [18,122]. In this regard, the addition of 10% of zeolite decreased the salinity to 2.8 mS cm^{-1} and improved compost maturity; meanwhile, about 18% of NH_3 loss was achieved [122].

4.5. Compressing and Covering

This approach depends on reducing the amount of O_2 supplied to the mixture, thus lowering the microbial activity and ammonization, which reduce CO_2 and NH_3 emissions during the composting process [101,123]. Additionally, covering reduces gaseous diffusion into the air and enhances the absorption of some gas emissions. Analysis revealed that this approach could reach a mitigation efficiency of 10.1% for CO_2 and 24.3% for NH_3 emission. However, it should be noted that this approach would increase the anaerobic conditions that ultimately promote the production of CH_4 [15,25,107,109]. Different materials are used as a cover for composting mixture. These materials include sawdust, plastic, soil, paper waste, woodchip, wheat straw, peat, and zeolite, among others. Sawdust or straw has a good performance in absorption of CO_2 and NH_3, whereas plastic cover renders the gas exchange, which reduces the dissipation of the emissions [15,25,109,124,125]. Different forms of zeolite were used as a cover or even mixed with the composting mixture and proved higher efficiency in reducing emission compared to other cover materials with almost no effect on the microbial activity [5,93,104,126,127]. This material contributes to increasing the pH and initial NH_3/NH_4^+ concentration, which reduces NH_3 losses such that a reduction of 44–60% of the NH_3 was obtained during poultry manure composting [128]. Similar results were observed by Madrini et al. [126] in composting of leftover food. It should be noted that the type of zeolite and its percentage within the mixture affects the reduction rate of emissions [5,127].

4.6. Biofiltration

Biofilters, which depend on adsorption or biodegradation of pollutants, have proven their relative efficiency in reducing emissions from the composting process, especially with NH_3, where almost about 90% of this gas was reduced [25,129]. Actually, ammonia emissions in a composting process of organic fraction of municipal solid wastes varied between 18 to 150 g $NH_3 \cdot Mg^{-1}$ waste [130], while ammonia concentrations up to 700 mg $NH_3 \cdot m^{-3}$ have been reported in exhaust gases from sludge composting [4]. As documented by Pagans et al. [131], the biofilter achieved a global ammonia removal efficiency of 95.9% at a loading rate range of 846–67100 mg $NH_3 \cdot m^{-3}$ biofilter$\cdot h^{-1}$, whereas higher removal rates were seen when the waste gas had high NH_3 concentrations (more than 2000 mg $NH_3 \cdot m^{-3}$). However, this approach is more feasible compared to other technologies when it is used in closed systems with collection equipment [15]. Furthermore, the complexity and uncertainty measures in operating the system, as well as understanding the biodegradation process, are critical for optimal performance. [9]. Concerning CH_4, CO_2, and N_2O emissions, the literature is lacking information about the efficiency of biofilter for treatment of these emissions [25].

4.7. Addition of Biochar

Biochar as an additive has been used in different research to mitigate the emissions resulting from composting processes [94,100,120,132,133]. This additive has been used as a sole material or mixed with other additives [134]. Noteworthy, under almost all studied conditions, promising results were obtained, despite the lack of clarity regarding its mechanism on promoting nitrogen assimilation and nitrification [5,90,102,135]. The change in nitrogen functional groups on the biochar surface was evidence for adsorption and microbial transformation of NH_3/NH_4^+ [136]. As indicated in several works, the biochar promoted microbial activity during the composting process, as it increases the nitrogen source and decreases toxicity of free NH_3 on the microbial activity [137]; hence, a high respiration rate as well as a fast decomposition of organic matter were recorded [135,137,138]. Additionally, this was associated with an increase in the temperature and NO_3 concentration along with a decrease in the pH and NH_4^+ concentrations [131,133]. Emissions of NH_3 and nitrogen losses were reduced by 64% and 52%, respectively, when biochar was mixed with poultry litters [101]. Similar results were observed when cornstalk biochar was used where cumulative NH_3 emissions were reduced by 24.8% [139]. The presence of the biochar boosted the activity of nitrifiers due to its high sorption capacity for gases and the high cation exchange capacity. According to Zhou et al. [140], adding modified biochar could significantly reduce NH_3 emissions by increasing the number of ammonia-oxidizing bacteria (AOB), inhibiting urease activity, and decreasing the abundance of nitrogen functional genes such as narG and nirS, facilitating the conversion of $NH^+{}_4$-N into $NO^-{}_3$-N and decreasing nitrogen loss. These conditions were responsible for promoting N_2O reduction up to 59.8% [141]. The effects of bamboo charcoal (BC) and bamboo vinegar (BV) on lowering NH_3 and N_2O emissions during aerobic composting (Wheat straw and pig manure) revealed that both BC and BV enhanced nitrogen conversion and compost quality, with the combination BC + BV treatment achieving the greatest results. The BC, BV, and BC + BV treatments decreased NH_3 emissions by 14.35%, 17.90%, and 29.83%, respectively, and the N_2O emissions by 44.83%, 55.96%, and 74.53%. BC and BV reduced the NH_3 and N_2O emissions during composting [142]. Similarly, Biochar (BC) and bean dregs' (BD) effects on nitrifiers and denitrifiers, as well as contributions to NH_3 and N_2O emissions, were investigated by Yang et al. [143]. When comparing the BD + BC treatment to the BD treatment, the highest value of NH_3 and N_2O emission was reduced by 32.92% and 46.61%, respectively. The number and structure of nitrogen functional genes were shown to be closely related to the synthesis of NH_3 and N_2O in the study. In this case, it was discovered that BD + BC enhanced the abundance of the AOB amoA gene, resulting in a reduction in NH_3 emission. The presence of nirS was more closely linked to the presence of N_2O. When compared to the BD treatment, the abundance of nirS in the BD + BC treatment was reduced by 18.93%, lowering N_2O emissions after composting. Furthermore, the nosZ-type gene was the most functional denitrification bacterial community to influence N_2O emissions. [143]. Noteworthy, when biochar is to be used, it is important to keep in mind that its characteristics have a major role on its efficiency.

5. Conclusions

Composting is a favorable technology to treat organic waste, but gaseous emissions are an issue of major concern for its development. Among them, GHG emissions are an important problem as they are responsible for the global warming effect. Carbon dioxide is not often considered, as it is considered biogenic. However, methane and nitrous oxide, related to anaerobic and anoxic conditions, must be accounted for when analyzing any composting process. Another important point is the release in the form of gaseous emissions of a vast family of compounds such as VOCs. These gases can be harmful, possess negative impacts, and, especially, are responsible for unpleasant odors. The origin of these gases is double (they can come from the substrate or be biologically or even chemically formed during the process) and they need the development of mitigation strategies based on relatively consolidated technologies (such as biofiltration) or new approaches, such as the use of materials as biochar. However, there is still a lack of reliable and full-scale data from composting emissions to have consistent mitigation strategies.

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