International Journal of
Environmental Research and Public Health

MDPI

Review

Measures for Controlling Gaseous Emissions during Composting: A Review

Minghan Li [1,2], Shuyan Li [1,*], Shigeng Chen [2], Qingyu Meng [2], Yu Wang [2], Wujie Yang [3], Lianhui Shi [1,*], Fangjun Ding [2,*], Jun Zhu [2], Ronghui Ma [3] and Xinsong Guo [2]

[1] College of Resource and Environment, National Engineering Laboratory for Efficient Utilization of Soil and Fertilizer Resources, Shandong Agricultural University, Tai'an 271018, China
[2] SDAU Fertilizer Science & Technology Co., Ltd., Tai'an 271608, China
[3] Shandong Agricultural Technology Extension Center, Jinan 250014, China
* Correspondence: lishuyan16@163.com (S.L.); shilh@sdau.edu.cn (L.S.); dfj401@163.com (F.D.)

Abstract: Composting is a promising technology for treating organic solid waste. However, greenhouse gases (methane and nitrous oxide) and odor emissions (ammonia, hydrogen sulfide, etc.) during composting are practically unavoidable, leading to severe environmental problems and poor final compost products. The optimization of composting conditions and the application of additives have been considered to mitigate these problems, but a comprehensive analysis of the influence of these methods on gaseous emissions during composting is lacking. Thus, this review summarizes the influence of composting conditions and different additives on gaseous emissions, and the cost of each measure is approximately evaluated. Aerobic conditions can be achieved by appropriate process conditions, so the contents of CH_4 and N_2O can subsequently be effectively reduced. Physical additives are effective regulators to control anaerobic gaseous emissions, having a large specific surface area and great adsorption performance. Chemical additives significantly reduce gaseous emissions, but their side effects on compost application must be eliminated. The auxiliary effect of microbial agents is not absolute, but is closely related to the dosage and environmental conditions of compost. Compound additives can reduce gaseous emissions more efficiently than single additives. However, further study is required to assess the economic viability of additives to promote their large-scale utilization during composting.

Keywords: composting; greenhouse gaseous; odors; additives

check for updates

Citation: Li, M.; Li, S.; Chen, S.; Meng, Q.; Wang, Y.; Yang, W.; Shi, L.; Ding, F.; Zhu, J.; Ma, R.; et al. Measures for Controlling Gaseous Emissions during Composting: A Review. *Int. J. Environ. Res. Public Health* **2023**, *20*, 3587. https://doi.org/10.3390/ijerph20043587

Academic Editor: Hyun-Sang Shin

Received: 7 January 2023
Revised: 11 February 2023
Accepted: 16 February 2023
Published: 17 February 2023

Copyright: © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

Urbanization, driven by global scientific and technological progress and economic development, has led to increased utilization of produced solid waste [1,2]. Classified according to its source, solid waste includes household waste produced by human activities, poultry manure produced by livestock breeding, dewatered sludge produced by sewage treatment, and other types of waste produced by agriculture, industry, and garden forestry. Among these, the daily disposal volume of municipal solid waste (MSW) is huge and constantly growing. According to the National Bureau of Statistics of the People's Republic of China [3], the annual volume of MSW in 2020 sharply increased to 235.12 million tons, which is an increase of 1.03% compared with the same period in 2019, and the harmless disposal rate reached 99% [3]. There is also annual production of 3.8 billion tons of poultry manure, which introduces a big problem in the harmless disposal of solid waste [4]. For clean production and sustainable development, the composting method has been extensively studied to improve safety and waste utilization efficiency. Composting studies indicate incomparable advantages over traditional solid waste disposal, both in laboratory experiments and real production, and it is especially suitable for the utilization of the perishable components of livestock, sewage sludge, and household waste [5–7].

However, although composting fulfills the fertilizer requirements for soil and crops, it also leads to many problems, especially regarding gaseous emissions. Untreated solid waste produces a large amount of GHGs, but even with composting treatment, a small amount of GHGs are emitted during composting or are released after application, posing a potential threat to the climate and atmosphere [8,9]. As an organic fertilizer, compost needs to provide sufficient nutrients to crops. However, gaseous emissions during composting cause the loss of carbon, nitrogen, and sulfur nutrients [10]. According to previous studies, ammonia (NH_3) and nitrous oxide (N_2O) contribute 79–94% and 9.2–9.9% to total nitrogen loss, respectively [11]. Meanwhile, methane (CH_4) emissions during composting lead to approximately 1.85% total carbon loss [12]. The major contributor to global warming potential (GWP) is N_2O emissions (81.44–95.02%), followed by CH_4 (0.82–7.14%) and NH_3 (3.80–11.42%) emissions, indicating that N_2O emissions are several times more critical for global warming than those of other gases [13]. Nowadays, GHG emissions have led to severe global warming, abnormal crustal movement, and impacts on biological activities, which are not neglectable [14,15]. To further improve the feasibility of safe composting and expand the production scale, it is necessary to take corresponding measures to mitigate GHG emissions. Additionally, the process of composting is accompanied by an unpleasant odor, which mainly originates from the volatile compounds containing sulfur and nitrogen [16,17]. Therefore, the construction of composting equipment and facilities should be improved to regulate the compost production conditions more strictly.

Previous studies confirmed that an improved aerobic fermentation process and composting additives can significantly reduce GHGs and odorous gaseous emissions. The inadequate physical properties of compost are among the primary factors leading to gaseous emissions. Adding organic and mineral materials can significantly enhance the pore structure of compost by increasing its specific surface area [18]. With a reduction in the anaerobic area, the loss of nutrients caused by the evaporation of CH_4 and other gaseous products is significantly lower [19,20]. Li et al. [21] used biochar and electric field-assisted composting to reduce GHGs by 31.6%, implying that combining measures and additives is very attractive for controlling gaseous emissions from composting. Adjusting the chemical environment and inoculating microbial agents can also promote compost maturation and reduce the emissions of related gases [22,23]. Yang et al. [24] demonstrated that the combination of dicyandiamide and phosphogypsum significantly reduced GHGs by 37.46%, demonstrating the great potential of using combined treatments in reducing gaseous emissions from composting. Furthermore, research on the influence of other novel, low-cost, and highly efficient additives and compound additives has certainly become one of the important future research directions. Therefore, using additives or other measures can enable the effective control of gaseous emissions during composting, representing a research hotspot toward improved environmental benefits from composting. Meanwhile, the development of composting must conform to stricter legal regulations, which requires gaseous emissions from composting to strictly meet the requirements of cleaner production to minimize the impact on global warming. Under this situation, it is urgent to review the efficiency of measures implemented to control gaseous emissions from composting as a scientific topic.

This review article focuses on the control strategies of GHGs and odorous gaseous emissions in the recent research literature. Based on the treatment process characteristics and the principle of minimizing gaseous emissions, the additives in this paper are divided according to the process conditions into physical, chemical, microbial, and compound additives. The advantages and disadvantages of additives are also reviewed. This review aims to provide a comprehensive analysis of gaseous emission control strategies during composting, summarize the current research results, and propose future research directions.

2. The Theory of Gaseous Emission in Composting

In the composting process, organic matter in solid waste is mineralized by microorganisms, and organic nitrogen is transformed into ammonium nitrogen, which mainly escapes in the form of NH_3. Organic carbon is decomposed to provide energy for microbial activities and mainly escapes in the form of carbon dioxide (CO_2). Sulfur-containing organics decompose and disperse in the form of dimethyl sulfide (Me_2S), dimethyl disulfide (Me_2SS), etc. [25]. In addition to the above gaseous emissions, there are small amounts of N_2O and CH_4 emitted. Excessive gaseous emissions during composting may affect the efficiency of the compost as a fertilizer. For the atmospheric environment, the aerobic composting process is dominated by vigorous microbial activities and continuous GHG output, causing severe air pollution.

In this review, the gaseous emissions of composting are classified into three types: nitrogenous, carbonaceous, and sulfurous gaseous emissions. The theory of each element is discussed as follows:

1. Nitrogen transformation and gaseous emissions
   (1) The metabolic pathway of NH_3: First, nitrogenous organic compounds from solid waste are mineralized into NH_4^+, and a small amount of NH_3 is directly produced by microorganisms [26]. Caused by the rising temperature of the composting pile, highly unstable NH_4^+ continues to transform into NH_3 (pathway ①) [27];
   (2) The metabolic pathway of N_2O: The generation of N_2O occurs via three pathways, as shown in Figure 1. First, under ammonification driven by ammonia-oxidizing bacteria, hydroxylamine is generated from NH_4^+ by ammonia monooxygenase as an intermediate product. After that, hydroxylamine is transformed into NO_2^- by hydroxylamine oxidoreductase [28,29]. The remaining NH_4^+ directly generates N_2O by incomplete nitrification (pathway ②) [30]. Second, with NO_2^- oxidized to NO_3^- by nitrite oxidoreductase, incomplete denitrification transforms a part of the NO_3^- into N_2O. A small amount of NO_3^- is reduced to NO_2^- by the nitrate reductase (pathway ③) [31]. Third, denitrifying bacteria transform the rest of the NO_2^- into NO by nitrite reductase and further convert it to N_2O by nitric oxide reductase (pathway ④) [32];
   (3) With the above N_2O emitted into the air, the rest is completely denitrified to N_2 by nitrous oxide reductase, so the nitrogen metabolic pathway during composting is over (pathway ⑤) [33].
2. Carbon transformation and gaseous emissions The major carbon loss in compost originates from CO_2 produced by aerobic decomposition and respiration by microbes, but this carbon loss is necessary for microbial activity (pathway ⑥) [34]. Compared with CO_2, CH_4 represents a more severe, but controllable, threat to global warming [8,35]. As mineralization proceeds, the composting pile continuously shrinks and compacts, creating more anaerobic areas [36]. In this situation, the activity and propagation of methanogens are improved, so more CH_4 is produced from the composting pile (pathway ⑦) [37].
3. Sulfur transformation and gaseous emissions Volatile sulfide compounds (VSCs) also result from the formation of anaerobic areas in compost. Therefore, odor generation can be used as qualitative proof of poor physical properties [38]. The degradation of sulfur-containing amino acids under anaerobic conditions and the methylation of hydrogen sulfide (H_2S) or methyl mercaptan (MeSH) lead to the emission of odorous gases (pathway ⑧), severely affecting human health and the compost's fertility [39]. VSCs include Me_2S, Me_2SS, H_2S, MeSH, ethyl mercaptan (EtSH), diethyl sulfide (Et_2S), carbonyl sulfide (COS), carbon disulfide (CS_2), etc. [40], and the emissions of Me_2S and Me_2SS may especially lead to strong sulfur loss with an unpleasant smell [41,42].

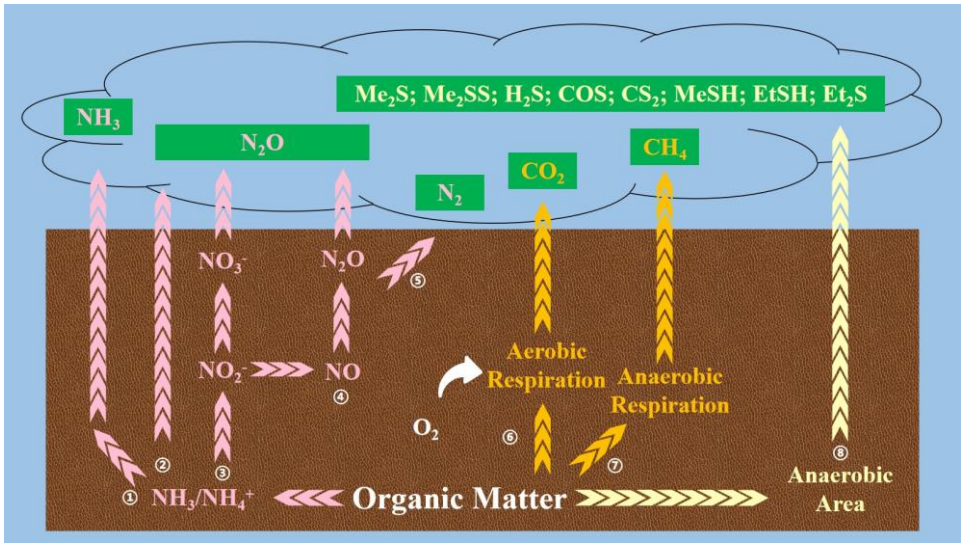


Figure 1. Conversion process of gaseous emissions during composting.

3. Control Strategy for Gaseous Emissions

3.1. Composting Process Conditions

3.1.1. Efficiency Analysis

As shown in Table 1, improvements in the process conditions were made to provide accurate and effective composting control; GHGs and odorous gaseous emissions can also be reduced.

The aeration mode has a decisive influence on the composting process. As a crucial process parameter, a higher aeration rate can greatly reduce the anaerobic area, but it faces stronger NH_3 emissions and temperature loss [43]. Conversely, lower aeration rates can cause anaerobic, incomplete nitrification, and incomplete denitrification reactions, leading to the production of GHGs and odors [44]. Therefore, as one of the most important composting parameters, it is necessary to have an appropriate aeration rate and method. An intermittent aeration rate of 0.3–0.5 L/min/kg DM has been reported to be a suitable aeration method [45]. Xu et al. [46] adopted an aeration rate of 0.48 L/min/kg DM for kitchen and garden waste co-composting. Compared with a treatment at a lower aeration rate, the experimental results showed that the aeration rate of 0.48 L/min/kg DM significantly reduced the emissions of CH_4, N_2O, and H_2S. It was demonstrated that a higher aeration rate inhibited the expression of functional genes related to GHGs and sulfurous odors emission. Thus, excessive GHGs and sulfurous odor emissions can be reduced [47]. Negative pressure aeration is a novel technology based on traditional passive aeration, where the oxygen supply depends on the temperature gap [48]. Wang et al. [49] observed that a negative pressure aeration rate of 0.75 L/min/kg DM reduced NH_3 volatilization by 55%, accompanied by small increases in CH_4 and N_2O emissions. Compared with passive aeration, negative pressure changed the airflow direction and captured more ammonium nitrogen in the composting pile [50]. Although CH_4 and N_2O emissions were slightly increased, negative pressure was more beneficial to reduce the total GHG emissions at the same aeration rate [49]. Compared with continuous aeration, intermittent aeration is more helpful for maintaining a constant temperature and reducing gaseous emissions [51]. According to the research by Ma et al. [52], an aeration interval of 30 min on–30 min off decreased CH_4 and N_2O emissions by 9.68% and 47.10%, respectively. Compared with treatments with an interval time of less than 30 min/h, 30–30 intermittent aeration was more detrimental to pore retention. Under such airflow conditions, the anaerobic area was greatly reduced, and CH_4 and N_2O emissions were also effectively inhibited [53]. In conclusion, the formulation of a specific experimental aeration method still needs to be adjusted according to the material and pre-experimental results, based on the existing research.

Membrane composting is a relatively mature technology that can effectively reduce air pollution caused by composting [54]. Xiong et al. [55] observed that applying the functional membrane-covering technique (FMCT) can reduce N_2O emission by 16.44–41.15% because the FMCT fixes the inner pressure to the micro-positive pressure, maintaining an appropriate temperature while ensuring aerobic conditions and oxygen utilization efficiency. Nitrifying bacteria are extremely sensitive to high temperatures, so denitrification and N_2O production may be simultaneously significantly inhibited [56]. Even so, the FCMT increased NH_3 emissions by 13.78–73.37%. During the thermophilic period, the FMCT treatment exhibited a more intense degree of mineralization, leading to the accumulation of NH_4^+/NH_3. The experimental data showed that the temperature and pH of the FMCT treatment were higher, causing stronger evaporation and NH_3 emissions [57]. Sun et al. [58] and Fang et al. [59] performed similar research on semi-permeable membrane-covered hyperthermophilic composting (smHTC). The results showed that smHTC significantly reduced the CH_4 and N_2O emissions, especially in the thermophilic phase. Compared with the common method, smHTC suppressed the expression of *mcrA* by 1.6 times, which is the key functional gene related to CH_4 emissions and oxidation [58]. In another dairy manure-composting experiment, smHTC reduced the CH_4 and N_2O emissions by 99.89% and 60.48% during the aeration interval, respectively [59]. The positive micro-pressure and aerobic environment facilitated oxygen permeation and utilization by microorganisms, which was created by smHTC. The high-temperature environment in the membrane intensified water volatilization, condensing a water layer close to the membrane, which quickly blocked part of the gaseous volatilization. However, with a decrease in humidity, the interception effect of the water layer decreased. The dissolved NH_4^+ was converted into NH_3 and re-released, which explained the sudden increase in the NH_3 emissions later. Compared with the inside gaseous emissions, the outside emissions were easier to control. This indicates that the correction of NH_3 emissions was limited and needed to be combined with other additives.

In addition, electric field-assisted composting is a recent research hotspot. By applying a 2 V direct-current electric field to the composting pile, the reproduction of electroactive bacteria was promoted, and oxygen utilization was improved [60]. The driving effect of the electric field on the ions accelerated the compost's maturation, promoted microbial activity, and produced more heat. An environment dominated by an electric field and high temperature can inhibit the activity of denitrifying bacteria, promote oxygen uptake, and reduce the production of N_2O and CH_4 [21,60]. Combining electric field composting technology with additives and further exploring the influence of the direct-current electric field on nitrogen fixation, ammonification, nitrification, and denitrification are future research directions.

Table 1. The effects of process conditions on GHGs and odors during composting.

Feedstock	Measure	Impact on Gaseous Emissions (Relative to Control)				Note	Reference
		CH_4	N_2O	NH_3	VSCs		
Cow manure, wheat straw	Functional membrane-covered composting		−16%	+14%		Lasted for 36 days; promoted temperature rise	[55]
Chicken manure, mushroom residue, crop stalk, bran	Semi-permeable membrane-covered composting	−79%	−45%			Lasted for 24 days; reduced emissions based on thermophilic phase; promoted temperature rise; initial C/N: 24	[58]
Cow manure	Semi-permeable membrane-covered composting	−100%	−61%			Lasted for 30 days; promoted temperature rise; initial C/N: 34	[59]

Table 1. *Cont.*

Feedstock	Measure	Impact on Gaseous Emissions (Relative to Control)				Note	Reference
		CH_4	N_2O	NH_3	VSCs		
Kitchen waste, garden waste	Aeration intensity (0.48 L/kg/min) [2]	↓	↓	↑	↓	Lasted for 35 days; suppressed temperature rise	[46]
Cow manure, corn stalk	Negative pressure aeration (0.75 L/min/kg) [2]	↑	↑	↓		Lasted for 35 days; decreased electrical conductivity	[49]
Chicken manure, mushroom residue	Intermittent aeration (10 min on–30 min off)	↑	↑			Lasted for 36 days; suppressed temperature rise; reduced emissions based on outside of membrane; initial C/N: 34	[52]
Chicken manure, rice husk	Electric field-assisted composting (2 V DC)	↓	↓			Lasted for 30 days; promoted temperature rise; increased electrical conductivity	[21]
Chicken manure, mature compost, rice husk, dewatered sewage sludge	Electric field-assisted composting (2 V DC)	↓	−73%			Lasted for 30 days; promoted temperature rise	[60]

Note: [2] dry weight basis; ↑: increase (no detailed data); ↓: decrease (no detailed data); VSCs: volatile sulfide compounds.

3.1.2. Cost Assessment and Economic Benefits

Although advanced process conditions can effectively alleviate gaseous emissions during composting, the related high costs cannot be ignored. Therefore, the above process conditions are more presented to provide new ideas for the construction of basic composting facilities. After stable and efficient process conditions are determined, it is necessary to continue to reduce the equipment cost in large-scale production and evaluate its economic benefits.

3.2. Physical Additives

According to previous research studies, physical additives are mainly used for preserving the pore structure of a composting pile and can be subdivided into organic physical additives and mineral physical additives [61].

3.2.1. Organic Physical Additives

Due to its large specific surface area and low cost, biochar has been widely studied as a physical additive in composting [29,62]. As shown in Table 2, biochar can be produced from bamboo, corn stalk, wheat straw, willow chips, and even poultry manure [19,20,63]. As reported by Zhang et al. [64], bamboo biochar exerted a considerable effect on the reduction in gaseous emissions during composting, decreasing the emissions of GHGs and NH_3 by 93.61% and 51.42%, respectively. Adding biochar can greatly inhibit the formation of an anaerobic area in a composting pile. As the efficiency of oxygen utilization improves, methanogenesis and incomplete denitrification are inhibited, thus reducing methane and nitrous oxide emissions [65]. Biochar can also regulate the activities of urease, catalase, and other key enzymes in compost, accelerate decomposition, and better fix the volatile ammonium nitrogen in the pores [66]. Additionally, biochar has the same correction effect for sulfur-containing odor emissions. Liu et al. [67] proved that biochar significantly mitigated H_2S, Me_2S, and Me_2SS emissions. By adding biochar to avoid the formation of an anaerobic area in a composting pile to the largest possible extent, odors produced by sulfur-containing amino acids are greatly reduced [68]. The use of apple pomace, wood vinegar, and other organic additives discarded as waste has also been reported [22,67,69,70]. In particular, additives such as apple pomace and furfural residue can neutralize an alkaline environment, inhibiting the shift in the chemical equilibrium toward the formation of

volatile NH_3 [71]. These additives have multiple advantages because their use enables, at the same time, a feasible way to recycle waste and a great gaseous emission reduction effect.

3.2.2. Mineral Physical Additives

As shown in Table 2, mineral additives, such as clay, medicinal stone, zeolite, diatomite, and bentonite, have mainly been used in previous studies [18,69]. Like organic additives, mineral additives provide a sufficient specific surface area and a suitable micropore structure, which are beneficial for oxygen diffusion and microbial activity. In addition, functional groups in minerals can reduce the volatilization of related gases through their complexation and ion exchange [72,73]. By employing diatomite, Ren et al. [74] reduced NH_3, N_2O, and CH_4 emissions by 23.70%, 84.16%, and 30.41%, respectively. The absorption capacity of microporous crystals could restrain the formation of an anaerobic area, and ions, such as NH_4^+, could be adsorbed simultaneously [75]. In particular, spectral data indicated that mineral additives can accelerate the humification of compost [76]. The formation of aromatic functional groups can reduce nutrient loss through a complexation reaction, thus controlling GHG emissions. Wang et al. [18] reported that adding zeolite, medical stone, and Ca-bentonite increased NH_3 emissions while reducing N_2O and CH_4 emissions. Furthermore, although the oxygen supply efficiency was improved, the airflow carried more NH_3 into the air [77]. Hence, the additive amount needs to be moderate to minimize GHG emissions.

Table 2. The effects of physical additives on GHGs and odors during composting.

Feedstock	Additive	Impact on Gaseous Emissions (Relative to Control)				Note	Reference
		CH_4	N_2O	NH_3	VSCs		
Pig manure, wheat straw	10% bamboo biochar [1]		↓	↓		Lasted for 27 days; suppressed temperature rise	[29]
Sewage sludge, straw	5% bamboo biochar [1]	−16%	−5%			Lasted for 29 days; promoted temperature rise	[19]
Chicken manure, tobacco waste	10% bamboo biochar [2]	↓	−94%	−51%		Lasted for 35 days; promoted temperature rise; decreased electrical conductivity	[64]
Pig manure, corn stalk	10% spent mushroom substrate [2]		−37%	−7%	↓	Lasted for 49 days; promoted temperature rise; H_2S: –13%, –33%; Me_2S and Me_2SS: both more than –50%	[67]
	10% straw biochar [2]		↑	−24%	↓		
Pig manure, sawdust	10% clay [2]	−46%	−87%			Lasted for 42 days; promoted temperature rise; initial C/N: 35	[76]
Chicken manure, caraganna microphylla straw	12.5% gasification filter cake [2]			↓		Lasted for 50 days; promoted temperature rise; initial C/N: 43	[78]
Pig manure, wheat straw	10% fine coal gasification slag [2]	−72%	−77%	−28%		Lasted for 42 days; promoted temperature rise; initial C/N: 29	[70]
Pig manure, sawdust	5% medical stone [2]	↓	↓	↓		Lasted for 36 days; promoted temperature rise	[69]
	5% zeolite [2]	↓	↓				
	2% wood vinegar [2]	↓	↓	↓			
Pig manure, sawdust	10% diatomite [2]	−30%	−84%	−24%		Lasted for 42 days; promoted temperature rise	[74]
Dewatered sewage sludge, wheat straw	5% apple pomace [2]	−22%	−33%	↓		Lasted for 45 days; similar temperature variation	[22]
Poultry manure, sugar cane straw, mature compost	10% green waste biochar [2]	↓	↓			Lasted for 60 days; similar temperature variation; both reduced CH_4 and N_2O significantly	[63]
	10% poultry litter biochar [2]	↓	↓				

Table 2. *Cont.*

Feedstock	Additive	Impact on Gaseous Emissions (Relative to Control)				Note	Reference
		CH_4	N_2O	NH_3	VSCs		
Sewage sludge, wheat straw	10% zeolite [2]	−88%	−84%	↑		Lasted for 56 days; promoted temperature rise; Ca-bentonite led to higher NH_3 emissions	[18]
	10% Ca-bentonite [2]	−86%	−81%	↑			
	10% medical stone [2]	−87%	−80%	↑			
Poultry manure, wheat straw	10% willow woodchips biochar [1]			↓		Lasted for 42 days; promoted temperature rise; NH_3 emissions reduced by over 50%	[62]
Cattle manure, rice straw	3% straw biochar (*w/v*)		−54%			Lasted for 65 days; promoted temperature rise	[79]

Note: [1] wet weight basis; [2] dry weight basis; ↑: increase (no detailed data); ↓: decrease (no detailed data); VSCs: volatile sulfide compounds.

3.2.3. Cost Assessment and Economic Benefits

Most of the physical additives reviewed above are recycled waste, highlighting their favorable, low-cost advantages. However, plausible future large-scale production needs a continuous and stable supply source. These problems are major challenges for physical additives and cost factors that must be pre-evaluated for large-scale operations.

3.3. Chemical Additives

As shown in Table 3, chemical additives can effectively reduce NH_3 emissions during composting. On one hand, chemical additives, such as acids, mitigate NH_3 emissions by adjusting the pH, which can neutralize the alkaline environment and inhibit the transformation of NH_4+ to NH_3 [80]. On the other hand, crystallization and precipitation methods can strengthen nitrogen retention to reduce NH_3 emissions [81]. By adding chemical additives, extra nutrients are provided, and the pore structure inside precipitates is conducive to material exchange and microbial attachment [82,83]. The statistics in Table 3 show that other GHGs and the odor reduction performance of chemical additives are not as significant as those for NH_3. Therefore, the action mechanism for other GHGs and odors should be analyzed under specific conditions.

3.3.1. pH Adjustment

As the main source of nitrogen loss in composting, NH_3 emissions are concentrated in the thermophilic period [76,84]. With the violent mineralization of organic matter, the content of ammonium nitrogen increases and is transformed into ammonia (as shown in Figure 1). Alkaline environments, high temperatures, and low moisture contents are unfavorable for the fixation of NH_3, while adjusting the pH via acidic substances is an effective strategy [20,85]. Nie et al. [2] reported that adding 1% lactic acid (on a dry weight basis) reduced nitrogen loss from NH_3 emissions by 14.65% and increased the relative abundance of lactic acid bacteria. Cao et al. [71] used sulfuric acid to adjust the compost's pH to 6. After acidification, the conversion of ammonium to NH_3 was inhibited, and NH_3 volatilization from the compost was significantly mitigated. Referring to the results of Pan et al. (2018), adding 1% citric acid or 3% phosphoric acid (on a dry weight basis for both) to compost could also alleviate the emissions of NH_3. Salts, such as $MgCl_2$ and $FeSO_4$, were found to reduce NH_3 emissions by 58.3% and 82.9%, respectively [85]. Therefore, it has been experimentally confirmed that organic/mineral acids and acidic salts can effectively reduce NH_3 emissions.

However, the influence of acid additives on GHGs is variable. As a strong mineral acid, the addition of sulfuric acid reduces the pH and inoculates the composting pile with SO_4^{2-}, alleviating CH_4 emissions [71]. Like the addition of sulfur powder, the sulfide concentration in the compost remains high after participating in microbial metabolism.

Pan et al. (2018) reported that 70.57% of CH_4 emissions were mitigated after sulfur addition. Thus, it can be confirmed that a high sulfate concentration can reduce CH_4 emissions by changing the redox potential and inhibiting the growth of methanogens [86–88]. A high concentration of ammonium nitrogen also has an inhibitory effect on methanogens, so more ammonia can be fixed under the action of acidic additives, and CH_4 production can be further reduced [89]. Although low pH values may stimulate N_2O emissions, Pan et al. [22] found that citric and phosphoric acids differently affected N_2O emissions. The related statistical data showed that citric acid reduced N_2O emissions by 51.26%, but phosphoric acid increased N_2O emissions by 31.89%. The emissions of CH_4 and N_2O are mainly generated by an anaerobic area and incomplete nitrification/denitrification [90]. Ren et al. [13] reported that a high dose of sodium selenite reduced N_2O emissions by 30.45–69.54%. In contrast, Wang et al. [91] observed that adding sodium selenite increased N_2O emissions by 29.7%, while sodium selenate reduced them by 69.3%. Adding sodium selenite and sodium selenate increased CH_4 emissions by 18.4% and 3.5%, respectively. According to the study by Li et al. [85], the addition of salts also had no significant correction effect on GHGs. Due to the differences in raw materials and composting conditions between various studies, different microbial communities exhibited different tolerance levels to acid addition and the formation mechanism of anaerobic areas [92]. Thus, it can be concluded that organic/mineral acids and salts have no significant correction effect on N_2O and CH_4 emissions.

The addition of salts can also reduce gaseous emissions through redox reactions. Previous studies proved that strong oxidants, such as hypochlorite and permanganate, can reduce NH_3 emissions by advancing nitrification [27,85]. Under the action of a strong oxidant, nitrogen is fixed as nitrate nitrogen, which is more stable [93]. Moreover, some studies also indicated that Fe_2O_3 has satisfactory performance in reducing the volatilization of sulfur-containing odors [17]. With Fe_2O_3 correction, the emissions of volatile sulfur compounds, such as COS, CS_2, MeSH, and Me_2SS, were reduced by 46.7–80.8%, but this still needs to be verified in further research.

3.3.2. Struvite Crystallization

Struvite crystallization has become a novel method to increase nitrogen stabilization, and it is used in agriculture as a slow-release fertilizer [40]. The main component of struvite crystallization is magnesium ammonium phosphate hexahydrate, which is mainly produced by the reaction of NH_4^+, Mg^{2+}, and PO_4^{3-} in compost [94,95]. HPO_4^{2-} and $H_2PO_4^-$ species derived from the hydrolysis of PO_4^{3-} continue to react with the above substrates to generate H^+, the environment of a composting pile is buffered, and the ammonium nitrogen can be fixed [73]. As shown in Table 3, Jiang et al. [81] used several different "magnesium salt + phosphate additive" combinations and verified that struvite crystallization effectively improved nitrogen fixation and decreased related gaseous emissions. Furthermore, Zhang et al. [83] found that adding calcium superphosphate reduced NH_3, CH_4, and H_2S by 37.9%, 35.5%, and 65.5%, respectively; moreover, the emissions of N_2O were also stronger, demonstrating the same result as Pan et al. [22]. However, Yuan et al. [82] and Zhang et al. [64] showed that N_2O emissions were reduced. Like the addition of magnesium salt and phosphate additives, calcium superphosphate participates in struvite crystallization via microbial metabolism. As the struvite crystallization process proceeds, free NH_4^+ in a composting pile exists more in a stable crystalline form and the precursor of NH_3 generation is controlled [96]. Previous studies confirmed that a high concentration of NH_4^+ can inhibit the reproduction of methanogens and methane metabolism [89]. Additionally, crystallization is helpful to maintain oxygen supply pores. According to the same mechanism, phosphogypsum can effectively reduce NH_3 and CH_4 emissions during composting, and the SO_4^{2-} component of phosphogypsum provides an additional effect for inhibiting the activity of methanogens [71,82,97]. The modification of the anaerobic area by struvite crystallization is also beneficial for controlling the emissions of sulfur odors [83]. Therefore, struvite crystallization can significantly mitigate NH_3 and

CH_4 emissions and enhance nitrogen fixation and oxygen supply efficiency, while the effect of struvite crystallization on N_2O emission is not significant [64,81,83].

3.3.3. Dicyandiamide

As a nitrification inhibitor, it was confirmed that dicyandiamide (DCD) could inhibit the metabolism of ammonia-oxidizing bacteria and control the emissions of N_2O [98,99]. The addition of DCD could reduce the emissions of NH_3, N_2O, and CH_4 by 9.37%, 31.79%, and 9.6%, respectively [24]. DCD was found to prevent the conversion of ammonium nitrogen to nitrite nitrogen while maintaining a high concentration of ammonium nitrogen in the system, so the emissions of NH_3 and CH_4 were controlled as well [71,88]. DCD was found to yield compost with a good maturity index, which could further verify the feasibility of applying DCD [100]. As more dicyandiamide is used in combination with other additives, it will be analyzed and discussed in the section on compound additives.

3.3.4. Cost Assessment and Economic Benefits

The costs of chemical additives are relatively low and the supply channel is more stable than that of physical additives. Indeed, the impacts of chemical additive residues on crop and compost efficiency need to be further verified and included in the economic benefit assessment.

Table 3. The effects of chemical additives on GHGs and odors during composting.

Feedstock	Additive	Impact on Gaseous Emissions (Relative to Control)				Note	Reference
		CH_4	N_2O	NH_3	VSCs		
Pig manure, corn stalk	0.2% dicyandiamide [2]	−20%	−32%	−9%		Lasted for 40 days; similar temperature variation initial C/N: 20	[24]
Pig manure, corn stalk	1.5% ferric oxide [1]				↓	Lasted for 14 days; promoted temperature rise; reduced volatile sulfur compounds by 46.7–80.8%	[17]
Goat manure, wheat straw	8 mg/kg sodium selenite [1]		−70%	↓		Lasted for 80 days; similar temperature variation	[13]
Goat manure, wheat straw	2 mg/kg sodium selenite [2]	+18%	−30%	−27%		Lasted for 80 days; similar temperature variation	[91]
	2 mg/kg sodium selenate [2]	+4%	−62%	−53%			
Poultry manure, sawdust	H_2SO_4 (pH = 6)	−20%	−18%	−21%		Lasted for 42 days; later, but higher, temperature peak	[71]
Chicken manure, tobacco waste	5% calcium superphosphate [2]	↓	−79%	−37%		Lasted for 35 days; promoted temperature rise	[64]
Dewatered sewage sludge, sawdust	5% magnesium chloride [2]	−23%		−59%		Lasted for 23 days; promoted temperature rise	[85]
	5% ferrous sulfate [2]	−25%	+ 16%	−83%			
Rice husk chicken manure, slaughter sludge	1% lactic acid [2]			−33%		Lasted for 28 days; promoted temperature rise	[2]
Dewatered sewage sludge, wheat straw	1% citric acid [2]	−33%	−51%	↓		Lasted for 45 days; similar temperature variation	[22]
	1% elemental sulfur [2]	−71%	+48%	↓			
	3% phosphoric acid [2]	−53%	+32%	↓			
	3% magnesium hydrogen phosphate [2]		−70%	↓			
	5% calcium superphosphate [2]	−43%	+15%	↓			

Table 3. *Cont.*

Feedstock	Additive	Impact on Gaseous Emissions (Relative to Control)				Note	Reference
		CH_4	N_2O	NH_3	VSCs		
Sewage sludge, corn stalk	10% phosphogypsum [2]	−81%	↑	−17%		Lasted for 35 days; later temperature peak	[82]
	10% superphosphate [2]	−75%	−55%	−36%			
Chicken manure, mushroom residue	0.25% sulfur powder (net weight)			↓		last for 21 days	[101]
Pig manure, woody peat	10% calcium superphosphate [2]	−36%	↑	−38%	↓	Lasted for 28 days; suppressed temperature rise; reduced H_2S by 66%	[83]
Pig manure, corn stalk	15% H_3PO_4 [3], 15% Mg $(OH)_2$ [3]			↓		Lasted for 35 days; similar temperature variation	[81]
	15% KH_2PO_4 [3], 15% $MgSO_4$ [3]	↓		↓			
	15% $Ca(H_2PO_4)_2$ [3], 15% $MgSO_4$ [3]	↓		↓			
	15% H_3PO_4 [3], 15% $MgSO_4$ [3]	↓		↓			

Note: [1] wet weight basis; [2] dry weight basis; [3] molar ratio of initial nitrogen; ↑: increase (no detailed data); ↓: decrease (no detailed data); VSCs: volatile sulfide compounds.

3.4. Microbial Additives

3.4.1. Efficiency Analysis

Microbial additives inoculate dominant bacteria in the compost, mainly in the form of bacterial agents, skipping the generation of natural succession, and they can significantly accelerate the maturation process and enhance microbial activity [102]. The microbial community structure of compost was changed by inoculation with a bacterial agent, and adverse bacteria were antagonized to achieve the purpose of inhibiting the loss of nutrients in the form of gases [103]. As shown in Table 4, the addition of bacterial agents as microbial additives mainly corresponded to the required composting stage; the composting process could be influenced by the regulation of the microbial community's structure. According to the research by Xue et al. [19], an aerobic microorganism agent significantly reduced CH_4 emissions. Inoculation with aerobic bacteria enhanced the mineralization intensity during the thermophilic period. With the accumulation of ammonium nitrogen, the activity of methanogens was inhibited, and CH_4 emissions were significantly reduced [88]. The CH_4 reduction performance of aerobic microbial inoculation was also reported by Gao et al. [23], but the emissions of N_2O were reduced. Xie et al. [104] also found that ammonia-oxidizing archaea reduced N_2O emissions. The addition of oxidizing bacteria could significantly activate native microbial communities in compost, exhibiting an earlier entrance into the thermophilic period, a higher peak temperature, and a longer duration of the thermophilic period [105]. However, the higher microbial activity induced rapid changes in the physical properties of a composting pile, which was the main reason for the generation of an anaerobic area during the thermophilic period [106]. It can be concluded that the capacity of a composting pile to hold NH_4^+ and NO_2^- is limited. When the microbial metabolism intensity exceeds the reactor capacity, incomplete nitrification/denitrification occurs, and N_2O emissions increase [107]. In contrast, an appropriate metabolic intensity beneath the concentration limit can provide a more comprehensive reduction in emissions [23]. Zhao et al. [108] isolated thermotolerant nitrifying bacteria (TNB) enriched in compost as a microbial agent. The TNB treatment promoted the nitration reaction and the conversion of ammonium to nitrate, reducing NH_3 emissions by 29.7%. Additionally, Chen et al. [109] observed that thermotolerant sulfide-oxidizing inoculants reduced NH_3 and H_2S emissions by 19.4% and 48.9%, respectively. It can be concluded that thermophilic/thermostable bacterial inoculants provide a more stable metabolic function

in the thermophilic phase. TNB alleviate NH_3 emissions through more intense nitrification [108]. Otherwise, thermotolerant sulfide-oxidizing inoculants inhibit the generation of H_2S by guiding efficient oxidation of its precursors, and metabolic acidification also alleviates NH_3 emissions [20,109]. Wang et al. [110] and Kuroda et al. [111] reported that *Bacillus* inoculation could effectively reduce NH_3 emissions. Qiu et al. [112] found that a nitrogen-retaining microbial agent also mitigated NH_3 emissions. As most of the bacterial agents added in experiments have been compound-specific bacteria prepared after separation and purification, no gas emission trend with an insignificant impact is recorded in Table 4. Furthermore, the effect of combined microbial agents and other additives will be further discussed in the following section about compound additives.

Table 4. The effects of microbial additives on GHGs and odors during composting.

Feedstock	Additive	Impact on Gaseous Emissions (Relative to Control)				Note	Reference
		CH_4	N_2O	NH_3	VSCs		
Sewage sludge, straw	0.3% aerobic microorganism agent [1]	−25%	↑			Lasted for 29 days; promoted temperature rise	[19]
	0.3% facultative anaerobic microorganism agent [1]	−8%	↑				
Kitchen waste, garden waste	0.9% aerobic microbial inoculant [1]	↓	↓	↑	↑	Lasted for 35 days; promoted temperature rise	[23]
Sewage sludge, rice husk	5% thermotolerant sulfide-oxidizing compound bacterial consortium (*v/w*)			−19%	↓	Lasted for 22 days; promoted temperature rise; reduced H_2S by 49%	[109]
Sewage sludge, spent mushroom substrate	5% thermophilic nitrifying bacteria (*v/w*)			↓		Lasted for 20 days; promoted temperature rise; initial C/N: 16	[108]
Chicken manure, rice husks	10% nitrogen-retaining microbial agent [1]			↓		Lasted for 45 days; promoted temperature rise	[112]
Poultry manure, sawdust	*Bacillus* stearothermophilus (8 g/kg)			↓		Lasted for 12 days; similar temperature variation; significantly reduced NH_3 emissions	[110]
Pig manure, sawdust	*Bacillus* sp.			↓		Lasted for 18 days; similar temperature variations	[111]
Chicken manure, rice husk, bran, mushroom residue	5% ammonia-oxidizing archaea (*w/v*)			↓		Lasted for 45 days; promoted temperature rise; initial C/N: 32; significantly reduced NH_3	[104]

Note: [1] wet weight basis; ↑: increase (no detailed data); ↓: decrease (no detailed data); VSCs: volatile sulfide compounds.

3.4.2. Cost Assessment and Economic Benefits

At present, most bacterial agents on the market are used to accelerate compost maturation, and their price is moderate. However, GHG emissions cannot be controlled specifically due to their composition. Therefore, bacterial agents that are more effective in controlling GHG emissions need to be further developed while reducing costs and improving economic benefits.

3.5. Compound Additives

3.5.1. Efficiency Analysis

Currently, there is increased research interest in using a variety of additives and technological processes to comprehensively control the loss of nutrients in the form of gaseous products. By enhancing the fixation of nutrients, it is possible to improve the quality of compost and the feasibility of its production.

Compared with solely electric field-assisted treatment, biochar combined treatment could further reduce CH_4 and N_2O emissions by 69.58% and 31.16% (compared with

an untreated control), respectively [21]. The pore structure of biochar provides a higher oxygen supply rate for a composting pile driven by the electric field, enhances microbial metabolism intensity, and changes the community structure [113]. Wang et al. [114] used biochar with wood vinegar in a combined treatment and reduced the CH_4, NH_3, and N_2O emissions by 62.75%, 35.85%, and 24.61%, respectively. As an organic physical additive, biochar provides additional aeration properties and does not affect composting via other reactions outside the carbon source. The addition of wood vinegar further reduced the release of NH_3 by regulating the pH environment, and a high concentration of NH_4^+ was also well-adsorbed by biochar [115]. Therefore, biochar and acidic chemical additives exhibit a combined and synergistic effect. Besides the combination of biochar and chemical additives, adding microbial agents is also an excellent combined treatment. Xue et al. [19] proved that combining different microbial agents and biochar could further enhance the reduction in GHG emissions (Table 5). Based on biochar modification, the combined treatment provided a larger space and a broader oxygen supply channel for vigorous life activities after inoculation [66]. It also avoided the occurrence of incomplete nitrification and denitrification [116]. However, the combination of mineral materials and acidic additives is prone to chemical reactions, which limits the application of this approach. Awasthi et al. [117] used biochar and calcium bentonite as compound additives. The combined treatment was shown to reduce CH_4 and N_2O emissions more than sole biochar addition, but resulted in higher NH_3 emissions. The same result was obtained in their earlier research [118]. As mineral additives, lime and zeolite behave like typical physical additives, providing improved pore structure to a composting pile and allowing microbial aerobic respiration [73]. An increase in NH3 volatilization may be due to the alkalization of the composting pile by dissolved lime [119]. Alkaline environments enhance the conversion of unstable ammonium nitrogen to NH_3, which can be attributed to other mineral additives, such as montmorillonite [120]. The reactions of mineral additives are usually accompanied by exothermic heat release. In addition, high treatment temperatures are not conducive to NH_3 retention [20,85]. Thus, the combination of different physical additives may provide better performance toward the mitigation of GHGs.

As mentioned above, dicyandiamide (DCD) is a harmless and mature nitrification inhibitor for the composting process. Yang et al. [24] and Yuan et al. [82] conducted similar studies on the combined effect of DCD and other phosphorus compounds. Jiang et al. [121] reported that a "dicyandiamide + thiophosphoric triamide" treatment significantly mitigated the emissions of N_2O and NH_3 by 63.9% and 26.3%, respectively. The phosphorus additive and DCD caused stronger accumulation of nitrogen in the form of ammonium nitrogen, and the combined treatments exhibited a higher NH_4^+ content. As mentioned in the analysis of the single effect of chemical additives, a higher NH_4^+ content is conducive to the inhibition of methanogens, which explains the superposition of the methane emission reduction effect in the combined treatment [89]. Under the action of DCD, the conversion pathway of ammonium nitrogen to nitrite nitrogen is blocked, which promotes the existence of more nitrogen in the form of ammonium nitrogen and significantly reduces the emissions of N_2O [122]. Generally, by adjusting the pH or generating struvite crystallization, ammonium nitrogen can be stably preserved and NH_3 emissions can be reduced [71,100]. In the case of NH_3 volatilization, the higher content of ammonium nitrogen under the combined treatment needs to be stabilized [66]. According to the inference, it can be concluded that the upper limit of ammonium fixation is determined by the internal physical properties of a composting pile and the addition of physical additives, such as biochar, can increase its capacity so the dynamic equilibrium of ammonium nitrogen is more favorable to nitrogen fixation [74,107]. After the use of a higher dose of DCD or its combined treatment, the mineralization extent is increased, the nitrification pathway is completely cut off, and the ammonium nitrogen that cannot be stably adsorbed only exists in the form of NH_3 with forced ventilation [82,115].

The remaining compound additives are basically reacted as a mixture. Liu et al. [67] added a compound fertilizer that contained calcium, magnesium, and phosphorus to

compost. It reduced the emissions of NH_3 by 42.9%, H_2S by 34.91%, Me_2S by 100%, and Me_2SS by 63.28%. $CaSO_4 \cdot H_2O$ and free phosphoric acid in compost can effectively adsorb NH_4^+ [67]. Struvite crystallization is also conducive to the fixation of more ammonium nitrogen [96]. Although NH_3 emissions were significantly reduced in this research, a higher concentration of free NH_4^+ could potentially lead to an increase in NH_3 emissions, which also depended on the adsorption capacity of the pile [97]. The generation of odors mainly originates from the anaerobic decomposition of proteins [38]. As Liu et al. [67] reported, the main odor components in volatile sulfur compounds are Me_2S and Me_2SS, and they are formed by the methylation of H_2S. Fertilizer compound treatment is more helpful in reducing the formation of odor precursors to weaken methylation and alleviate odor emissions.

Chen et al. [123] specifically focused on chicken manure composting and employed wheat straw as a bulking agent. Compound treatment mitigated NH_3, N_2O, and CH_4 emissions by 41.4%, 9.0%, and 55.9%, respectively. A direct positive correlation was found between the amount of the compound additive added and the extent of the reduction in NH3 and CH4 emissions. Because of the high temperature formed due to the compound additive, nitrifying bacteria and methanogens were strictly inhibited [76,124]. Under the combined action of biochar and inoculated microorganisms, the compost maintained good metabolic efficiency, anaerobic areas were rarely produced, and N_2O and CH_4 emissions were greatly reduced [125]. As discussed in Section 3.4, the strong microbial activity and high NH_4^+ content that form at higher temperatures require stronger adsorption and fixation capabilities. The aeration conditions provided by 10% chicken manure biochar (CMB) were matched by a 10% chicken manure integrated microbial consortium (CMMC). Thus, nitrogen was mostly fixed in the form of ammonium nitrogen, and the emissions of NH_3 were effectively reduced [115].

The application of mature compost has recently become a hot topic in the composting field [126]. The essence of mature compost is the backfill of finished compost products, which helps to reduce the cost under continuous production conditions [126,127]. Although backfilled mature compost undergoes certain nutrient loss, its use as an additive can provide a pore structure and microbial community that raw materials cannot reach [128]. Yang et al. [129] reported that the addition of mature compost could reduce the emissions of NH_3, N_2O, and CH_4 by 58.0%,73.6%, and 44.8%, respectively. In a sense, mature compost is equivalent to the inoculation of a physical additive and a microbial agent. Mixing mature compost provides the composting pile with stronger microbial activity and an aeration effect [130]. Similar to the study by Chen et al. [109], the same theory can explain the reduction in CH_4 and N_2O emissions. Mixing highly humified mature compost is conducive to enhancing the adsorption of ammonium nitrogen in a composting pile, which can significantly reduce ammonia volatilization [131,132]. Luo et al. [133] observed almost the same trend of mature composting reducing GHG emissions, but the NH_3 emission reduction performance was not sufficiently explained. Different treatment methods of mature compost lead to different emission reduction effects when used as an additive. Finally, it is more effective to use a mixed treatment for mature compost addition [129].

3.5.2. Cost Assessment and Economic Benefits

Compound additives include “process + additives” and “additive-combined treatment”, leading to higher costs than those incurred in the case of single measures. However, compared with single measures, combined treatments exhibit better performance in reducing GHGs and odors [19,21,24]. The specific economic benefits should be evaluated in accordance with the actual situation.

Table 5. The effects of compound additives on GHGs and odors during composting.

Feedstock	Additive	Impact on Gaseous Emissions (Relative to Control)				Note	Reference
		CH_4	N_2O	NH_3	VSCs		
Chicken manure, rice husk	electric field-assisted composting (2 V) +10% biochar [1]	−70%	−31%			Lasted for 30 days; promoted temperature rise; increased electrical conductivity	[21]
Pig manure, apple sawdust	5% biochar [2] + 1.0% wood vinegar [2]	−63%	↓	−36%		Lasted for 64 days; similar temperature variation	[114]
Sewage sludge, straw	5% bamboo biochar [1] +0.3% aerobic microorganism agent [1]	−45%	↓			Lasted for 29 days; promoted temperature rise	[19]
	5% bamboo biochar [1] +0.3% facultative anaerobic microorganism agent [1]	−44%	↓				
Dewatered sewage sludge, wheat straw	12% wheat straw biochar [2] + 4% calcium-bentonite [2]	↓	↓	↑		Lasted for 43 days; promoted temperature rise	[117]
	30% zeolite [2] + 1% lime [2]	↓	↓	↑		Lasted for 56 days; promoted temperature rise	[118]
Pig manure, corn stalk	0.2% dicyandiamide [2] + 6.6% phosphogypsum [2]	−39%	−36%	−18%		Lasted for 40 days; similar temperature variation; initial C/N: 17, 16; increased electrical conductivity	[24]
	0.2% dicyandiamide [2] + 6.6% superphosphate [2]	−33%	−25%	−21%			
Pig manure, sawdust	0.5% thiophosphoric triamide [2] +0.25% dicyandiamide [2]		−64%	−27%		Lasted for 20 days; similar temperature variation	[121]
Sewage sludge, corn stalk	10% phosphogypsum [2] + 2.5% dicyandiamide [3]	↓	−86%	+20%		Lasted for 35 days; later temperature peak; both reduced CH_4 emissions by more than 50%	[82]
	10% superphosphate [2] + 2.5% dicyandiamide [3]	↓	−88%	−12%			
Pig manure, corn stalk	10% calcium magnesium phosphate fertilizer [2]		↑	−43%	↓	Lasted for 49 days; promoted temperature rise; H_2S: –35%; Me_2S: –100%; Me_2SS: –63%	[67]
Chicken manure, wheat straw	10% chicken manure integrated microbial consortium [2] + 10% chicken manure biochar [2]	−56%	−9%	−41%		Lasted for 42 days; similar temperature variations	[123]
Kitchen waste, corn stalk	10% mature compost (mix) [1]	−45%	−74%	−58%		Lasted for 35 days; promoted temperature rise	[129]
Pig manure, corn stalk	5% mature compost (cover) [1]	−59%	↓	+61%		Lasted for 30 days; promoted temperature rise; all reduced N_2O emissions significantly	[133]
	5% mature compost (mix) [1]	−53%	↓				
	5% mature compost (cover + mix) [1]	−65%	↓				

Note: [1] wet weight basis; [2] dry weight basis; [3] molar ratio of initial nitrogen; ↑: increase (no detailed data); ↓: decrease (no detailed data); VSCs: volatile sulfide compounds.

4. Prospective

Based on the review of different additives and their reaction modes, the appropriate use of additives can effectively accelerate the composting period, improve product quality, and reduce air pollution. In particular, mineral additives are expensive and cannot be recycled, so they are not the first choice for production applications. Mineral additives and chemical additives trigger chemical reactions in a composting pile and release ions,

reflected as increased electrical conductivity, and may increase the toxic effect on crops [134]. Although organic physical additives have lower costs and considerable efficiency, their preparation and supply restrict the production scale [67,123]. Similarly, the current composting process and microbial additives are mainly used to accelerate maturation, and they lack pertinence for gaseous emission reductions during composting [108,109]. Also, processes such as membrane-covered composting and electric field-assisted composting are expensive for large-scale production [58,60]. A comprehensive consideration of cost and economic benefits will help to improve production feasibility and facilitate long-term development. With the promotion of composting and the expansion of the production scale, it is necessary to conduct stricter assessments of cleaner production and more complete quantitative gas emission monitoring in the whole process. Therefore, the future prospectives for GHG and odor reduction during composting are as follows:

1. Before composting: more low-cost and recyclable materials should be developed as additives; continuous and stable supply will be an important criterion for judging additives;
2. During composting: the use of microbial agents should be more targeted, not only for accelerating maturation, but also for screening highly efficient strains that are more conducive to GHG and odor emissions reduction;
3. After composting: expand from the laboratory scale to industrial production; continuously and quantitatively monitor GHGs and odor emissions, and unify the measurement method and magnitude; ensure strict control of GHGs and odor emissions throughout the process, from compost production to crop planting.

5. Conclusions

This study summarizes the influence of composting conditions and different additives on gaseous emissions. Greenhouse gases can be effectively reduced by adjusting composting conditions. Anaerobic gaseous products can be diminished by the application of physical porous additives. Chemical additives significantly reduce gaseous emissions, but their side effects on compost application must be eliminated. The reduction effects of microbial additives are influenced by the addition amounts and their microenvironment. Compound additives can further reduce gaseous emissions. However, further studies are required to assess the economic viability of additives to promote their large-scale application during composting.

Author Contributions: Conceptualization, M.L.; methodology, M.L. and S.L.; validation, Q.M., Y.W. and J.Z.; formal analysis, M.L.; resources, R.M.; writing—original draft preparation, M.L.; writing—review and editing, M.L. and S.L.; supervision, L.S. and F.D.; project administration, S.C. and W.Y.; funding acquisition, X.G. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Key Research and Development Program of China (2019YFE0122700), National Key Research and Development Program of China (2017YFD0800602), Natural Science Foundation of Shandong Province (ZR2020QE238), Major Agricultural Application Technology and Innovation Project of Shandong Province (SD2019ZZ020) and Science and Technology Innovation Development Project of Tai'an City (2020NS074).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: We conducted secondary data analysis of publicly available data.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

References

1. Song, B.; Manu, M.K.; Li, D.; Wang, C.; Varjani, S.; Ladumor, N.; Michael, L.; Xu, Y.; Wong, J.W.C. Food waste digestate composting: Feedstock optimization with sawdust and mature compost. *Bioresour. Technol.* **2021**, *341*, 125759. [CrossRef] [PubMed]
2. Nie, E.; Gao, D.; Zheng, G. Effects of lactic acid on modulating the ammonia emissions in co-composts of poultry litter with slaughter sludge. *Bioresour. Technol.* **2020**, *315*, 123812. [CrossRef] [PubMed]
3. NBS. National Bureau of Statistics of the People's Republic of China (NBS). Available online: https://data.stats.gov.cn (accessed on 1 January 2023).
4. Yao, X.; Zhou, H.; Meng, H.; Ding, J.; Shen, Y.; Cheng, H.; Zhang, X.; Li, R.; Fan, S. Amino acid profile characterization during the co-composting of a livestock manure and maize straw mixture. *J. Clean. Prod.* **2021**, *278*, 123494. [CrossRef]
5. Goyer, C.; Neupane, S.; Zebarth, B.J.; Burton, D.L.; Wilson, C.; Sennett, L. Diverse compost products influence soil bacterial and fungal community diversity in a potato crop production system. *Appl. Soil Ecol.* **2022**, *169*, 104247. [CrossRef]
6. Abbey, L.; Ofoe, R.; Gunupuru, L.R.; Ijenyo, M. Variation in frequency of CQA-tested municipal solid waste compost can alter metabolites in vegetables. *Food Res. Int.* **2021**, *143*, 110225. [CrossRef]
7. Rehman, R.A.; Qayyum, M.F. Co-composts of sewage sludge, farm manure and rock phosphate can substitute phosphorus fertilizers in rice-wheat cropping system. *J. Environ. Manag.* **2020**, *259*, 109700. [CrossRef]
8. Cao, Y.; Wang, X.; Misselbrook, T.; Wang, R.; Zheng, X.; Ma, L. Quantification of N and C cycling during aerobic composting, including automated direct measurement of N2, N2O, NO, NH3, CO2 and CH4 emissions. *Sci. Total Environ.* **2023**, *857*, 159177. [CrossRef]
9. Duan, Z.; Lu, W.; Mustafa, M.F.; Du, J.; Wen, Y. Odorous gas emissions from sewage sludge composting windrows affected by the turning operation and associated health risks. *Sci. Total Environ.* **2022**, *839*, 155996. [CrossRef]
10. Zhang, X.; Ma, D.; Lv, J.; Feng, Q.; Liang, Z.; Chen, H.; Feng, J. Food waste composting based on patented compost bins: Carbon dioxide and nitrous oxide emissions and the denitrifying community analysis. *Bioresour. Technol.* **2022**, *346*, 126643. [CrossRef]
11. Shan, G.; Li, W.; Gao, Y.; Tan, W.; Xi, B. Additives for reducing nitrogen loss during composting: A review. *J. Clean. Prod.* **2021**, *307*, 127308. [CrossRef]
12. Zhang, Z.; Liu, D.; Qiao, Y.; Li, S.; Chen, Y.; Hu, C. Mitigation of carbon and nitrogen losses during pig manure composting: A meta-analysis. *Sci. Total Environ.* **2021**, *783*, 147103. [CrossRef] [PubMed]
13. Ren, X.; Wang, Z.; Zhao, M.; Xie, J.; Zhang, Z.; Yang, F.; Wang, Q.; Ding, Y. Role of selenite on the nitrogen conservation and greenhouse gases mitigation during the goat manure composting process. *Sci. Total Environ.* **2022**, *838*, 155799. [CrossRef] [PubMed]
14. Mora, C.; Spirandelli, D.; Franklin, E.C.; Lynham, J.; Kantar, M.B.; Miles, W.; Smith, C.Z.; Freel, K.; Moy, J.; Louis, L.V.; et al. Broad threat to humanity from cumulative climate hazards intensified by greenhouse gas emissions. *Nat. Clim. Chang.* **2018**, *8*, 1062–1071. [CrossRef]
15. Wong, M.S.; Jin, X.M.; Liu, Z.Z.; Nichol, J.E.; Ye, S.R.; Jiang, P.; Chan, P.W. Geostationary Satellite Observation of Precipitable Water Vapor Using an Empirical Orthogonal Function (EOF) based Reconstruction Technique over Eastern China. *Remote Sens.* **2015**, *7*, 5879–5900. [CrossRef]
16. Zheng, G.; Cheng, Y.; Zhu, Y.; Yang, J.; Wang, L.; Chen, T. Correlation of microbial dynamics to odor production and emission in full-scale sewage sludge composting. *Bioresour. Technol.* **2022**, *360*, 127597. [CrossRef] [PubMed]
17. Gao, X.; Yang, F.; Cheng, J.; Xu, Z.; Zang, B.; Li, G.; Xie, X.; Luo, W. Emission of volatile sulphur compounds during swine manure composting: Source identification, odour mitigation and assessment. *Waste Manag.* **2022**, *153*, 129–137. [CrossRef]
18. Wang, M.; Awasthi, M.K.; Wang, Q.; Chen, H.; Ren, X.; Zhao, J.; Li, R.; Zhang, Z. Comparison of additives amendment for mitigation of greenhouse gases and ammonia emission during sewage sludge co-composting based on correlation analysis. *Bioresour. Technol.* **2017**, *243*, 520–527. [CrossRef]
19. Xue, S.; Zhou, L.; Zhong, M.; Kumar Awasthi, M.; Mao, H. Bacterial agents affected bacterial community structure to mitigate greenhouse gas emissions during sewage sludge composting. *Bioresour. Technol.* **2021**, *337*, 125397. [CrossRef]
20. He, X.; Yin, H.; Han, L.; Cui, R.; Fang, C.; Huang, G. Effects of biochar size and type on gaseous emissions during pig manure/wheat straw aerobic composting: Insights into multivariate-microscale characterization and microbial mechanism. *Bioresour. Technol.* **2019**, *271*, 375–382. [CrossRef]
21. Li, X.; Zhao, Y.; Xu, A.; Chang, H.; Lin, G.; Li, R. Conductive biochar promotes oxygen utilization to inhibit greenhouse gas emissions during electric field-assisted aerobic composting. *Sci. Total Environ.* **2022**, *842*, 156929. [CrossRef]
22. Pan, J.; Cai, H.; Zhang, Z.; Liu, H.; Li, R.; Mao, H.; Awasthi, M.K.; Wang, Q.; Zhai, L. Comparative evaluation of the use of acidic additives on sewage sludge composting quality improvement, nitrogen conservation, and greenhouse gas reduction. *Bioresour. Technol.* **2018**, *270*, 467–475. [CrossRef] [PubMed]
23. Gao, X.; Xu, Z.; Li, Y.; Zhang, L.; Li, G.; Nghiem, L.D.; Luo, W. Bacterial dynamics for gaseous emission and humification in bio-augmented composting of kitchen waste. *Sci. Total Environ.* **2021**, *801*, 149640. [CrossRef] [PubMed]
24. Yang, Y.; Yin, Z.; Li, L.; Li, Y.; Liu, Y.; Luo, Y.; Li, G.; Yuan, J. Effects of dicyandiamide, phosphogypsum and superphosphate on greenhouse gas emissions during pig manure composting. *Sci. Total Environ.* **2022**, *846*, 157487. [CrossRef] [PubMed]
25. Zhao, S.; Yang, X.; Zhang, W.; Chang, J.; Wang, D. Volatile sulfide compounds (VSCs) and ammonia emission characteristics and odor contribution in the process of municipal sludge composting. *J. Air Waste Manag. Assoc.* **2019**, *69*, 1368–1376. [CrossRef] [PubMed]

26. Huang, Y.; Li, D.; Wang, L.; Yong, C.; Sun, E.; Jin, H.; Huang, H. Decreased enzyme activities, ammonification rate and ammonifiers contribute to higher nitrogen retention in hyperthermophilic pretreatment composting. *Bioresour. Technol.* **2019**, *272*, 521–528. [CrossRef] [PubMed]
27. Mei, J.; Ji, K.; Su, L.; Wu, M.; Zhou, X.; Duan, E. Effects of FeSO4 dosage on nitrogen loss and humification during the composting of cow dung and corn straw. *Bioresour. Technol.* **2021**, *341*, 125867. [CrossRef] [PubMed]
28. Zhao, Y.; Li, W.; Chen, L.; Zhou, Y. Characterization of heterotrophic nitrification by a thermotolerant Brevibacillus Agri N2 isolated from sewage sludge composting. *Environ. Res.* **2022**, *214*, 113903. [CrossRef]
29. He, X.; Yin, H.; Fang, C.; Xiong, J.; Han, L.; Yang, Z.; Huang, G. Metagenomic and q-PCR analysis reveals the effect of powder bamboo biochar on nitrous oxide and ammonia emissions during aerobic composting. *Bioresour. Technol.* **2021**, *323*, 124567. [CrossRef]
30. Yin, S.; Zhang, W.; Tong, T.; Yu, C.; Chang, X.; Chen, K.; Xing, Y.; Yang, Y. Feedstock-dependent abundance of functional genes related to nitrogen transformation controlled nitrogen loss in composting. *Bioresour. Technol.* **2022**, *361*, 127678. [CrossRef]
31. Li, H.; Wei, Z.; Song, C.; Chen, X.; Zhang, R.; Liu, Y. Functional keystone drive nitrogen conversion during different animal manures composting. *Bioresour. Technol.* **2022**, *361*, 127721. [CrossRef]
32. Fang, T.; Wang, T.; Zhao, M.; Bai, L.; Deng, Y.; Ruan, W. Food waste digestate composting enhancement by sodium polyacrylate addition: Effects on nitrogen transformation processes and bacterial community dynamics. *J. Environ. Manag.* **2023**, *325*, 116531. [CrossRef] [PubMed]
33. Hoang, H.G.; Thuy, B.T.P.; Lin, C.; Vo, D.-V.N.; Tran, H.T.; Bahari, M.B.; Le, V.G.; Vu, C.T. The nitrogen cycle and mitigation strategies for nitrogen loss during organic waste composting: A review. *Chemosphere* **2022**, *300*, 134514. [CrossRef] [PubMed]
34. Wen, X.; Sun, R.; Cao, Z.; Huang, Y.; Li, J.; Zhou, Y.; Fu, M.; Ma, L.; Zhu, P.; Li, Q. Synergistic metabolism of carbon and nitrogen: Cyanate drives nitrogen cycle to conserve nitrogen in composting system. *Bioresour. Technol.* **2022**, *361*, 127708. [CrossRef] [PubMed]
35. Bharali, A.; Baruah, K.K.; Bhattacharya, S.S.; Kim, K.-H. The use of Azolla caroliniana compost as organic input to irrigated and rainfed rice ecosystems: Comparison of its effects in relation to CH4 emission pattern, soil carbon storage, and grain C interactions. *J. Clean. Prod.* **2021**, *313*, 127931. [CrossRef]
36. Zhou, S.; Kong, F.; Lu, L.; Wang, P.; Jiang, Z. Biochar—An effective additive for improving quality and reducing ecological risk of compost: A global meta-analysis. *Sci. Total Environ.* **2022**, *806*, 151439. [CrossRef]
37. Xiao, R.; Awasthi, M.K.; Li, R.; Park, J.; Pensky, S.M.; Wang, Q.; Wang, J.J.; Zhang, Z. Recent developments in biochar utilization as an additive in organic solid waste composting: A review. *Bioresour. Technol.* **2017**, *246*, 203–213. [CrossRef]
38. Guo, R.; Li, G.; Jiang, T.; Schuchardt, F.; Chen, T.; Zhao, Y.; Shen, Y. Effect of aeration rate, C/N ratio and moisture content on the stability and maturity of compost. *Bioresour. Technol.* **2012**, *112*, 171–178. [CrossRef]
39. Schiavon, M.; Martini, L.M.; Corrà, C.; Scapinello, M.; Coller, G.; Tosi, P.; Ragazzi, M. Characterisation of volatile organic compounds (VOCs) released by the composting of different waste matrices. *Environ. Pollut.* **2017**, *231*, 845–853. [CrossRef]
40. Rech, I.; Kamogawa, M.Y.; Jones, D.L.; Pavinato, P.S. Synthesis and characterization of struvite derived from poultry manure as a mineral fertilizer. *J. Environ. Manag.* **2020**, *272*, 111072. [CrossRef]
41. Maulini-Duran, C.; Artola, A.; Font, X.; Sánchez, A. A systematic study of the gaseous emissions from biosolids composting: Raw sludge versus anaerobically digested sludge. *Bioresour. Technol.* **2013**, *147*, 43–51. [CrossRef]
42. Zang, B.; Li, S.; Michel, F.C.; Li, G.; Zhang, D.; Li, Y. Control of dimethyl sulfide and dimethyl disulfide odors during pig manure composting using nitrogen amendment. *Bioresour. Technol.* **2017**, *224*, 419–427. [CrossRef] [PubMed]
43. Zhao, Y.; Lou, Y.; Qin, W.; Cai, J.; Zhang, P.; Hu, B. Interval aeration improves degradation and humification by enhancing microbial interactions in the composting process. *Bioresour. Technol.* **2022**, *358*, 127296. [CrossRef] [PubMed]
44. Zeng, J.; Shen, X.; Yin, H.; Sun, X.; Dong, H.; Huang, G. Oxygen dynamics, organic matter degradation and main gas emissions during pig manure composting: Effect of intermittent aeration. *Bioresour. Technol.* **2022**, *361*, 127697. [CrossRef] [PubMed]
45. Cao, L.; Liao, L.; Su, C.; Mo, T.; Zhu, F.; Qin, R.; Li, R. Metagenomic analysis revealed the microbiota and metabolic function during co-composting of food waste and residual sludge for nitrogen and phosphorus transformation. *Sci. Total Environ.* **2021**, *773*, 145561. [CrossRef]
46. Xu, Z.; Qi, C.; Zhang, L.; Ma, Y.; Li, J.; Li, G.; Luo, W. Bacterial dynamics and functions for gaseous emissions and humification in response to aeration intensities during kitchen waste composting. *Bioresour. Technol.* **2021**, *337*, 125369. [CrossRef]
47. Shen, Y.; Ren, L.; Li, G.; Chen, T.; Guo, R. Influence of aeration on CH4, N2O and NH3 emissions during aerobic composting of a chicken manure and high C/N waste mixture. *Waste Manag.* **2011**, *31*, 33–38. [CrossRef]
48. Wang, Y.; Tang, Y.; Li, M.; Yuan, Z. Aeration rate improves the compost quality of food waste and promotes the decomposition of toxic materials in leachate by changing the bacterial community. *Bioresour. Technol.* **2021**, *340*, 125716. [CrossRef]
49. Wang, X.; Bai, Z.; Yao, Y.; Gao, B.; Chadwick, D.; Chen, Q.; Hu, C.; Ma, L. Composting with negative pressure aeration for the mitigation of ammonia emissions and global warming potential. *J. Clean. Prod.* **2018**, *195*, 448–457. [CrossRef]
50. Lin, C. A negative-pressure aeration system for composting food wastes. *Bioresour. Technol.* **2008**, *99*, 7651–7656. [CrossRef]
51. Jiang, T.; Li, G.; Tang, Q.; Ma, X.; Wang, G.; Schuchardt, F. Effects of aeration method and aeration rate on greenhouse gas emissions during composting of pig feces in pilot scale. *J. Environ. Sci.* **2015**, *31*, 124–132. [CrossRef]

52. Ma, S.; Xiong, J.; Cui, R.; Sun, X.; Han, L.; Xu, Y.; Kan, Z.; Gong, X.; Huang, G. Effects of intermittent aeration on greenhouse gas emissions and bacterial community succession during large-scale membrane-covered aerobic composting. *J. Clean. Prod.* **2020**, *266*, 121551. [CrossRef]
53. Zeng, J.; Yin, H.; Shen, X.; Liu, N.; Ge, J.; Han, L.; Huang, G. Effect of aeration interval on oxygen consumption and GHG emission during pig manure composting. *Bioresour. Technol.* **2018**, *250*, 214–220. [CrossRef] [PubMed]
54. Fang, C.; Yuan, X.; Liao, K.; Qu, H.; Han, L.; He, X.; Huang, G. Micro-aerobic conditions based on membrane-covered improves the quality of compost products: Insights into fungal community evolution and dissolved organic matter characteristics. *Bioresour. Technol.* **2022**, *362*, 127849. [CrossRef] [PubMed]
55. Xiong, J.; Su, Y.; He, X.; Han, L.; Guo, J.; Qiao, W.; Huang, G. Effects of functional-membrane covering technique on nitrogen succession during aerobic composting: Metabolic pathways, functional enzymes, and functional genes. *Bioresour. Technol.* **2022**, *354*, 127205. [CrossRef] [PubMed]
56. Liu, N.; Hou, T.; Yin, H.; Han, L.; Huang, G. Effects of amoxicillin on nitrogen transformation and bacterial community succession during aerobic composting. *J. Hazard. Mater.* **2019**, *362*, 258–265. [CrossRef]
57. Cui, P.; Chen, Z.; Zhao, Q.; Yu, Z.; Yi, Z.; Liao, H.; Zhou, S. Hyperthermophilic composting significantly decreases N2O emissions by regulating N2O-related functional genes. *Bioresour. Technol.* **2019**, *272*, 433–441. [CrossRef]
58. Sun, B.; Bai, Z.; Li, Y.; Li, R.; Song, M.; Xu, S.; Zhang, H.; Zhuang, X. Emission mitigation of CH4 and N2O during semi-permeable membrane covered hyperthermophilic aerobic composting of livestock manure. *J. Clean. Prod.* **2022**, *379*, 134850. [CrossRef]
59. Fang, C.; Yin, H.; Han, L.; Ma, S.; He, X.; Huang, G. Effects of semi-permeable membrane covering coupled with intermittent aeration on gas emissions during aerobic composting from the solid fraction of dairy manure at industrial scale. *Waste Manag.* **2021**, *131*, 1–9. [CrossRef]
60. Tang, J.; Li, X.; Zhao, W.; Wang, Y.; Cui, P.; Zeng, R.J.; Yu, L.; Zhou, S. Electric field induces electron flow to simultaneously enhance the maturity of aerobic composting and mitigate greenhouse gas emissions. *Bioresour. Technol.* **2019**, *279*, 234–242. [CrossRef]
61. Liu, X.; Zhang, L. Effects of additives on the co-composting of forest residues with cattle manure. *Bioresour. Technol.* **2023**, *368*, 128384. [CrossRef]
62. Janczak, D.; Malińska, K.; Czekała, W.; Cáceres, R.; Lewicki, A.; Dach, J. Biochar to reduce ammonia emissions in gaseous and liquid phase during composting of poultry manure with wheat straw. *Waste Manag.* **2017**, *66*, 36–45. [CrossRef]
63. Agyarko-Mintah, E.; Cowie, A.; Singh, B.P.; Joseph, S.; Van Zwieten, L.; Cowie, A.; Harden, S.; Smillie, R. Biochar increases nitrogen retention and lowers greenhouse gas emissions when added to composting poultry litter. *Waste Manag.* **2017**, *61*, 138–149. [CrossRef] [PubMed]
64. Zhang, B.; Xu, Z.; Jiang, T.; Huda, N.; Li, G.; Luo, W. Gaseous emission and maturity in composting of livestock manure and tobacco wastes: Effects of aeration intensities and mitigation by physiochemical additives. *Environ. Technol. Innov.* **2020**, *19*, 100899. [CrossRef]
65. Duan, Y.; Yang, J.; Guo, Y.; Wu, X.; Tian, Y.; Li, H.; Awasthi, M.K. Pollution control in biochar-driven clean composting: Emphasize on heavy metal passivation and gaseous emissions mitigation. *J. Hazard. Mater.* **2021**, *420*, 126635. [CrossRef]
66. Yin, Y.; Yang, C.; Li, M.; Zheng, Y.; Ge, C.; Gu, J.; Li, H.; Duan, M.; Wang, X.; Chen, R. Research progress and prospects for using biochar to mitigate greenhouse gas emissions during composting: A review. *Sci. Total Environ.* **2021**, *798*, 149294. [CrossRef] [PubMed]
67. Liu, Y.; Ma, R.; Li, D.; Qi, C.; Han, L.; Chen, M.; Fu, F.; Yuan, J.; Li, G. Effects of calcium magnesium phosphate fertilizer, biochar and spent mushroom substrate on compost maturity and gaseous emissions during pig manure composting. *J. Environ. Manag.* **2020**, *267*, 110649. [CrossRef]
68. Nguyen, M.K.; Lin, C.; Hoang, H.G.; Sanderson, P.; Dang, B.T.; Bui, X.T.; Nguyen, N.S.H.; Vo, D.-V.N.; Tran, H.T. Evaluate the role of biochar during the organic waste composting process: A critical review. *Chemosphere* **2022**, *299*, 134488. [CrossRef] [PubMed]
69. Mao, H.; Zhang, H.; Fu, Q.; Zhong, M.; Li, R.; Zhai, B.; Wang, Z.; Zhou, L. Effects of four additives in pig manure composting on greenhouse gas emission reduction and bacterial community change. *Bioresour. Technol.* **2019**, *292*, 121896. [CrossRef]
70. Liu, T.; Kumar Awasthi, M.; Kumar Awasthi, S.; Ren, X.; Liu, X.; Zhang, Z. Influence of fine coal gasification slag on greenhouse gases emission and volatile fatty acids during pig manure composting. *Bioresour. Technol.* **2020**, *316*, 123915. [CrossRef]
71. Cao, Y.; Wang, X.; Liu, L.; Velthof, G.L.; Misselbrook, T.; Bai, Z.; Ma, L. Acidification of manure reduces gaseous emissions and nutrient losses from subsequent composting process. *J. Environ. Manag.* **2020**, *264*, 110454. [CrossRef]
72. Awasthi, M.K.; Pandey, A.K.; Bundela, P.S.; Wong, J.W.C.; Li, R.; Zhang, Z. Co-composting of gelatin industry sludge combined with organic fraction of municipal solid waste and poultry waste employing zeolite mixed with enriched nitrifying bacterial consortium. *Bioresour. Technol.* **2016**, *213*, 181–189. [CrossRef] [PubMed]
73. Li, D.; Manu, M.K.; Varjani, S.; Wong, J.W.C. Mitigation of NH3 and N2O emissions during food waste digestate composting at C/N ratio 15 using zeolite amendment. *Bioresour. Technol.* **2022**, *359*, 127465. [CrossRef] [PubMed]
74. Ren, X.; Wang, Q.; Awasthi, M.K.; Zhao, J.; Wang, J.; Liu, T.; Li, R.; Zhang, Z. Improvement of cleaner composting production by adding Diatomite: From the nitrogen conservation and greenhouse gas emission. *Bioresour. Technol.* **2019**, *286*, 121377. [CrossRef] [PubMed]
75. Zheng, R.; Ren, Z.; Gao, H.; Zhang, A.; Bian, Z. Effects of calcination on silica phase transition in diatomite. *J. Alloys Compd.* **2018**, *757*, 364–371. [CrossRef]

76. Ren, X.; Wang, Q.; Li, R.; Chang, C.C.; Pan, J.; Zhang, Z. Effect of clay on greenhouse gas emissions and humification during pig manure composting as supported by spectroscopic evidence. *Sci. Total Environ.* **2020**, *737*, 139712. [CrossRef]
77. Awasthi, M.K.; Wang, Q.; Awasthi, S.K.; Wang, M.; Chen, H.; Ren, X.; Zhao, J.; Zhang, Z. Influence of medical stone amendment on gaseous emissions, microbial biomass and abundance of ammonia oxidizing bacteria genes during biosolids composting. *Bioresour. Technol.* **2018**, *247*, 970–979. [CrossRef]
78. Wang, X.; Zheng, W.; Ma, Y.; Ma, J.; Gao, Y.m.; Zhang, X.; Li, J. Gasification filter cake reduces the emissions of ammonia and enriches the concentration of phosphorous in Caragana microphylla residue compost. *Bioresour. Technol.* **2020**, *315*, 123832. [CrossRef]
79. Li, S.; Song, L.; Jin, Y.; Liu, S.; Shen, Q.; Zou, J. Linking N2O emission from biochar-amended composting process to the abundance of denitrify (nirK and nosZ) bacteria community. *AMB Express* **2016**, *6*, 37. [CrossRef]
80. Tong, B.; Wang, X.; Wang, S.; Ma, L.; Ma, W. Transformation of nitrogen and carbon during composting of manure litter with different methods. *Bioresour. Technol.* **2019**, *293*, 122046. [CrossRef]
81. Jiang, T.; Ma, X.; Yang, J.; Tang, Q.; Yi, Z.; Chen, M.; Li, G. Effect of different struvite crystallization methods on gaseous emission and the comprehensive comparison during the composting. *Bioresour. Technol.* **2016**, *217*, 219–226. [CrossRef]
82. Yuan, J.; Li, Y.; Chen, S.; Li, D.; Tang, H.; Chadwick, D.; Li, S.; Li, W.; Li, G. Effects of phosphogypsum, superphosphate, and dicyandiamide on gaseous emission and compost quality during sewage sludge composting. *Bioresour. Technol.* **2018**, *270*, 368–376. [CrossRef] [PubMed]
83. Zhang, D.; Luo, W.; Yuan, J.; Li, G.; Luo, Y. Effects of woody peat and superphosphate on compost maturity and gaseous emissions during pig manure composting. *Waste Manag.* **2017**, *68*, 56–63. [CrossRef] [PubMed]
84. Chen, M.; Huang, Y.; Liu, H.; Xie, S.; Abbas, F. Impact of different nitrogen source on the compost quality and greenhouse gas emissions during composting of garden waste. *Process Saf. Environ. Prot.* **2019**, *124*, 326–335. [CrossRef]
85. Li, Y.b.; Liu, T.t.; Song, J.l.; Lv, J.h.; Jiang, J.s. Effects of chemical additives on emissions of ammonia and greenhouse gas during sewage sludge composting. *Process Saf. Environ. Prot.* **2020**, *143*, 129–137. [CrossRef]
86. Yang, L.L.; Huang, Y.; Zhao, M.X.; Huang, Z.X.; Miao, H.F.; Xu, Z.Y.; Ruan, W.Q. Enhancing biogas generation performance from food wastes by high-solids thermophilic anaerobic digestion: Effect of pH adjustment. *Int. Biodeterior. Biodegrad.* **2015**, *105*, 153–159. [CrossRef]
87. Niu, Q.G.; Takemura, Y.; Kubota, K.; Li, Y.Y. Comparing mesophilic and thermophilic anaerobic digestion of chicken manure: Microbial community dynamics and process resilience. *Waste Manag.* **2015**, *43*, 114–122. [CrossRef]
88. Linquist, B.A.; Adviento-Borbe, M.A.; Pittelkow, C.M.; van Kessel, C.; van Groenigen, K.J. Fertilizer management practices and greenhouse gas emissions from rice systems: A quantitative review and analysis. *Field Crop. Res.* **2012**, *135*, 10–21. [CrossRef]
89. Wang, Q.; Awasthi, M.K.; Ren, X.; Zhao, J.; Li, R.; Wang, Z.; Wang, M.; Chen, H.; Zhang, Z. Combining biochar, zeolite and wood vinegar for composting of pig manure: The effect on greenhouse gas emission and nitrogen conservation. *Waste Manag.* **2018**, *74*, 221–230. [CrossRef]
90. Mao, H.; Zhang, T.; Li, R.H.; Zhai, B.N.; Wang, Z.H.; Wang, Q.; Zhang, Z.Q. Apple pomace improves the quality of pig manure aerobic compost by reducing emissions of NH3 and N2O. *Sci. Rep.* **2017**, *7*, 870. [CrossRef]
91. Wang, Z.; Ding, Y.; Ren, X.; Xie, J.; Kumar, S.; Zhang, Z.; Wang, Q. Effect of micronutrient selenium on greenhouse gas emissions and related functional genes during goat manure composting. *Bioresour. Technol.* **2022**, *349*, 126805. [CrossRef]
92. Cáceres, R.; Malińska, K.; Marfà, O. Nitrification within composting: A review. *Waste Manag.* **2018**, *72*, 119–137. [CrossRef]
93. Mei, J.; Li, B.; Su, L.; Zhou, X.; Duan, E. Effects of potassium persulfate on nitrogen loss and microbial community during cow manure and corn straw composting. *Bioresour. Technol.* **2022**, *363*, 127919. [CrossRef] [PubMed]
94. Ariyanto, E.; Sen, T.K.; Ang, H.M. The influence of various physico-chemical process parameters on kinetics and growth mechanism of struvite crystallisation. *Adv. Powder Technol.* **2014**, *25*, 682–694. [CrossRef]
95. Triger, A.; Pic, J.-S.; Cabassud, C. Determination of struvite crystallization mechanisms in urine using turbidity measurement. *Water Res.* **2012**, *46*, 6084–6094. [CrossRef] [PubMed]
96. Yang, F.; Li, G.; Shi, H.; Wang, Y. Effects of phosphogypsum and superphosphate on compost maturity and gaseous emissions during kitchen waste composting. *Waste Manag.* **2015**, *36*, 70–76. [CrossRef]
97. Li, Y.; Luo, W.; Li, G.; Wang, K.; Gong, X. Performance of phosphogypsum and calcium magnesium phosphate fertilizer for nitrogen conservation in pig manure composting. *Bioresour. Technol.* **2018**, *250*, 53–59. [CrossRef]
98. Luo, Y.; Li, G.; Luo, W.; Schuchardt, F.; Jiang, T.; Xu, D. Effect of phosphogypsum and dicyandiamide as additives on NH3, N2O and CH4 emissions during composting. *J. Environ. Sci.* **2013**, *25*, 1338–1345. [CrossRef]
99. Dai, Y.; Di, H.J.; Cameron, K.C.; He, J.-Z. Effects of nitrogen application rate and a nitrification inhibitor dicyandiamide on ammonia oxidizers and N2O emissions in a grazed pasture soil. *Sci. Total Environ.* **2013**, *465*, 125–135. [CrossRef]
100. Jiang, T.; Ma, X.; Tang, Q.; Yang, J.; Li, G.; Schuchardt, F. Combined use of nitrification inhibitor and struvite crystallization to reduce the NH3 and N2O emissions during composting. *Bioresour. Technol.* **2016**, *217*, 210–218. [CrossRef]
101. Lu, Y.; Gu, W.; Xu, P.; Xie, K.; Li, X.; Sun, L.; Wu, H.; Shi, C.; Wang, D. Effects of sulphur and Thiobacillus thioparus 1904 on nitrogen cycle genes during chicken manure aerobic composting. *Waste Manag.* **2018**, *80*, 10–16. [CrossRef]
102. Liu, Z.; Wei, Y.; Li, J.; Ding, G.-C. Integrating 16S rRNA amplicon metagenomics and selective culture for developing thermophilic bacterial inoculants to enhance manure composting. *Waste Manag.* **2022**, *144*, 357–365. [CrossRef]

103. Xie, T.; Zhang, Z.; Zhang, D.; Wei, C.; Lin, Y.; Feng, R.; Nan, J.; Feng, Y. Effect of hydrothermal pretreatment and compound microbial agents on compost maturity and gaseous emissions during aerobic composting of kitchen waste. *Sci. Total Environ.* **2023**, *854*, 158712. [CrossRef] [PubMed]
104. Xie, K.; Jia, X.; Xu, P.; Huang, X.; Gu, W.; Zhang, F.; Yang, S.; Tang, S. Improved composting of poultry feces via supplementation with ammonia oxidizing archaea. *Bioresour. Technol.* **2012**, *120*, 70–77. [CrossRef] [PubMed]
105. Li, S.; Li, J.; Yuan, J.; Li, G.; Zang, B.; Li, Y. The influences of inoculants from municipal sludge and solid waste on compost stability, maturity and enzyme activities during chicken manure composting. *Environ. Technol.* **2017**, *38*, 1770–1778. [CrossRef] [PubMed]
106. Jiang, J.; Kang, K.; Wang, C.; Sun, X.; Dang, S.; Wang, N.; Wang, Y.; Zhang, C.; Yan, G.; Li, Y. Evaluation of total greenhouse gas emissions during sewage sludge composting by the different dicyandiamide added forms: Mixing, surface broadcasting, and their combination. *Waste Manag.* **2018**, *81*, 94–103. [CrossRef] [PubMed]
107. Li, Q.; Guo, X.; Lu, Y.; Shan, G.; Huang, J. Impacts of adding FGDG on the abundance of nitrification and denitrification functional genes during dairy manure and sugarcane pressmud co-composting. *Waste Manag.* **2016**, *56*, 63–70. [CrossRef] [PubMed]
108. Zhao, Y.; Li, W.; Chen, L.; Meng, L.; Zheng, Z. Effect of enriched thermotolerant nitrifying bacteria inoculation on reducing nitrogen loss during sewage sludge composting. *Bioresour. Technol.* **2020**, *311*, 123461. [CrossRef] [PubMed]
109. Chen, L.; Li, W.; Zhao, Y.; Zhou, Y.; Zhang, S.; Meng, L. Effects of compound bacterial agent on gaseous emissions and compost maturity during sewage sludge composting. *J. Clean. Prod.* **2022**, *366*, 133015. [CrossRef]
110. Wang, Y.; Bi, L.; Liao, Y.; Lu, D.; Zhang, H.; Liao, X.; Liang, J.B.; Wu, Y. Influence and characteristics of Bacillus stearothermophilus in ammonia reduction during layer manure composting. *Ecotoxicol. Environ. Saf.* **2019**, *180*, 80–87. [CrossRef]
111. Kuroda, K.; Waki, M.; Yasuda, T.; Fukumoto, Y.; Tanaka, A.; Nakasaki, K. Utilization of *Bacillus* sp. strain TAT105 as a biological additive to reduce ammonia emissions during composting of swine feces. *Biosci. Biotechnol. Biochem.* **2015**, *79*, 1702–1711. [CrossRef]
112. Qiu, Z.; Li, M.; Song, L.; Wang, C.; Yang, S.; Yan, Z.; Wang, Y. Study on nitrogen-retaining microbial agent to reduce nitrogen loss during chicken manure composting and nitrogen transformation mechanism. *J. Clean. Prod.* **2021**, *285*, 124813. [CrossRef]
113. Ye, J.; Joseph, S.D.; Ji, M.; Nielsen, S.; Mitchell, D.R.G.; Donne, S.; Horvat, J.; Wang, J.; Munroe, P.; Thomas, T. Chemolithotrophic processes in the bacterial communities on the surface of mineral-enriched biochars. *ISME J.* **2017**, *11*, 1087–1101. [CrossRef] [PubMed]
114. Wang, X.; Liu, X.; Wang, Z.; Sun, G.; Li, J. Greenhouse gas reduction and nitrogen conservation during manure composting by combining biochar with wood vinegar. *J. Environ. Manag.* **2022**, *324*, 116349. [CrossRef] [PubMed]
115. Akdeniz, N. A systematic review of biochar use in animal waste composting. *Waste Manag.* **2019**, *88*, 291–300. [CrossRef]
116. Duan, P.; Wu, Z.; Zhang, Q.; Fan, C.; Xiong, Z. Thermodynamic responses of ammonia-oxidizing archaea and bacteria explain N2O production from greenhouse vegetable soils. *Soil Biol. Biochem.* **2018**, *120*, 37–47. [CrossRef]
117. Awasthi, M.K.; Wang, Q.; Chen, H.; Wang, M.; Awasthi, S.K.; Ren, X.; Cai, H.; Li, R.; Zhang, Z. In-vessel co-composting of biosolid: Focusing on mitigation of greenhouse gases emissions and nutrients conservation. *Renew. Energy* **2018**, *129*, 814–823. [CrossRef]
118. Awasthi, M.K.; Wang, Q.; Huang, H.; Ren, X.; Lahori, A.H.; Mahar, A.; Ali, A.; Shen, F.; Li, R.; Zhang, Z. Influence of zeolite and lime as additives on greenhouse gas emissions and maturity evolution during sewage sludge composting. *Bioresour. Technol.* **2016**, *216*, 172–181. [CrossRef]
119. Qi, C.; Yin, R.; Cheng, J.; Xu, Z.; Chen, J.; Gao, X.; Li, G.; Nghiem, L.; Luo, W. Bacterial dynamics for gaseous emission and humification during bio-augmented composting of kitchen waste with lime addition for acidity regulation. *Sci. Total Environ.* **2022**, *848*, 157653. [CrossRef]
120. Zhu, L.; Yang, H.; Zhao, Y.; Kang, K.; Liu, Y.; He, P.; Wu, Z.; Wei, Z. Biochar combined with montmorillonite amendments increase bioavailable organic nitrogen and reduce nitrogen loss during composting. *Bioresour. Technol.* **2019**, *294*, 122224. [CrossRef]
121. Jiang, J.; Yu, D.; Wang, Y.; Zhang, X.; Dong, W.; Zhang, X.; Guo, F.; Li, Y.; Zhang, C.; Yan, G. Use of additives in composting informed by experience from agriculture: Effects of nitrogen fertilizer synergists on gaseous nitrogen emissions and corresponding genes (amoA and nirS). *Bioresour. Technol.* **2021**, *319*, 124127. [CrossRef]
122. Zou, Y.; Hu, Z.; Zhang, J.; Xie, H.; Guimbaud, C.; Fang, Y. Effects of pH on nitrogen transformations in media-based aquaponics. *Bioresour. Technol.* **2016**, *210*, 81–87. [CrossRef] [PubMed]
123. Chen, H.; Awasthi, S.K.; Liu, T.; Duan, Y.; Ren, X.; Zhang, Z.; Pandey, A.; Awasthi, M.K. Effects of microbial culture and chicken manure biochar on compost maturity and greenhouse gas emissions during chicken manure composting. *J. Hazard. Mater.* **2020**, *389*, 121908. [CrossRef] [PubMed]
124. de la Rosa, J.M.; Paneque, M.; Miller, A.Z.; Knicker, H. Relating physical and chemical properties of four different biochars and their application rate to biomass production of Lolium perenne on a Calcic Cambisol during a pot experiment of 79days. *Sci. Total Environ.* **2014**, *499*, 175–184. [CrossRef] [PubMed]
125. Chen, W.; Liao, X.; Wu, Y.; Liang, J.B.; Mi, J.; Huang, J.; Zhang, H.; Wu, Y.; Qiao, Z.; Li, X.; et al. Effects of different types of biochar on methane and ammonia mitigation during layer manure composting. *Waste Manag.* **2017**, *61*, 506–515. [CrossRef]
126. Yang, W.; Zhang, L. Addition of mature compost improves the composting of green waste. *Bioresour. Technol.* **2022**, *350*, 126927. [CrossRef]

127. Li, X.; Wang, P.; Chu, S.; Xu, Y.; Su, Y.; Wu, D.; Xie, B. Short-term biodrying achieves compost maturity and significantly reduces antibiotic resistance genes during semi-continuous food waste composting inoculated with mature compost. *J. Hazard. Mater.* **2022**, *427*, 127915. [CrossRef]
128. Ma, C.; Hu, B.; Wei, M.-B.; Zhao, J.-H.; Zhang, H.-Z. Influence of matured compost inoculation on sewage sludge composting: Enzyme activity, bacterial and fungal community succession. *Bioresour. Technol.* **2019**, *294*, 122165. [CrossRef]
129. Yang, F.; Li, Y.; Han, Y.; Qian, W.; Li, G.; Luo, W. Performance of mature compost to control gaseous emissions in kitchen waste composting. *Sci. Total Environ.* **2019**, *657*, 262–269. [CrossRef]
130. Wang, Y.; Tang, Y.; Yuan, Z. Improving food waste composting efficiency with mature compost addition. *Bioresour. Technol.* **2022**, *349*, 126830. [CrossRef]
131. Sun, C.; Wei, Y.; Kou, J.; Han, Z.; Shi, Q.; Liu, L.; Sun, Z. Improve spent mushroom substrate decomposition, bacterial community and mature compost quality by adding cellulase during composting. *J. Clean. Prod.* **2021**, *299*, 126928. [CrossRef]
132. Xu, Z.; Li, R.; Wu, S.; He, Q.; Ling, Z.; Liu, T.; Wang, Q.; Zhang, Z.; Quan, F. Cattle manure compost humification process by inoculation ammonia-oxidizing bacteria. *Bioresour. Technol.* **2022**, *344*, 126314. [CrossRef] [PubMed]
133. Luo, W.H.; Yuan, J.; Luo, Y.M.; Li, G.X.; Nghiem, L.D.; Price, W.E. Effects of mixing and covering with mature compost on gaseous emissions during composting. *Chemosphere* **2014**, *117*, 14–19. [CrossRef] [PubMed]
134. Rizzo, P.F.; Young, B.J.; Pin Viso, N.; Carbajal, J.; Martínez, L.E.; Riera, N.I.; Bres, P.A.; Beily, M.E.; Barbaro, L.; Farber, M.; et al. Integral approach for the evaluation of poultry manure, compost, and digestate: Amendment characterization, mineralization, and effects on soil and intensive crops. *Waste Manag.* **2022**, *139*, 124–135. [CrossRef] [PubMed]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.