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Review

Recent Trends and Advances in Additive-Mediated Composting Technology for Agricultural Waste Resources: A Comprehensive Review

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Cite This: *ACS Omega* 2024, 9, 8632−8653 **Read Online**

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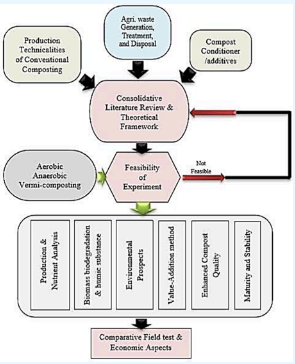


ABSTRACT: Agriculture waste has increased annually due to the global food demand and intensive animal production. Preventing environmental degradation requires fast and effective agricultural waste treatment. Aerobic digestion or composting uses agricultural wastes to create a stabilized and sterilized organic fertilizer and reduces chemical fertilizer input. Indeed, conventional composting technology requires a large surface area, a long fermentation period, significant malodorous emissions, inferior product quality, and little demand for poor end results. Conventional composting loses a lot of organic nitrogen and carbon. Thus, this comprehensive research examined sustainable and adaptable methods for improving agricultural waste composting efficiency. This review summarizes composting processes and examines how compost additives affect organic solid waste composting and product quality. Our findings indicate that additives have an impact on the composting process by influencing variables including temperature, pH, and moisture. Compost additive amendment could dramatically reduce gas emissions and mineral ion mobility. Composting additives can (1) improve the physicochemical composition of the compost mixture, (2) accelerate organic material disintegration and increase microbial activity, (3) reduce greenhouse gas (GHG) and ammonia (NH_3) emissions to reduce nitrogen (N) losses, and (4) retain compost nutrients to increase soil nutrient content, maturity, and phytotoxicity. This essay concluded with a brief summary of compost maturity, which is essential before using it as an organic fertilizer. This work will add to agricultural waste composting technology literature. To increase the sustainability of agricultural waste resource utilization, composting strategies must be locally optimized and involve the created amendments in a circular economy.

1. INTRODUCTION

Agricultural waste is any waste generated during agricultural operations, primarily crop residue and livestock waste. Because of the rising population, urbanization, and changes in consumer behavior, agricultural waste creation rises every year globally.[1,2] Most of the agricultural waste generated as a byproduct of agricultural production is released into the environment without being treated, being burned on a large scale, or being disposed of at random. This results in resource depletion, soil and water pollution, fires, as well as more serious ecological and environmental issues.[3] Agricultural waste combustion produces a lot of smoke and hazardous pollutants, primarily CO, CO_2, and NO_X and other hazardous and poisonous gases. Therefore, the critical concerns pertaining to the sustainable growth of human society is how to manage such growing quantities of solid waste. Organic garbage makes up the majority (46%) of the total solid waste.[1] Therefore, how to deal with the environmental pollution caused by agricultural waste has become a major problem that developing countries urgently need to solve. The organic portion of wastes, on the contrary, is a valuable organic resource that can be recycled and turned into value-added bioproducts by the application of different energy recovery processes.[4−6] Therefore, an adequate management of organic solid waste is essential.[2]

Conversely, the widespread agricultural practices under inorganic fertilizers has led to an acceleration in environmental contamination. The aforementioned areas demonstrate specific evidence. (1) The soil exhibits compacting, limited cultivability, and reduced capacity to function as a soil buffer. The nutritional content in the soil is uneven as a result of the excessive and unnecessary use of nitrogen (N) fertilizer, which is abundant in nitrogen, while regions dedicated to farming are

Received: August 31, 2023
Revised: January 18, 2024
Accepted: January 23, 2024
Published: February 16, 2024

https://doi.org/10.1021/acsomega.3c06516

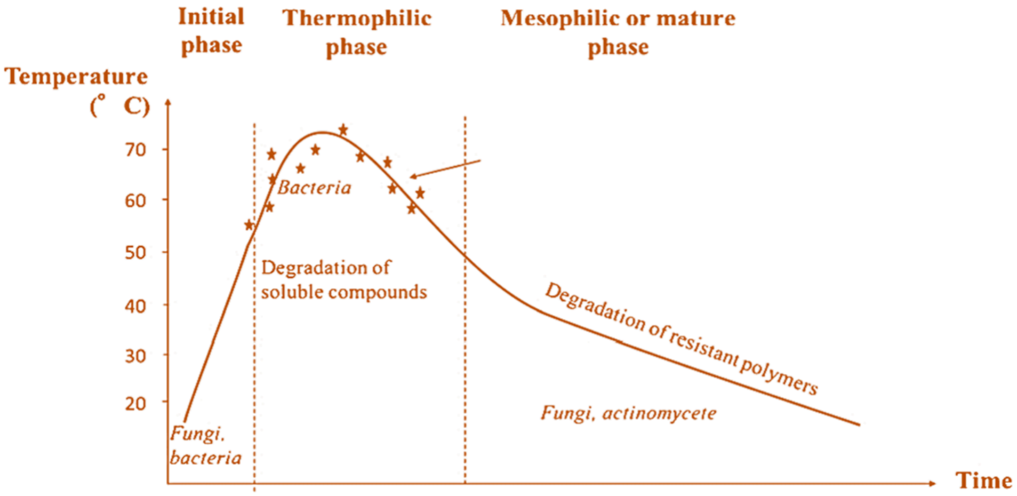


Figure 1. Composting temperature variations and the resulting microbial populations and organic molecules. Phases during which pathogen microorganisms are eliminated are marked with stars.[22]

experiencing a continual deficiency in potassium (K) and phosphorus (P).[7] (3) Both the quantity and quality of agricultural products suffer as a result of the reduction in fertilizer benefits. Food and vegetables, for instance, lack quality which evolved into a key characteristic of modern agricultural goods. (4) It contaminated the soil health, harming the populations of helpful microbes. Numerous chemicals pollute the environment in which people live and pose a major hazard to their health. The food chain is the entry point for these chemical compounds into the ecological cycle.[8,9]

The problems of improper treatment of agricultural wastes and low comprehensive utilization levels have become increasingly prominent, which has become a shortcoming of rural environmental governance. The harmless treatment and productive use of agricultural waste will minimize the release of hazardous chemicals, reducing soil, air, water, and other environmental pollution. Therefore, the transformation of agricultural waste products, including as straw, livestock waste, and poultry manure, into an organic fertilizer that is both highly effective and environmentally friendly holds significant importance in stimulating the sustainable growth of the agricultural economy and enhancing the ecological environment.[10] Combining the domestic situation and foreign studies, many applied and sustainable agricultural waste treatment technologies can be utilized and promoted such as the carbonization and activation utilization, feed utilization, biotransformation, fertilizer utilization, anaerobic composting, and aerobic/microbial composting.[11] The processes of composting and vermicomposting are two methods for converting agricultural waste into natural fertilizer through biological breakdown.[6,12,13] The resulting amendments can be utilized to increase carbon retention in soil.[14−17] Application of compost results in enhanced soil structure, decreased erosiveness, and increased water-retentiveness.[18]

1.1. Aerobic Digestion Process.

Aerobic digestion (composting) is a biochemical fermentation process that uses microorganisms to convert biodegradable organic matter into stable humus under controlled conditions. Because it does not harm the environment, especially the soil, compost/organic fertilizer is produced.[19] Compost or organic fertilizer is the result of the transformation of organic matter from an unstable condition into a stable humus substance, which does not harm the environment, especially the soil environment. The composted material experiences large changes in volume and weight throughout the composting process. Weight and volume typically decrease by 30% to 50%[19] as a result of the decomposition and conversion of volatile substances like carbon. Based on this original composting technique, the modern composting process was established and is broken down into aerobic composting and anaerobic composting. The final product is stable and pathogen- and phytotoxic-free.[20] A composting cycle includes initial activation, the thermophilic phase, and the maturation phase (Figure 1). Microbial populations mineralize sugars during the early activation, which lasts 1−3 days and creates CO_2, NH_3, organic acids, and heat.[21]

This stage raises composting pile temperature. In the thermophilic phase, temperature peaks. Composting is best at 40−65 °C, where pathogens die at 55 °C. Table 1 shows the temperature and heat duration needed to kill common pathogens during composting. Here, thermophilic bacteria degrade lignin, cellulose, and lipids.[21] Table 2 shows microorganism development at different temperatures.[23] Microbial activity decreases due to biodegradable chemical reduction, lowering temperature during mesophilic maturation. Microbial populations vary with composting pile temperature.[22,24] Bacteria predominate above 60 °C, whereas fungi are absent.[25]

Table 1. Sanitized Conditions for Various Widespread Pathogens in the Digestion Process

Pathogens	Sanitary temperature	Sanitized time
Salmonella typhi	55−60 °C	30 min
Salmonella	56 °C OR 60 °C	60 min OR 14−24 min
Shigella	55 °C	60 min
Escherichia coli	55 °C OR 60 °C	60 min OR 15−20 min
Amoeba	68 °C	60 min
Hookless striped worm	71 °C	5 min
Ancylostoma americanus	45 °C	50 min
Brucella abortus	61 °C	3 min
Micrococcus pyogenes	50 °C	10 min
Streptococcus fermentans	54 °C	10 min
Mycobacterium bovis	55 °C	45 min

Table 2. Interaction between Fermentation Temperature and Microbial Agent

Temperature/°C	Mesophilic	Thermophile	Hyperthermophile
25–38	Excited state	N/A	N/A
38–45	Inhibited state	Start to grow	N/A
45–55	Destruction state	Excited state	N/A
55–60	Bacterial flora decline	Inhibition state (slight)	N/A
60–70	-	Inhibition state (obvious)	Start to grow
>70	-	Destruction state	Growth period

As a result, temperature and the relative presence of microbes are solid indicators of the compost's development, and Figure 2 clearly shows this process. The phases of heating up, elevated temperatures, cooling, and decomposition constitute a full composting process. Different bacteria, actinomycetes, fungus, and protozoa are found in each stage. Until a stable humic material is created, the microbes utilize the agricultural waste and stage products as a source of food and energy at each stage.

1.1.1. Principles of the Aerobic Composting Process. Composting and aerobic digestion are substitutes for each other, and both processes use microbes to break down agricultural waste.[16] The type of biological waste can influence the choice of organic substrate during the fermentation process. The bacillus that is resistant to high temperatures, a lack of carbon dioxide, and oxygen is dried to create the microbial fertilizer inoculum, which can then be kept for a long period. When Xi and He[26] and Li and He[27] introduced various additions to the fermentation of biological waste, the findings indicated the inoculum's effects clearly, and within a short period of time, they had completely decomposed high-quality organic fertilizer.[28−30] The completed organic fertilizer can be used on regular farms to enhance soil quality and make it more conducive to growing "green food" and raising the quality of that food.

Aerobic bacteria, actinomycetes, fungi, etc. oxidize small fermentation substrate molecules to fuel biological growth, aeration, temperature, moisture, pH, C/N, particle size, etc. They also aid in the growth and reproduction of microorganisms, decompose a portion of macromolecular organic materials, and generate additional bacteria to advance the fermentation process. To create humus soil, which may be utilized to improve soil, the organic matter is fermented. The aerobic digestion of agricultural waste can be represented by the chemical reaction equation shown below:

Oxidation of organic matter without nitrogen.

$$\begin{aligned} &C_xH_yO_z + (x + 0.5y + 0.5z)O_2 \\ &\quad \rightarrow xCO_2 + 0.5yH_2O + \text{Energy} \end{aligned} \tag{1}$$

Oxidation of organic matter containing nitrogen.

$$\begin{aligned} &C_nH_tN_uO_v \cdot aH_2O + bO_2 \rightarrow C_wH_xN_yO_z \cdot hH_2O + dH_2O \\ &\quad (\text{gas}) + cH_2O\ (\text{liquid}) + fCO_2 + gNH_3 + \text{Energy} \end{aligned} \tag{2}$$

shows the formation of cellular substances.

$$\begin{aligned} &n(C_xH_yO_z) + NH_3 + (nx + 0.25ny - 0.5nz - 5x)O_2 \\ &\quad \rightarrow C_3H_7NO_2\ (\text{Cytoplasm}) + (nx - 5)CO_2 \\ &\quad + 0.5(ny - 4) + H_2O + \text{Energy} \end{aligned} \tag{3}$$

Oxidation process of intracellular substances.

$$C_3H_7NO_2 + 5O_2 \rightarrow 5CO_2 + 2H_2O + NH_3 + \text{Energy} \tag{4}$$

Most of the time, aerobic composting of agricultural waste takes place in an environment that is natural. Temperature, moisture, pH, C/N ratio, and particle size affect rapid aerobic composting fermentation.[21,31] Microorganisms and agricultural waste type are internal factors, while ventilation, oxygen supply, temperature, moisture content, pH value, C/N, particle size, etc. (Table 3) affect aerobic composting.[31−33]

1.2. Limitations of Conventional Agricultural Waste Composting. Agricultural waste contains a lot of organic matter and high levels of nitrogen, phosphorus, and potassium, which are required for crop growth. Common processes for turning agricultural waste into organic fertilizer include aerobic composting. Composting is a more effective way to treat agricultural waste than other methods because it improves soil structure and acceleration of the geochemical process pertaining to the availability of essential nutrients for crops, along with the enhancement of soil fertility levels.[39]

On the other hand, traditional composting methods exhibit several drawbacks. These include a substantial requirement for

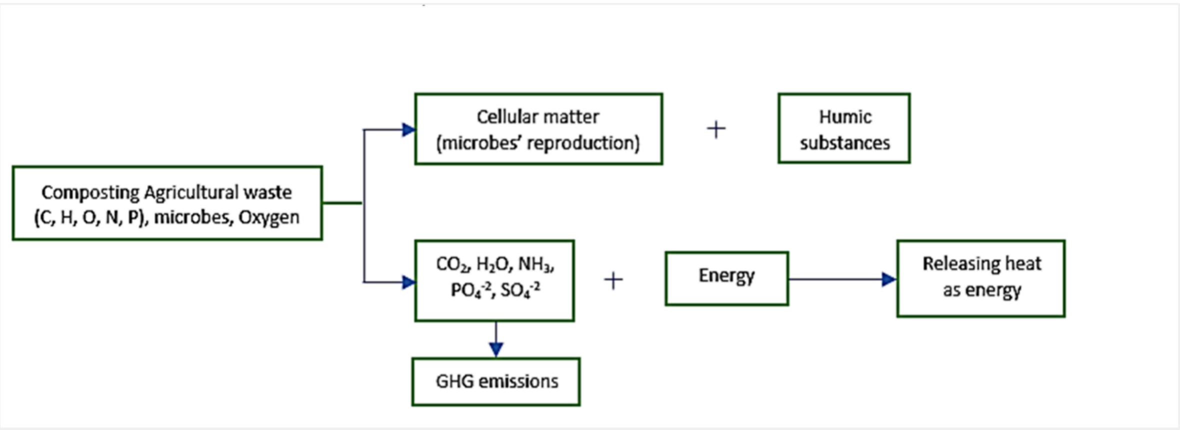


Figure 2. Schematic diagram of the aerobic composting reaction process.

Table 3. Various Compost Factors and Their Significance

Factor		Significances	Literature
Properties of compost substrates	C/N ratio	Low C/N ratio substrates lose nitrogen by NH_3 volatilization, while high C/N ratio substrates compost more slowly.	33
	Biochemical composition	It demonstrates their ability for biodegradation, or stable feedstocks are difficult to disintegrate during composting.	32,34
	Particle size	Small particle substrates—likely to encourage the formation of clumps.	21
		Large particle substrates— difficult to disintegrate.	
	Moisture	Acts as a conduit for the transfer of nutrients within the compost mixture and has an impact on gas exchange within the compost heap.	31
	pH	Influences NH_3 volatilization in addition to microbial activity.	35
Environmental factors	Temperature	Indicates the level of microbial activity and the stage of composting. High temperature is beneficial for compost sanitary.	33,36
	Aeration	Compost aeration has a substantial impact on the quality of the compost as well as the GHG emission.	37,38

surface area, an extended fermentation period, significant emission of malodorous substances during the fermentation process, suboptimal product quality, and limited demand for substandard products. The negative reputation places restrictions on how widely the procedure can be used and promoted. Moreover, conventional aerobic composting is occasionally ineffective for decomposition due to the physiochemical characteristics of organic waste. These properties reduce composting temperature, which reduces decomposition and sanitation. NH_3, H_2S, and other pollutants can also occur from conventional aerobic composting.[40] Furthermore, the loss of organic nitrogen and carbon during the composting process is significant. However, by raising the treatment temperature above 70 °C, pathogens in animal manure can be destroyed in just 10 to 30 min.[41]

The presence of elevated levels of nitrogen in livestock manure gives rise to a significant issue in conventional agricultural waste composting, namely, the release of various nitrogen compounds into the atmosphere; i.e., NH_3, N_xO, NO_x, CH_4, VOCs, and other molecules that are chemically related to these are all examples of these compounds. The primary component of the gaseous emissions is NH_3, and conventional composting significantly wasted nitrogen resources by emitting ammonia at a rate of between 70 and 88%.[42] These odor emissions are hazardous to the environment because NH_3 is offensive, irritating, and smelly. The compost's value as a fertilizer is also reduced by the NH_3 loss. Compost quality has been significantly impacted by the loss of carbon and nitrogen, and the acidification induced by the released ammonia gas has decreased biodiversity. A number of environmental issues have been brought on by the greenhouse gases created, which have increased global warming.

1.3. Research Purpose and Significance. Considering the preceding discourse, it is vital to do research on expeditious and innocuous approaches for generating compost of high quality. An enhanced and environmentally viable aerobic composting process holds significant potential for effectively managing the substantial volume of valuable organic waste. Based on the domestic and foreign research on agricultural solid waste composting, it is worth exploring the composting of additives and agricultural straw waste into resources, which is also important for the optimization of agricultural straw waste composting technology and the enhancement of organic fertilizer standards. To expedite and sustain thermophile temperature levels, composting practices employ a range of physicochemical and microbiological techniques. These techniques include the incorporation of bulking agents, the regulation of ventilation, and the application of compost additives/conditioners during the initial phase of composting.[43] The reduction in the carbon-to-nitrogen (C/N) ratio inside the compost matrix is a significant factor that contributes to the emission of greenhouse gases. Therefore, carbon-rich additives (such as wood chips, mushroom residues, rice bran, biochar, minerals, etc.) in the composting system have become an important way to regulate nitrogen loss and control greenhouse gas emissions.[44,45]

In order to explore the impact of additives on the composting process of agricultural waste, as well as the resultant compost quality and microorganism composition, this study offers a novel approach and theoretical framework for enhancing the optimization of agricultural solid waste composting. This study examines the composting process of normal agricultural straw waste, with the addition of biochar/mineral as a conditioner. The aim is to investigate the impact of these additives on the microbiological, chemical, and physical parameters of the composting system. The present study aimed to investigate the variations observed in composting techniques, the quality of compost produced, and the reactions exhibited by crucial microbial populations upon the introduction of compost additives during the composting process.

This research study's value and significance can also be seen in its useful results, which have provided valuable pieces of reference information for developing effective strategies to produce quality organic fertilizer from agricultural wastes within a short duration. Thus, this study's results could serve as vital reference information for effective aerobic composting systems, operational guidelines, optimization of process parameters, process scaling up to a large industrial scale, resource recovery/recycling, and efficient waste management. Moreover, the results of this study have, without doubt, contributed immensely to the academic body of knowledge and to bridging the existing research gaps in the field of research studies.

1.4. Development Approaches in Aerobic Composting Technology: Additive-Mediated Composting. In accordance with the discussion above, it is crucial to research quick and risk-free ways to create high-quality compost. The direction of optimizing the country's agricultural solid waste composting technology is mainly to shorten the composting time, reduce the generation and emission of waste gas from composting, and reduce the composting quality deterioration caused by the loss of composting nutrients.[46] Thus, improving the composting process for these issues is crucial for agricultural waste treatment and disposal. Temperature, pH, carbon−nitrogen ratio, seed germination index, ammonium

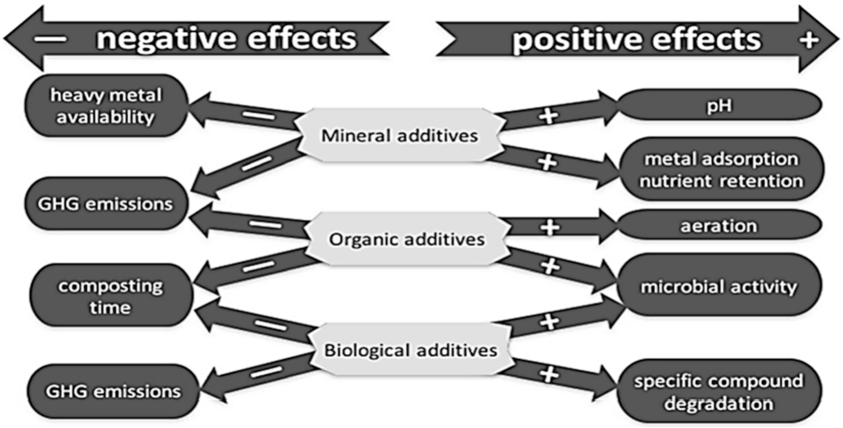


Figure 3. Prospective consequences, both good and bad, of biological, organic, and inorganic additives. When selecting an additive, a choice between these consequences must be established.

nitrogen, and nitrate nitrogen all affect composting quality and smoothness.[47] Due to high refractory cellulose, agricultural waste composting is slowed by a lack of organic materials. Additionally, most nutrients like carbon, nitrogen, and others are lost during composting, lowering compost quality. Due to high composting temperatures and insufficient carbon sources in the substrate,[48] nitrogen is volatilized and lost as NH_3, NO, N_2O, and N_2.[49] Moreover, NH_3, NO, and N_2O are polluting gases; NH_3 is the main source of odor; and N_2O is a greenhouse gas.[50]

Therefore, adding readily available carbon sources/organic matter to the composting system of agricultural straw waste has become a feasible optimization method. Exploring the effect of adding readily available carbon sources (OM) and inorganic matter on the composting process, the effect of nitrogen retention and the effect of functional microbial communities optimize the agricultural waste composting. Compost conditioner refers to additives that are added in small amounts (relative to the mass of raw biomass materials in compost) to significantly optimize and adjust the composting process or composting products (Figure 3). Conditioners include some cheap crude chemical additives (ferrous sulfate, sodium humate, superphosphate),[51] biochar,[52] and carbon-rich biomass (corn stalks, sawdust, waste mushroom culture substrate).[53]

These additives can be categorized into three distinct groups: mineral, organic, and biological.[21,54]

(1) Organic additives: The C/N ratio of many livestock and poultry manures is relatively low, and it is added with various carbon-rich substances to the pile to adjust the C/N to 25:1–35:1.[55] Wei and Yuan[56] used corn stalks to adjust the initial C/N of cow dung compost to 24.84, which is conducive to the rapid decomposition of compost. Li and Yuan[57] used straw and urea to adjust the carbon–nitrogen ratio of the pile and found that straw can improve the ventilation of the pile, promote the decomposition of the pile, and reduce the loss of nitrogen. Mei and Li[58] found that adding straw to manure compost can increase the C/N ratio of the compost and reduce the nitrogen loss rate. Zhuang and Shan[59] found that adding sawdust to cow dung compost can increase the C/N ratio, porosity, and degradable carbon content of the compost and promote microbial composting. A highly stable organic composting component, bio charcoal, a pyrolysis output with a high aromatic content, is also gaining popularity.[60,61] Composts' ability to retain carbon can be enhanced through biochar, which would help to slow global warming.[62,63] Biochar has the functions of improving the quality of composting, adsorption of pollutants, and reducing greenhouse gas emissions. It has been a research hotspot in the field of compost additives in recent years.[64]

(2) Inorganic/mineral additives: Microbial reproduction and metabolism depend on pH. The optimal pH for methanogens is 6.5–7.5. It will struggle to thrive below pH 6, reducing methane emissions.[65] Feces acidification increases hydrogen ions, inhibits NH_4^+-N to NH_3, and prevents nitrogen loss.[66] Kupper and Häni[67] showed that compared to the control group spring, summer, and autumn NH_3 emissions fell 66%, 44%, and 71%. Aboltins and Melece[68] conducted a meta-analysis of 89 literatures on greenhouse gas and NH_3 emission reduction in the process of livestock and poultry manure treatment and concluded that manure acidification can simultaneously reduce CH_4, N_2O, and NH_3 emissions. Wang and Xue[69] conducted a systematic assessment of the greenhouse gas and NH_3 emissions of the entire cow or pig manure treatment chain and found that the acidification of biogas slurry can reduce CH_4 emissions by 87%, which can reduce the greenhouse gas and NH_3 emissions of the entire treatment chain. In addition to improving compost porosity, temperature, oxygen content, methanogen inhibition, and CH_4 emissions, high-porosity, high-specific-surface-area mineral additives can adsorb nitrate nitrogen and N_2O in the pile, reducing N_2O emissions.[70] These additions benefit from their wide availability and low cost as industrial waste.[71] Adding more than 10% of the dry weight (more than 4% of the wet weight) of calcium super phosphorus to pig manure composting reduces NH_3, CO_2, CH_4, and N_2O emissions and improves carbon and nitrogen storage, according to Xie and Tran.[72] Li and Wang[73] and Mei and Li[58] reported that when calcium superphosphate was added to chicken dung NH_3 emissions dropped 31.1% compared to the control. Few studies have examined carbon, nitrogen, and humic material changes during organic–inorganic co-composting, despite the necessity of using fertilizers to prevent nitrogen loss. The production method, biological effectiveness of fertilizers, and nutrient content of compost may all benefit from clarification of these changes. How the addition of a mineral additive to organic–inorganic aerobic co-composting affected the amounts of carbon, nitrogen, and humic compounds was investigated.[74] The data showed that adding inorganic fertilizers did not affect compost fermentation. This ingredient

Table 4. Overview of the Different Additives Used in Agricultural Waste Aerobic Composting and Their Major Effects

Feedstock	Additives	Influences
Sewage sludge + rapeseed marc	Bamboo biochar (600 °C) 0%, 1%, 3%, 5%, 7%, 9% (FW)	Adding 9% biochar into the composting feedstock decreased TN loss by 64.1% and produced more stable Cu^{2+} and Zn^{2+} compost.[132] Improved porosity and compost maturity.[121]
Poultry waste	Pine chips biochar (400 °C) @ 0%, 5%, 20% (DW)	The increase in biochar addition rates resulted in higher pH and peak pile temperatures. A fall in NH_3 emissions and 52% less total N loss.[42]
Poultry waste	Wood biochar (300–450 °C) @ 50% (FW)	Composting had a major effect by the addition of biochar. Higher biological waste degradation, compost maturityk and less odor emissions and N loss.[60]
Poultry manure + apple pomace, rice straw, and oak bran	Wood biochar (400–600 °C) 2% (v/v)	Increased the decomposition of organic matter despite a decline in microbial biomass. A wide variety of fungus in compost added with charcoal.[133]
Cattle manure + apple pomace, rice straw, and rice bran	Wood biochar (400–600 °C) 20% (w/w)	The increased aeration resulted in decreased methanogens (McrA) while methanotrophs (pmoA) grew.[37]
Poultry waste + sawdust	Nutshell, hard wood shaving, chicken litter @ 5%, 10% (fresh weight basis)	This produced increased respiration rates which showed higher OM degradation and increased microbial activity. The compost showed lower NH_3 emissions with enhanced maturity in compost.[111]
Poultry waste + tomato stalk	1% commercial biochar	Adding biochar increased pile's temperature and extended thermophilic phase and exerted a less significant impact on bacterial diversity.[120]
Sewage sludge + wood chip	Woody material 4% (wet weight basis)	Increasing pile temperature and disintegration of organic matter, while showing lower NH_3 emissions in the first week of composting.[134]
Sewage sludge + rice straw	Wood (500–600 °C) 6% 12%, 18% (wet weight)	Due to increased porosity of sewage sludge, OURs improved and accelerated humification and degradation.[46]
Poultry manure + barley straw	Holm oak biochar (650 °C) 3% (wet weight)	Holm oak biochar improved aeration, reducing composting time by 4 weeks (20%) and increasing stabilization and detoxifying while promoting organic matter decomposition. There is no visible impact on CO_2, CH_4, or N_2O emission and reducing N loss by 15%.[123,135]
Poultry manure + wheat straw	Woodchips 5%; 10% (wet weight)	The addition of woodchip biochar has shortened composting time due to higher pile peak temperature.[83]
Poultry manure + rice straw	Rice straw (400–500 °C) 2% (dry weight)	Modified microbial genetic makeup and increased C catabolic capability.[136]
Cow manure/poultry manure + apple pomace, rice straw, and rice bran	Hard wood (550 °C) 10% (v/v)	Stability and recalcitrant nature of the compost were improved with microbial communities. Improving FA fractions.[137]
Municipal solid waste + green waste	Holm oak (650 °C) 10% (dry weight)	It accelerated the decomposition of organic matter and reduced the emission of GHGs. Decreased N losses and greater concentration of P that is readily available.[114]
Poultry litter + sugar cane straw	(Green waste + poultry) biochar (550 °C) 10% (dry weight)	Reduced total GHG emissions, improved N retention, and decreased NH_3 emissions because the adsorption capacity of biochar may fix the nutrients. A 60% less loss of NH_3 and 51% reduction in TN losses.[138,139]
Sewage sludge + wheat straw	Wheat straw 2%, 4%, 6%, 8%, 12%, 18% (dry weight)	The amendment encouraged humification and the decomposition of organic substances with low N losses. The heavy metal and emission of GHG (NH_3, CH_4, and N_2O) were decreased by 58.03–65.17%, 92.85–95.34%, and 95.14–97.28%, respectively, but CO_2 emissions rose.[140,141]
River sediment + rice straw, bran, and vegetable	Rice straw (500 °C) 2%	Rice straw affected the diversity of the bacterial community and suppressed the availability of heavy metal.[142,143]
Layer manure + saw dust	Corn stalk; Bamboo; Woody; Layer manure; Coir (450–500 °C) 10% (wet weight)	The nitrification and pile temperature were increased, and the emissions of NH_3 and CH_4 were reduced.[144,145]
Fishpond sediment + green waste, rock phosphate	Coir (450 °C) 0%, 20%, 30% (v/v)	A 24 day reduced compost production time, improved nitrification, enzyme activity, microbial population, nutrient content, and better grade compost.[35]
Chicken manure + tomato stalk	Wheat straw 1% (w/w, wet weight)	Quick thermophilic phase attainment, higher temperature, and longer duration. Raising germination index.[120]
Green waste + spent mushroom	Coconut husk fiber 20–30% (w/w, dry weight)	Improving particle size distribution and the free air space. Increasing the nutritional and CEC contents.[115]
Cow dung + hydrilla + sawdust	Wood 5% (w/w, wet weight)	This showed a prolonged thermophilic phase with 39% reduction in air-filled porosity and a 45% increase in TN.[146]

Table 4. continued

Feedstock	Additives	Influences
Sewage sludge + wheat straw	Wheat straw 8–12% (w/w, dry weight)	Speeds up the humification process with a decrease in the odorous index and volatile fatty acids[147]
Sewage sludge + paddy straw	Wood 6–18% (w/w, wet weight)	A rise in the rate of O_2 absorption. Adding 13–26% more FA-like chemicals and 15–30% more HA-like compounds, respectively.[148]
Poultry manure + rice husk + apple pomace	Oak 2% (v/v)	The increased rate of enzymatic activity accelerated the humification process by 10% by increasing HS carbon.[133]
Manure	Charcoal 9% and 28%	With pH drop and greater GI, it accelerated the thermophilic phase change. Cu and Zn mobility decreased by 35%, 65%, and 39%, while the TKN loss decreased.[105] Reducing NH_3 and CH_4 losses. A 27–32% drop in CO_2-equivalent GHG emissions.[38] A 6.9%–7.4% increase in C–CO_2 emissions.[83]
Manure	Biochar 50% (fresh weight)	Biochar significantly improved humification. Maintaining the nitrogen and organic materials in compost.[60]
Manure	Chestnuts, leaf litter (25%)	Except for Zn, the co-composts' heavy metal content was within the allowable limit.[149]
Manure	Phosphogypsum 10–30% dw	In manure composted with mineral additives, TC, TN, and mineral N in the finished compost product were unaffected. The EC and TS content increased while pH decreased. The composting showed a significant reduction in CH_4 emissions. By modifying the nitrification process, the N_2O emission was decreased. There is no negative impact on the germination index or the breakdown of organic materials.[150,151]
Manure	Compost inoculum 33% dw	Accelerating the succession of the microbial community which reduces the time needed for composting. After the thermogenic phase, harmful bacteria in compost are eliminated.[152]
Manure	Biochar, sawdust 5%, 10% (wet weight)	This resulted in higher respiration rate, increased bacterial activity, and reduced nitrate leaching and NH_3 emission.[111]
Manure	Ash 0–20%	Ash amendment reduced the amount of nitrogen loss, quick OM mineralization, and rise in humic acid. The improved aeration of pile produced less odorous fumes.[153]
Manure	10%, Straw	The highest temperature and organic matter degradation.[154]
Manure	Zeolite 0.4, 1.0, 2.5, and 6.25%	Considerable fall in the concentration of ammonia nitrogen. The substrates' temperature remained in the thermophilic range. Zeolite showed 60% less ammonia volatilization and pH less than 5. A decrease in soluble P because of the development of low solubility and slow release of the N source.[155,156]
Manure	Bentonite 0%, 2.5%, 5%, 7.5%, and 10% dw	No significant variations in pH and temperature but promoted OM decomposition. The TKN content increased while lowering the C/N ratio. Decrease in the amount of extractable heavy metals.[97]
Manure	Rock-P 0%, 2.5%, 5.0%, and 7.5% (w/w, dw)	The amount of bioavailable Cu fractions decreased. The exchangeable and reducible fractions contained zinc. By complexing the metal ions with inorganic components, you can decrease the availability of metal.[157]
Manure	Rice straw 25% (w/w, fresh weight)	Increased the quantity of N and P while lowering the amounts of NH_4^+–N and soluble P fractions. A decline in labile P and increase in pH, a decline in OM, and a reduction in the C/N ratio.[158]
Manure	Elemental S (2 mol H^+ mol^{-1} S)	There was a 90–95% reduction in the loss of N from aerobic conditions due to ammonia (NH_3) volatilization. There was a 60% reduction in NH_3 loss.[106]
Manure	Rock-P 4% fw	Maximum water-soluble P and K release. Improved P and K soil fertility status, higher yield, absorption, and nutrient recoveries. A rise in the amount of accessible phosphorus (41% of the total phosphorus).[159,160]
Manure	28%, 3% Rock-P, phosphogypsum	Significant increases in accessible P levels (13 times) were seen in soil. Soil function was altered, and soil biochemical characteristics were improved by the application of P-enriched OMC.[161]
Manure	Mg hydroxide, phosphoric acid 3.8%, 7.3% and 8.9% of dw	Initial N content loss to total nitrogen loss fell from 35% to 12%, 5%, and 1%. The final compost increased total nitrogen by 10–12 g/kg and NH_4^+–N by 8–10 g/kg. Mature was best. Best Mg and P salt dosages are 20% of starting nitrogen.[162,163]
Manure	5%, 20% fw biochar	Temperatures and CO_2 reached at significantly greater levels. Poultry litter that has been modified with biochar breaks down more quickly. Ammonia emissions decreased by as much as 64%. Losses of total N were decreased by up to 52%.[42]
FW	50% fw sawdust	Faster acidification and composting timeframes and a lower pH upon completion. As a result of increased airflow through the particles, the pace of composting quickened and temperature increased.[96]
FW and GW	Ash (8%, 16%) and (25%, 50%)	The addition of ash had no negative effects and met with all legal requirements. Measurements of soil respiration showed that composts with additives performed better.[164] Ash led to a 75% increase in the volume of water that could be stored. As basal respiration, organic, soluble, and microbial biomass carbon levels increased, the activity of the enzymes b-glucosidase, L-asparaginase, alkali phosphatase, and arylsulphatase all reduced in the composted products.[98]
FW	Microbial inoculum (500 mL solution (1:20))	Development of stable, mature compost. Within a week of the microbial inoculum, the thermophilic phase was produced. The germination index (>80%) and self-heating test.[110]
FW	Biochar (300–450 °C) 10%, 15% (w/w)	Enhanced the physiochemical makeup of the finished compost and the composting process. Attained the thermophilic temperature quickly, which affected OM degradation by 14.4–15.3%, NH_4 concentration by 37.8–45.6%, and NO_3 concentration by 50–62%.[61]
FW	Coal fly ash (25%, 33%, 50%), lime (2%, 4%)	Additives inactivated the pathogens, maintaining a pH of 12 for around 4 days. Effective in minimizing poststabilization regrowth and devitalizing the pathogens.[100]
FW	Cornstalks, sawdust, spent mushroom 15% (5% each)	Compost achieved the highest maturity (germination index rose from 53% to 111% and the C/N ratio dropped from 23 to 16). Minimal effect on NH_3 emissions but reduced leachate formation, CH_4, and N_2O emissions. Reduced overall greenhouse gas emissions (to 33 kg CO_2-eq t^{-1} dry matter).[45]
FW	100 g of Na acetate	Acetate raised the pH level to a value between 5.2 and 5.5. A favorable impact on organic material degradation and reducing propionic and butyric acid generation.[165]

Table 4. continued

Feedstock	Additives	Influences
GW	Biochar, clay 10%, 25%, and 50%	Biochar reduces (44%) carbon mineralization during co-composting and produces lower emissions of CO_2.[166]
GW	10%, Rock-P, sediment	There was an increase in nitrogen oxide emissions but a decrease in methane, ammonia, and hydrogen sulfide emissions of about 35.5−65.5%. During the composting of manure, the overall emissions of greenhouse gases (GHG) were reduced by about 34.7%. Produced more humic acid, as evidenced by the E4/E6 ratio. Delayed biological organic matter decomposition and created mature compost with increased electrical conductivity.[167]
GW	Jaggery, fly ash (5% each)	Additives showed a big impact on cellulose activity and microbial development. The C/N ratio was reduced by more than 8%.[85]
GW	Biochar (20%, 30%), spent mushroom (35%, 55%)	Biochar boosts compost nutrients. Improved compost's dehydrogenase activity, temperature, particle size distribution, open air space, cation exchange capacity, nitrogen transformation, organic matter degradation, humification, element concentrations, and seed germination toxicity.[115]
MSW	Bagasse, paper, peanut shell, sawdust (10−40%)	Bagasse biochar has optimized the moisture up to 60% and produces more FAS.[102]
MSW	Rice straw 10%, 20%, and 30%	Decrease in emissions of sulfur compounds that are noxious. Decrease in emissions of VFAs, alcohols, aldehydes, ketones, aromatics, and ammonia.[168]
MSW	5% and 10% of Zeolite	The finished compost's ammonia content decreased. The rates of ammonia uptake were 74.94 and 87.98%.[169]
MSW	40% (w/w) of reed straw, 12% zeolite, plastic tubes, woodchips (50% each), and inoculum (2.5 and 5 mL kg^{-1} dry MSW)	Range of cumulative emissions of N_2O, CH_4, and CO_2 was 92.8, 5.8, and 260.6 mg kg^{-1} DM to 274.2, respectively. The range of cumulative NH_3 emission was 3.0 to 8.1 g kg^{-1} DM.[170] The emission factors given have lower values.[171] Increased the rate of maturity and humification.[172]
SWS	12% and 1% Biochar, lime 10%, 15%, 30%, and 1% zeolite and lime	Accelerated disintegration rate, decreased the emission of N_2O, CH_4, and ammonia, and greater levels of the substances fulvic acid (3.79%) and humic acid (17.23%). HM bioavailability was successfully decreased (34.81% Cu, 56.7% Zn, 87.96% Pb, and 86.5% Ni). High mature compost with increased nutrient concentrations in compost by increasing the adsorption of ammonium ions and decreasing ammonia loss and N_2O emission.[36,173]
SWS	Bamboo charcoal @ 0%, 1%, 3%, 5%, 7%, 9% (w/w)	Considerably lessen nitrogen loss with the total nitrogen loss decreased by 64.1%. Reduced up to 44.4% and 19.3%, respectively, in the mobility of Cu and Zn in the sludge.[132]
SWS	Woodchips, rice husk @ 1:1 to 1:4 (biosolids:woodchips)	Compost pore space, oxygen, operating temperature, and heavy metal concentrations were according to CCME (1996) standards.[174]
SWS	Yeast inoculum (8.13×10^7 and 5.37×10^6 CFU/g-ds)	During the heating stage, raw materials and acetic acid were degraded.[91]
SWS	5%, 10%, and 15% Coal fly ash and 1.5% and 3% lime	The 28-day composting period could be shortened (composting time by 35%) while increasing the breakdown efficiency by high pH. The amount of heavy metals was within the permitted range.[100]
SWS	25%, 33%, and 50% Coal fly ash and 2% and 4% lime	Bacterial colony was totally rendered inert. Slowed the regrowth after stabilization.[175]
SWS	Lime 2.0% (w/w)	Percentage of compounds like humic acid rose from 20.5% to 40.9% and 20.6% to 32.6%, respectively, through expediting the maturation process and improving the transition of organic matter. The copper's transformation was only marginally impacted, and zinc's transformation from exchangeable and reducible fractions to oxidizable and residual fractions was improved.[176]
SWS	25% Zeolite	Zeolites completely eliminated Ni, Cr, and Pb, as well as a sizable portion (more than 60%) of Cu, Zn, and Hg. Low metal concentrations (<1 mg/kg) were found in zeolite leachates.[177]
SWS	20% Red mud 30% fly ash	Germination index and electric conductivity both rose, whereas the pH and total organic carbon decreased. Sludge's toxicity was eliminated, and its stabilization was expedited. By raising the residual fractions, the amount of heavy metals overall was decreased.[178]
Sewage sludge	10% Coal fly ash and 20% phosphate rock	The earthworm development, reproduction, and metal concentrations (apart from Zn and Cd) were all significantly greater. The mixtures' concentrations of total metal and total organic carbon (TOC) decreased.[179]
Rice straw	Red mud, 25 g (w/w)	Significant changes were seen in the pH, water extractable organic carbon (WEOC), and total organic carbon (TOC). The heavy metals that have had the greatest efficiency loss. Following the addition of the additives, the microbial biomass in the treated soil rose.[180]
Chicken manure + sawdust	Straw biochar (0.42 cm^3/g pore size) 25% (w/w, wet weight)	The cornstalk biochar, free load bacteria, mixed load bacteria, and separate load bacteria groups reduced NH_3 by 12.43%, 5.53%, 14.57%, and 22.61%, respectively. Total nitrogen loss, electrical conductivity, water-soluble carbon, and ammonium nitrogen decreased. Increased seed germination, microbial diversity, and lactic acid bacteria during composting.[181]

increased compost bin temperature, pH, and oxygen, speeding organic−inorganic co-composting fermentation.[75]

(3) Biological agents: The inoculation of biological agents can promote compost maturity, shorten the fermentation time, and help the nitrogen preservation and harmlessness of compost.[76] The microorganisms in the biological agent can convert a large amount of NH_4^+-N in the manure of livestock and poultry through nitrification into nitrate and then generate N_2 through denitrification, and NH_4^+-N can also be fixed into microbiological protein nitrogen, thereby reducing NH_4^+-N content, reducing the synthesis of NH_3.[77] Zhou and Liang[78] added a genetically enriched stable microbial community CC-E in feces from cattle, and the amount of NH_3 emissions within 20 days after addition to the heap was reduced by 63% compared with the control. Mao and Zhang[79] found that bamboo charcoal was compounded with two kinds of bacterial powder and then added to the manure pile, and the peak emissions of CH_4, N_2O, and NH_3 were significantly lower than those of the control. Wang and Xu[80] believed that adding biological carbon composite bacteria to pig dung could significantly reduce NH_3 and N_2O emissions: they decreased by 70.54% compared with the control group, and N_2O emissions decreased by 29.01%, which enhanced the carbon and nitrogen storage effect of the pile.[81,82]

1.5. Research Trends of Additive-Mediated Aerobic Composting. Through introducing an inoculum or organic or mineral components that alter aeration, temperature, moisture, pH, nutrients available, etc. during the composting process, additives can directly or indirectly modify the indigenous microbial community (Table 4).

1.5.1. Temperature Profile. The composting process is significantly influenced by temperature, which not only reflects the level of composting and the growth rate of microorganisms but also reduces pathogen hazards in living organism-derived materials.[83,84] When microbial activity is stimulated by additives, the thermophilic phase commences early and lasts longer than would be the case with conventional composting.[15,85,86] Commercial components like zeolite, kaolinite, chalk, ashes, and sulfates or biochar accelerated agricultural and food waste composting by 2−3 weeks.[87] After 50−60 days, biochar-modified compost stabilized.[61] Biochar, zeolite, jaggery, and polyethylene glycol raise composting temperatures quickly in animal dung, food waste, and green waste.[85,88,89] Similar temperature trends have been found in composting with biological or organic additives.[90,91] These additions may accelerate temperature rise due to increased microbial biomass and activity. Research has indicated that throughout the composting process of the same material the temperature rises rapidly after adding biochar to the compost, generally can enter the high temperature period 6−7 days in advance, prolong the high temperature retention time, promote the rapid degradation of organic matter in the compost, and significantly accelerate the composting process.[42,64,88] This may be because the rich pore structure of biochar provides a favorable environment for microbial activities, and enhanced microbial activities release heat, which increases the temperature of the pile.

1.5.2. Moisture Content of the Matrix. The oxygen intake, microbial activity, and decomposition rate of composting depend on moisture. Therefore, an adequate moisture content minimizes the time it takes for composting to mature.[21,92] A range of around 50−60% of water is thought to be the optimum amount of water for organic matter biodegradation.[55,93] High humidity, however, could encourage anaerobic conditions and odor development during composting. Because they can partially absorb leachate, fibrous materials[94] are utilized as bulking agents to reduce organic waste moisture.[94,95] Air flow through sawdust particles increased water absorption and degradation, according to Chang and Chen.[96] Water losses may be reduced by the inclusion of materials having strong water retention capabilities, like clays. Due to bentonite's ability to swell, Li and Wang[97] demonstrated that the buffered initial moisture decrease and improved water retention capacity when composting green wastes with ash[98] or adding phosphate rock[35] to green waste composting improved water retention capacity and buffered initial moisture loss. Eggshells may reduce biological activity but not water retention. However, research shows that biochar composting increases the moisture content of the same material. A biochar-containing system has more moisture due to its high water holding capacity (WHC).[99]

1.5.3. pH Value. The pH level of the pile has a significant impact on the environment in which microorganisms can survive and regulate the movement of heavy metals inside the pile. Microbial activity is influenced by pH variations during composting, resulting in decreasing initially and an increase in the latter stages.[31] Adding pH-raising chemicals to acid feedstocks such as food waste improves composting.[100] A study found that adding an inoculum community raised composted food waste pH from 4.3 to 6.3.[90] Higher biological activity breaks down acids and organics. Bulking materials including bagasse, paper, peanut shells, sawdust, and Ca-bentonite raise composting pH like fly ash, lime, or red mud.[101−103] Alkaline additions may slow metabolism. Initial sludge cocomposition with 25% fly ash had less thermophilic bacteria, according to Wong and Fang.[104] Because bamboo charcoal or zeolite absorbs ammonia from organic nitrogen mineralization, these additives may minimize pH rise during the thermophilic phase. Lower pH may limit nitrogen loss because ammonia volatilizes at high pH.[105] Finally, adding elemental sulfur to poultry manure composting significantly decreased pH,[106] primarily as a result of H_2SO_4 being produced during elemental sulfur's oxidation, which raised the proportion of H^+ ions.

1.5.4. Pile Aeration. According to Gao and Li,[107] forced aeration through pipes[108] and mechanically moving the composted material[38,109,110] are the best ways to provide the appropriate aeration needed for composting. Biochar, residual crops straw, woodchip or sawdust, and crushed branches boost the composting pile's natural aeration and porosity, reducing the cost of pile turnover or forced aeration.[88] The presence of bulking agents, which have a low moisture content and a large number of pores, results in the formation of inter- and intraparticle voids.[102] The inclusion of biochar, which has a porous structure, has the potential to significantly improve the aeration of compost.[89] There exists a clear correlation between the surface area that is subjected to microbial attack and the biological oxidation rate.[33]

1.5.5. Organic Matter. According to research, biochar promotes more to the decomposition of soluble organic carbon during composting than it does in systems with no biochar addition.[111] The incorporation of biochar to organic matter that has been decomposed enhances the porosity of the material because of the enormous porosity and variety of pores in biochar. Through the stimulation of microbial and enzymatic activity, biochar also effectively expedited the decomposition of organic matter.[112,113] The absorption of molecules like NH_3, NH_4^+, H_2S, and SO_4^{2-} by biochar is the cause of the acceleration of the rate of decomposition of organic matter.[114] Functional groups on biochar's surface increased the chemical absorption of nutrients and organic carbon, minimizing effluent loss from compost.[115] Biochar also increased compost aeration, aiding heap operations. Wang and Tu's[116] and Awasthi and Wang's[36] experiments on sewage sludge−wheat straw compost (biochar from wheat straw, 600 °C) corroborated this finding. Biochar-enriched compost yields higher humus acids.[36,116]

1.5.6. Microbial Biodiversity. In composting, various types of bacteria play different roles in the degradation of lignin. Due to the synergistic effect of various types of bacteria, lignin completes the entire chemical process of degradation in composting. Therefore, in the process of composting, it is necessary to understand the amount, diversity, and group structure of the microbial ecosystem in the compost. Due to their nutrient and readily available carbon levels, additives affect compost microbial populations via affecting pile temperature, moisture, and aeration.[117] In the enzymatic decomposition of cellulose during the composting of green wastes, the additive increased the quantity of microorganisms.[85] Fishpond sediments, wasted mushroom substrate, and charcoal were also added with similar outcomes.[115,118−120] Biochar regulates moisture and aeration, which affects composting temperature, and its porous nature may stimulate microbial activity.[89] Biochar application rates above 20% can slow organic material biodegradation.[121]

1.5.7. Key Nutrients. The inorganic nitrogen in compost transforms during the process from NH_4^+ to NO_3. The bioavailability of nitrogen declines as the process proceeds onward.[122] According to a study by López-Cano and Roig,[123] composting two-phase olive mill waste with sheep dung at 650 °C with 4% (dry weight) oak wood biochar helped nitrification. Biochar slows ammonification and creates a nitrifying bacteria-friendly environment. Biochar increased compost nitrogen. With biochar, NH_4^+ or volatile NH_3^- adsorption on charcoal lowers compost N losses.[105,123] In a study by López-Cano and Roig,[123] BC compost had twice as much NO_3^- as compost without biochar. In addition to nitrogen, compost contains P, K, Ca, Mg, Na, and S. P and K are found in larger concentrations than the other macroelements in composted material, depending on the type. Usually unaffected by composting materials, the effectiveness of compost as a soil fertilizer is diminished when such components are lost during the composting process.[122] Because biochar contains the previously mentioned macroelements, adding it to compost organic matter improves the compost's fertilizing characteristics.[113]

1.5.8. Organic Pollutants. Black carbon (BC) and other carbonaceous sorbents, for example, strongly bind to organic contaminants.[124] Thus, considerable BC sorption reduces organism bioaccumulation, reducing the risk of contaminated matrices. PCBs, PCDD/F, pesticides, linear alkylbenzenesulfonates (LAS), nonylphenol (NP), and polycyclic aromatic hydrocarbons (PAH) may be found in composts.[125] They may be present in substantial quantities in composts made from sewage sludge. According to microbial activity, certain pollutants are converted into metabolites or mineralized; some contaminants remain in compost; whereas others are leached.[125] Because biochar absorbs organic pollutants from water, soil, and sewage sludge, its bioavailable concentration decreases,[126] and microorganisms that might be able to degrade them are stimulated. There have not been any studies done yet on how biochar affects the amount of contaminants in compost. However, studies on sewage sludge show that adding biochar for 30 days reduces the bioavailable portion of PAHs by 17.4% to 58.0%. Studies on biochar aging show that it reduces its affinity for organic pollutants.[127]

1.5.9. Humic Substances. The metabolic activities that decompose and convert plant and microbial leftovers generate humus (HS), a complex heterogeneous combination of polydisperse compounds. It is Earth's main organic carbon reservoir. HS can stabilize soil structure, control the carbon and nitrogen cycle, stimulate plant and microorganism growth, limit heavy metal mobility and toxicity, and preserve plant growth and terrestrial life. Humic compounds are classified by solubility as fulvic acid (FA), humic acid (HA), and humin. Additives improve composting performance, microbial activity, speed, and humification. Microbial agents, regulators, metal oxides, humus precursors, and bulking agents are common compost additives.[128] Järup[129] discovered that biochar increased compost quality, specifically FA generation. The lignocellulosic part of the carton can boost water retention and HS formation when employed as a filler.[130] Sener and Sehirli[131] found that iron oxide promoted FA to HA conversion, which increased with iron oxide concentration. Protein precursors (amino acids) can boost HS and HA synthesis in lignocellulosic biomass composts.[131] Table 4 shows the comprehensive literature on different compost additives used and their effects on various compost characteristics, nutrient retention, global warming reduction potential, better compost quality, and finally the biological diversity. The compost additives made the compost more stable and mature to use as soil conditioner, while suppressing the availability of heavy metals into the soil. The soil applied with compost can be more efficient in water holding capacity or high water productivity for crops. Table 4 showed the effect agricultural waste composting amended with various additives (type of additives) prepared under different preparation conditions.

1.6. Environmental Assessment of Additive-Mediated Composting.

Ammonia (NH_3), CO_2, N_2O, CO, and other gaseous products of the organic matter's degradation are released during composting. Most of those are greenhouse gases with damage to the environment. Due to the loss of nutrients in the pile as well as their impact on climate change, the release of those gases should be reduced. Some research results show that the emission of CO_2 causes a loss of 11.4−22.5% of the total carbon in chicken manure, and the emission of CH_4 causes a loss of 0.004−0.2% of the total carbon; while the emission of N_2O causes a loss of 0.05−0.1% of total nitrogen, and the emission of NH_3 causes a loss of 0.8−26.5% of total nitrogen.[182]

1.6.1. Odor Emissions. Composting releases NH_3 and sulfur compounds, which smell bad. Due to NH_3 emissions, which damage the environment and stink, compost loses agronomic value. Shao and Zhang[168] found that adding rice straw (1:5) to the composting pile of municipal wastes improved oxygen transmission and reduced the overall production of foul-smelling gases that contained sulfur. Similar outcomes have been attained with the addition of ash and biochar[42,111,132] addition. For this, natural zeolite can be added, with the amount affecting odor reduction. Additives may increase ammonia losses by stimulating microbial activity.[61,183] The ammonia emissions, however, were unaffected by organic

Table 5. GHG Emissions from Different Feedstock Compost Amended with Additives

Feedstock	Additive	Duration (days)	Gaseous emissions (reported on 100 days) CO$_2$ (g kg^{-1})	N$_2$O (g kg^{-1})	CH$_4$ (g kg^{-1})	Literature
Cattle manure	Crop straw	99	166.67	9.01	0.078	191
	Woodchips	99	147.07	9.02	0.085	
Sewage sludge	Cotton stalks	105	239.77	-	-	21
Poultry manure, olive wastewater	Cotton stalks	105–140	196–200	-	-	
Sewage sludge, olive wastewater	Corn stalks	112–119	260–270	-	-	
City refuse	Sorghum residues	133	179.31	-	-	
Duck manure	Reed straw + Zeolite	31	405.84	0.14	<0.01	
Cattle and poultry manure	Barley waste	31	300	0.08	1.19	38
Animal manure + food waste (75:25)	Plastic tubes (3:1)	28	225.71	0.02	0.08	38
	Plastic tubes (6:1)	28	233.21	0.02	0.13	
	Woodchips (3:1)	28	171.43	0.03	0.12	
	Woodchips (6:1)	28	178.57	0.05	0.14	
	Biochar (3:1)	28	147.14	0.01	0.02	
	Biochar (6:1)	28	162.14	0.01	0.04	
	Barley straw (3:1)	28	179.64	0.01	0.08	
	Lupine residues (3:1)	28	118.57	0.01	0.68	
Kitchen waste	Sawdust	28	-	0.78	0.15	95
	Cornstalks	28	-	0.4	-	
	Spent mushroom substrate	28	-	1.04	0.05	
Municipal wastes	Woodchips	24	-	<0.01	0.01	171
	Polyethylene tubes	24	-	<0.01	<0.01	
Hen manure + Sawdust	Straw (450–500 °C), 10% fw	15	-	-	-	181
Poultry manure + Wheat straw	Bamboo (450–500 °C), 2–10% dw	42	5.5–72.6	12.4–81.6	12.5–72.9	192
Chicken manure + Wheat straw	Chicken manure (550–600 °C), 2–10% dw	42	-	4.7–15.1	20.5–61.5	193
Layer manure + Sawdust	Cornstalk, Bamboo woody, Layer manure Coir (450–500 °C), 5% dw	15	-	-	15.5–26.1	144
Sewage sludge + Wheat straw	Wheat straw (450–500 °C), 10% fw	56	-	95.1–97.3	92.8–95.3	140
Poultry litter + Sugar cane straw	Green waste, Poultry litter (500 °C), 2–18% dw	60	-	68.2–74.9	77.8–83.3	139
Green waste + Municipal solid waste	Holm oak (650 °C), 10% dw	90	52.9	14.2	95.1	114
Cattle manure + Rice-chaff	Wheat straw (450 °C), 3% dw	65	-	54.1	-	194
Hen manure + Barley strawEffect of Additives on Heavy Metals	Hardwood + Softwood (4:1) (500–700 °C), 27% dw	31	21.5–22.9	16.1–35.3	77.9–83.6	38

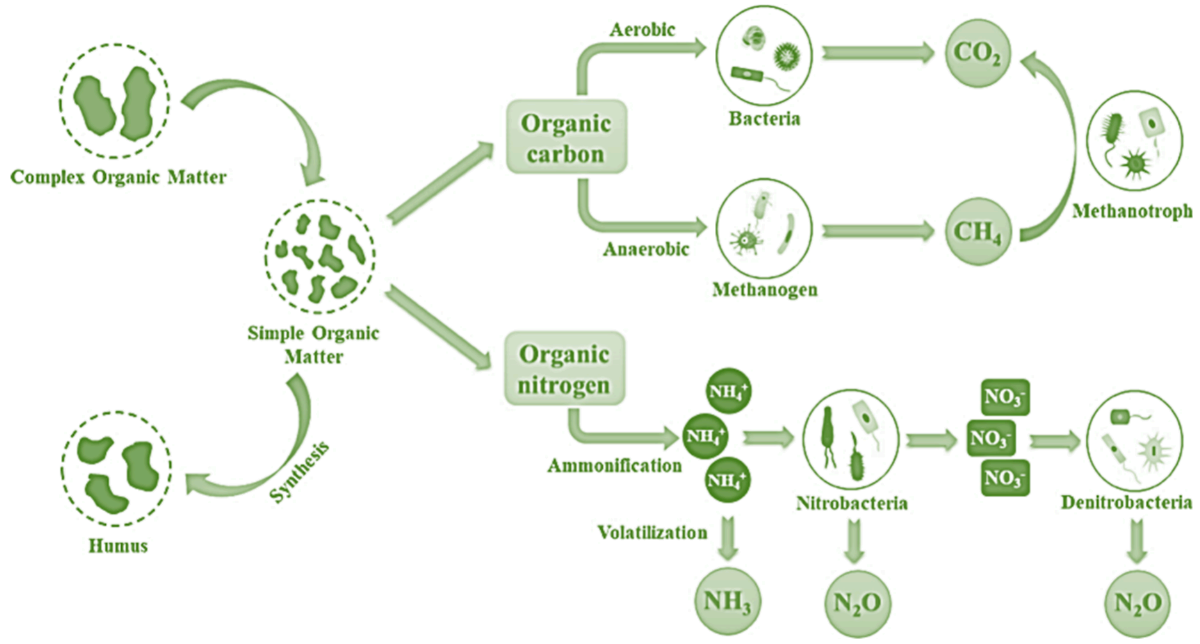


Figure 4. Schematic showing the microbiological processes involved in the production of greenhouse gases during composting.

inputs including sawdust, cornstalks, and wasted mushroom substrates.[45,184] Chemical additives might reduce sulfur-containing chemical odors without harming composting by lowering dimethyl sulphide and dimethyl disulfide emissions.[184,185] Chemical additives such magnesium hydroxide−phosphoric acid absorbent mixtures, calcium superphosphate,[167] and other phosphate and magnesium salts can reduce ammonia losses during composting.

1.6.2. GHG Emissions. In Table 5, it is depicted how much greenhouse gas (GHG) was produced during the composting of various at-the-start feedstocks with various additives. Despite extensive research, there are little findings on GHG emissions from co-composting systems. Additionally, in national GHG records, only CH_4 and N_2O emissions from composting are considered; CO_2 emissions of a biogenic origin are not taken into account.[102] The compost pile's feedstock and aeration rate may affect N_2O and CH_4 emission. The amount of added bulking agent and composting pile rotation frequency must be regulated to reduce GHG emissions, particularly gaseous N losses.[15,171,186] Under aerobic conditions, incomplete nitrification or denitrification can cause N_2O losses, or under anaerobic conditions, where a lack of oxygen causes nitrate accumulation, N losses can happen. Different additives affect N_2O emissions differently depending on the feedstock and type. Mineral additives like phosphogypsum lowered N_2O emissions from composted manure by increasing SO_4^{2-} concentration or modifying the nitrification process.[151] Sawdust significantly reduced N_2O emissions during kitchen trash composting,[95] whereas woodchips and polyethylene tubes as bulking agents had no effect on municipal waste composting.[171] When oxygen levels in a composting pile are too low or there are anaerobic zones present, CH_4 emissions typically result.[138] CH_4 emissions seem to depend more on addition qualities of feedstock properties than N_2O emissions. Thus, methanotrophic bacteria to improve CH_4 oxidation and lower CH_4 emissions and organic fillers to bulk up anaerobic zones to prevent expansion[45,171] or capture released gases[45,171] can lower CH_4 emissions.[173] The efficacy with which additives reduce CH_4 emissions may depend on their physical characteristics, such as particle size. For instance, after adding some organic bulking agents, like sawdust and wasted mushrooms, compact zones with even higher CH_4 emissions may occur,[171] and due to their higher surface area, tiny biochar particles may capture more gas. CO_2 emissions may depend on the addition, especially how easily organic molecules degrade (Figure 4).

Paper, straw, peat, and other easily decomposable organic materials enhance these emissions,[106] while lignin-rich organic materials decrease them.[38,106] Comparing biochar to conventional compost throughout the composting process shows inconsistent impacts on CO_2 emissions, either increasing[88,187] or decreasing.[38] Vermicomposting also showed such inconsistent results.[83,166,188] However, reducing composting CO_2 emissions without impacting biodegradation is difficult.[166,189]

When biochar was added to cow dung compost, Jindo and Sonoki[137] discovered that the formation of CH_4 was slowed while the oxidation was increased, reducing the overall CH_4 emission. In their study of the impact of adding biochar during the composting of manure, Wang and Lu[190] discovered that the addition of biochar greatly decreased the overall N_2O emissions, particularly during the late composting phase. Adding biochar to compost can considerably lower N_2O emissions while decomposing chicken manure. By incorporating 20% more biochar than the control, N_2O emissions can be cut by 59.8%. This is mostly because biochar is alkaline, and the high pH value during composting greatly alters the richness of denitrifying bacteria, causing a decrease in N_2O-producing bacterial communities and an increase in N_2O-consuming bacterial communities. Municipal sludge compost can cut greenhouse gas emissions by 10.39% by adding biochar. Composting has many drawbacks, and one of them is that a significant amount of NH_3 is volatilized during the high temperature stage, which results in significant nitrogen loss. According to Steiner and Das[42] adding 20% biochar to the composting of nitrogen-rich chicken dung not only sped up the process but also cut the emission of NH_3 by 64%. Czekała and Malińska[88] reduced NH_3 emissions by 30% and 44%, respectively, by adding 5% and 10% biochar to compost.

Chowdhury and de Neergaard[38] found that adding 27% dry weight of biochar to composted chicken manure made from 80% hardwood and 20% softwood reduced CH_4 emissions by 27 to 32%. The compost contained 12% dry biochar. The compost with biochar had 80% lower CH_4 emission than the compost without biochar due to its better oxygen conditions. Similar research was done on sewage sludge and wheat straw compost. Awasthi and Wang[173] examined how biochar and zeolites affect composting gas emissions. Wheat straw was pyrolyzed at 500−600 °C to form biochar, and 12% (dry weight) was added to compost.

Biochar made up 3% of the compost mixture. When biochar was added to compost, the overall N_2O emission was reduced by 25.9%. The authors provided the following explanation for why there was less emission from compost including biochar than compost without biochar: reduced NO_2, which is a precursor to nitrous oxide conversion, biochar, which elevates the composted mixture's pH, and increased bacteria that reduce N_2O and decreased enzymes that promote its formation.[179] Other research claims that adding biochar to decomposed material increases gas emissions. Compost made from chicken manure with biochar (27%) emits 6−8% more CO_2 than compost made from chicken dung without biochar, according to Chowdhury and de Neergaard.[38] The increased aeration of the composted mass brought on by the addition of biochar is likely what resulted in the higher CO_2 emission seen in the research mentioned above. High porosity and specific surface area are typical characteristics of biochar, which unquestionably contribute to enhanced aeration of decomposed matter. Additionally, it speeds up the compost material's decomposition, causing CO_2 emissions.

There are reports that show that biochar does not affect gas emissions during composting; however, it may decrease or increase greenhouse gas emissions. The results of two studies, one by Sánchez-Garcia smf Alburquerque[135] on the emission of the same gases during composting of poultry manure with barley straw and one by López-Cano and Roig[123] found no difference in CO_2, CH_4, and N_2O emission (holm oak wood) biochar.[123,135] As opposed to the preceding investigations, the composted materials' various qualities, coupled with biochar properties and composting conditions, may have contributed to the observed variances. The immobilization of NH_3 is mainly caused by two processes: (1) the activity of nitrifying bacteria—biochar fosters the growth of nitrifying bacteria by providing an environment that is conducive to their growth. (2) Biochar absorbed NH_3 and NH_4^+ during composting—biochar has an affinity for NH_3, reducing its availability and losses.

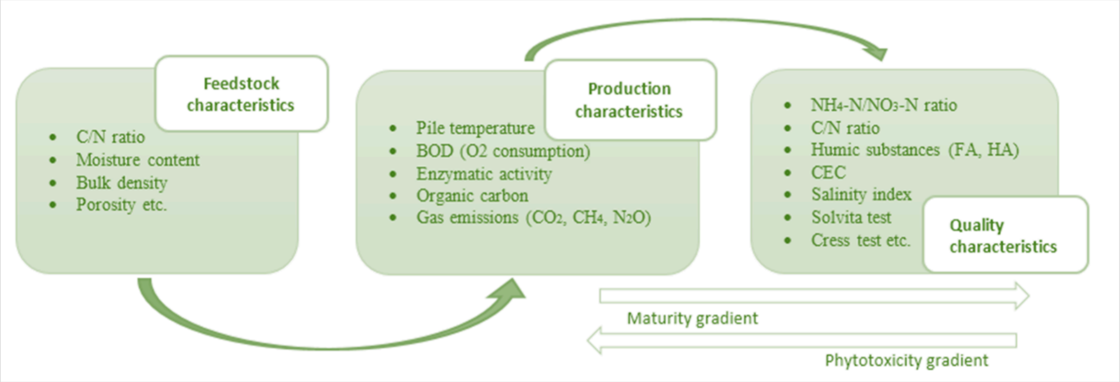


Figure 5. Classification of composting parameters.[200]

Table 6. Compost Quality Is Currently Characterized by Current Parameters Studied in the Literature

Physical		Odor, color, temperature, particle size, and inert materials
Chemical	C, N analyses	C/N ratio in solid and water extract
	Cation exchange capacity	CEC, CEC/total organic-C ratio, etc.
	Water-soluble extract	pH, EC, organic-C, ions, etc.
	Mineral nitrogen	NH_4-N content, NH_4-N/NO_3-N ratio
	Pollutants	Heavy metals and organics
	Organic matter quality, humification	Lignin, complex carbohydrates, lipids, sugars, etc. make up the organic composition
		Elemental and functional group investigations, molecular weight distribution, the E4/E6 ratio, pyrolysis GC-MS, NMR, FTIR, fluorescence, and other methods define humification indices and humic-like substances
Biological	Microbial activity indicators	O_2 uptake/consumption, CO_2 production, self-heating test, and biodegradable components
		Enzyme activity (phosphatases, dehydrogenases, proteases, etc.)
		ATP content
		Nitrogen mineralization−immobilization potential, nitrification, etc.
		Microbial biomass
	Phytotoxicity	Germination and plant growth tests
		Others: Viable weed seed, pathogen, and ecotoxicity tests

1.7. Passivation.

When livestock and poultry are fed mineral-rich feed over an extended period of time, the resulting manure has high concentrations of heavy metals like Cu, Zn, and Cd and easily pollutes the environment when applied to farmland. When livestock and poultry are fed mineral-rich feed over an extended period of time, the resulting manure has high concentrations of heavy metals like Cu, Zn, and Cd and easily pollutes the environment when applied to farmland. Duan and Yang[195] added biochar, microbiological agents, and chemical adsorbents to the pig manure compost for aerobic composting in order to lower the amount of heavy metals in the compost. They also studied the effects of various passivators on Cu and Zn in the composting system. Biochar was found to be the best passivator after extensive comparison and analysis of the passivation from the perspectives of passivation impact, input cost, biomass, etc. Li and Wang[196] observed that when rice husk composting included oak charcoal the total content of Cu and Zn increased, but the proportion of accessible Cu and Zn steadily declined. The passivation rate of Cu reached 65.94% when Zhou and Meng[197] added peanut shell charcoal to the compost made from a mixture of manure and straw. With a passivation rate of 57.2%, the addition of maize straw charcoal resulted in the best passivation rate for Pb. The result of passing Cd through sawdust charcoal is 94.67% passivation. Proper biochar addition can strengthen the bioavailability of heavy metals by promoting the composting process and fungal residue while also converting Zn and Cu to the direction of low activity.[192] Li and Song[194] arrived to an alternative conclusion. In the composting of manure and sludge, they thought biochar had an activating impact on Pb but no discernible passivation effect on Zn, Cu, or Cd. There is an ongoing debate over the effect of biochar on the bioavailability of heavy metals in animal and poultry manure, and more research is required.

Biochar's usefulness in reducing heavy metal bioavailability and mobility during composting and using composts created with biochar to soil is not supported by all studies. Holm oak wood-derived biochar had no significant effect on the total and water-soluble content of Cu, Zn, Ni, Pb, and Cr, according to López-Cano and Roig.[123] Most investigations have shown that composting reduces heavy metal bioavailability. However, biochar efficiency and composting raw materials reduce metal bioavailability. The decrease in bioavailability in the research may be due to functional groups reducing oxygen. Mostly due to microbial oxidation, biochar surface cation exchange capacity improves.[198] Increasing CEC and biochar sorption ability may also affect soluble organic matter sorption with various functional groups.[39,199] The biochar in the compost then holds onto the DOC, which is another factor adsorbing heavy metals.

1.8. Research Trends of Compost Maturity Evaluation.

To be safe in soil, compost must be stable or mature and have no phytotoxic chemicals or plant or animal illnesses. The following compost groups are based on fertilization preparation: when stable, microbiological processes stop, mature, as phytotoxins are reduced, and both, the compost is "finished".

Sometimes "stable" and "mature" are interchangeable. Microbial mineralization and humification stabilize compost organic matter, which is called compost maturity. Composting product performance depends on age, as is widely known. Standardizing compost maturity procedures is difficult due to the complexity and diversity of composting materials and settings. However, compost maturity is assessed by physical, chemical, biological, and spectroscopic methods. Composting parameters were divided by Azim and Soudi,[200] and their relationships are displayed in Figure 5.

Several factors change during composting, allowing for compost assessment.[201] Many criteria have been set for compost maturity; however, most only apply to municipal garbage composts. Maturity factors include physical, chemical, biological, and microbiological activity (Table 6).

Nitrification indicates compost ripeness. When NH_4^--N drops and NO_3^--N appears, the composting material is ready.[202] Zucconi[203] set a maximum of 0.04% for mature municipal rubbish compost since excessive NH_4^--N indicated unsterilized material. Bernai and Paredes[204] defined NH_4-N/NO_3-N ratios below 0.16 as compost maturity indices for all origins (Table 7).

Table 7. Maturity Indices Established for Composts of Different Sources

Parameter	Limiting value	Reference
Water-soluble (C/N)	5−6	137
Germination index	>50%	111
NH_4-N	<0.4 g/kg	205
C/N	<20 preferably <10	137
CO_2 release rate	≤120 mg CO_2/kg/h	114
Water-soluble organic-C	≤10 g/kg; <17 g/kg	114
Water-soluble (C/N)	≤16	205
Water-soluble organic-C/total organic-N	≤0.70; <0.55	137
C_{EX}	≤60 g/kg	206
C_{FA}	≤12.5 g/kg	206
C_{EX}/water-soluble organic-C	≥6.0	206
C/N	<12	205
NH_4−N/NO_3−N	<0.16	114
NH_4−N	<0.4 g/kg	137
Mineralizable C in 70 days	<30%	114
NO_3−N/CO_2−C ratio (per day)	>8	207
Water-soluble organic-C	≤4.0 g/kg	205

The design and implementation of quality requirements help form a compost material market that supports waste composting.[208,209] However, government and nongovernment organizations have set compost quality standards,[210−214] which include inert pollution, organic contaminants and heavy metals, sanitization (pathogens and phyto-pathogens), maturity and stability, weed seeds, water, OM, and nutritional content. International harmonization of such standards is needed. Researchers have long recognized the importance of maturity and stability in compost quality. However, the most reliable indices appear to be the only way to determine composted material maturity/stability.[215] The CCQC maturity assessment[216] considered composts with a C/N ratio >25 immature. At C/N of 25, a group stability and maturity test was chosen (Table 8). According to the TMECC (2002) and CCQC maturity index, the material is highly mature, mature, or immature.

Table 8. Assessment of Maturity Using the CCQC Maturity Index C/N Ratio of 25

Stability thresholds				
Method	Units	Very stable	Stable	Unstable
Specific oxygen uptake rate	mg O_2/g OM/d	<3	3−10	>10
CO_2 evolution rate	mg CO_2-C/g OM/d	<2	2−4	>4
Dewar self-heating test	Dewar index	V	V	<V
Headspace CO_2 (solvita)	Color code	7−8	5−6	1−4
Biologically available C	mg CO_2-C/g C/d	<2	2−4	>4
Maturity thresholds				
Method	Units	Very mature	Mature	Immature
NH_4-N	mg/kg dw	<75	75−500	>500
NH_4-N/NO_3-N	-	<0.5	0.5−3.0	>3
Seedling germination	% of control	>90	80−90	<80
Seedling vigor	% of control	>95	85−95	<85
In-vitro germination index	% of control	>90	80−90	<80
Earthworm bioassay	% weight gain	<20	20−40	>40
NH_3 (solvita)	Color code	5	4	3−1
VFA	mmol/g dw	<200	200−1000	>1000

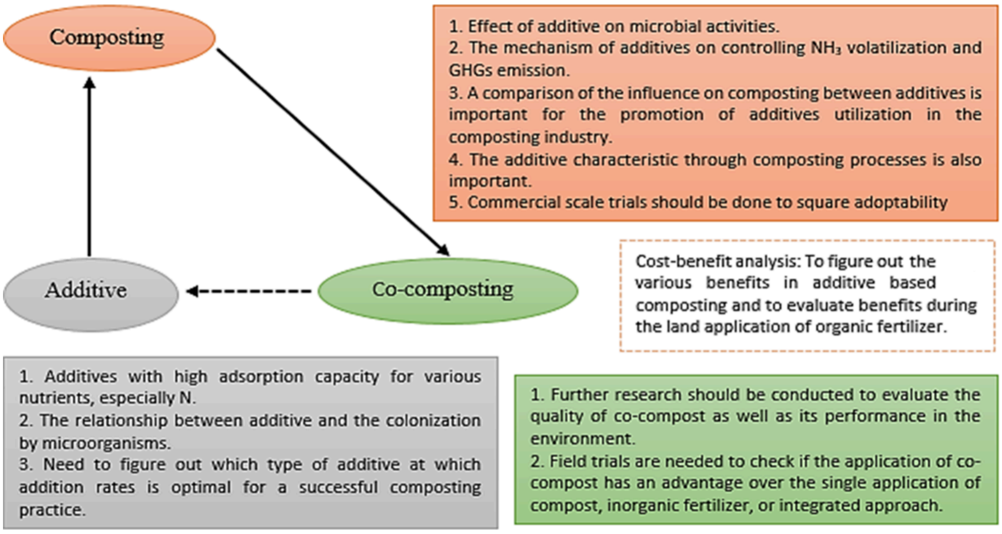
1.9. Effect of Additives on Compost Maturity and Quality.

Jindo and Sonoki[137] studied the effects of biochar (10% fresh weight) made from broad-leaved tree (*Quercus serrata*) wood at 550 °C on organic matter during cattle or chicken dung composting. The C/N ratio and HA/FA compost maturity indicators were identified. Both treatments with and without biochar had lower C/N ratios during composting due to substrate mineralization or nitrogen increase after carbon decomposition.[137,217] Compared to the substance being composted without the addition of biochar, the C/N ratio decreased noticeably less with the addition of biochar. A further study by Zhang and Chen[113] suggests that biochar-derived carbon and decreased compound mineralization in composts may cause this effect. Since bacteria cannot consume biochar carbon, the C/N ratio must not change considerably with carbon stability.[42,218] Additionally, Jindo and Sonoki[137] noted that the inclusion of biochar increased the value of HA/FA, which dictated the extent of polymerization of humification process products. This resulted from humus components adhering to the biochar's surface and speeding up the production of aromatic polymers.[137] Adding biochar to compost increases its GI value, which implies it removes phytotoxins faster.[105] Biochar may aid compost maturation. Biochar, an NH_3^- and water-soluble NH_4^+ absorber, reduces nitrogen loss during manure composting. The humus content of the compost can be increased, and the composting process can be greatly accelerated by the addition of biochar. According to Steiner and Das,[42] adding 20% biochar to piles of animal and poultry dung can cut the overall nitrogen loss by 52%.

1.10. Feasibility of Composting Technology.

1.10.1. Plant Growth Stimulator.

Few studies, including none that were conducted in the field, evaluated the effect of co-composts on plant growth.[164,219] The germination index serves as a biological measure for assessing the toxicity and maturity of compost. It is commonly utilized in the process of



1. Effect of additive on microbial activities.
2. The mechanism of additives on controlling NH_3 volatilization and GHGs emission.
3. A comparison of the influence on composting between additives is important for the promotion of additives utilization in the composting industry.
4. The additive characteristic through composting processes is also important.
5. Commercial scale trials should be done to square adoptability

Cost-benefit analysis: To figure out the various benefits in additive based composting and to evaluate benefits during the land application of organic fertilizer.

1. Additives with high adsorption capacity for various nutrients, especially N.
2. The relationship between additive and the colonization by microorganisms.
3. Need to figure out which type of additive at which addition rates is optimal for a successful composting practice.

1. Further research should be conducted to evaluate the quality of co-compost as well as its performance in the environment.
2. Field trials are needed to check if the application of co-compost has an advantage over the single application of compost, inorganic fertilizer, or integrated approach.

Figure 6. Future applications of biochar as an addition in the composting of organic solid waste are schematically illustrated.

analyzing the effect that co-composts have on plants.[220] A compost is considered phytotoxin-free if the germination index is greater than 50%. Since additives affect nutrient availability, their presence may affect this germination index. However, some studies found that bentonite and alkaline materials inhibit plant growth.[97,221] Composting pig dung with bamboo charcoal and bamboo vinegar, as demonstrated by Chen and Huang,[222] resulted in an increase of this index of up to 95%. Furthermore, the application of co-compost can alter how much nutrition plants absorb. Zayed and Abdel-Motaal[223] demonstrated that the biological additive amended composting improved the plant uptake of phosphorus while reducing bacterial development in the rhizosphere. Similar to this, mineral additions can improve plants' access to nutrients. Phosphate rock-enriched compost gave seedlings more phosphorus than a standard growing medium,[224] while adding waste mica boosted biomass output, absorption, and P and K recoveries.[159] Furthermore, metal transfers to plants were restricted by the use of particular amendments that could absorb heavy metals. Finally, the few co-compost field studies conducted revealed potential for improved soil fertility and potential soil revegetation in damaged areas. Kuba and Tschöll[164] found that co-compost with 16% wood ash increased plant cover on ski slopes better than mineral and organic fertilizers. Similar findings were made by Chowdhury and Bolan[219] who found that using co-composts (biowastes with an alkaline amendment) to replant an urban dump soil increased soil fertility.

1.10.2. Economical and Practical Aspects. The composting method is great for making soil amendments, but its economic sustainability depends on start-up costs, production volume, feedstock quality, and local end-product prices.[225] Lim and Lee[225] estimate that a composting facility costs 4.37 million USD annually (initial investment, operation, and maintenance) and benefits 1.10 million USD. Composting takes a long time;[31] therefore, utilizing chemicals to speed up the process can save money. It is not economical to screen and reuse additives. To generate a high-quality product, additives must be inexpensive and effective. Jaggery and polyethylene glycol, for example, which are pricey,[85] but also bentonite or allophane,[226] which are affordable and plentiful, might help the composting process. To lower the cost of composting, it is also necessary to optimize the additive to organic waste ratio. For instance, a 1:1 proportion (sawdust/sludge) proved effective and cost-effective compared to a 3:1 proportion. Low sawdust ratios, however, resulted in a lower-quality final product, as evidenced, for instance, by a low germination index.[227]

Furthermore, compared to high sawdust proportions, a low sawdust proportion requires a longer composting procedure. Finally, there are a number of trade-offs to consider while choosing additives. The additives must be personalized to the region, the location of the composting facility, and the season while considering the additive cost, accessibility throughout both space and time (e.g., agricultural leftovers collected periodically), and abundance. In addition, vermicomposting also makes money since it produces better end products than traditional composting does.[228] We believe that adding worms will improve composting by increasing food availability, stabilizing carbon, speeding up composting, and reducing GHG emissions.[229] Compared to standard composting, with or without additions, this method may have a higher ROI and lower annual cost. However, a thorough economic study is required to take into consideration the financial benefits and drawbacks of the various composting methods. Vermicomposting, for instance, might make pile turning less expensive, but the amount of space needed to handle an equivalent volume of organic waste may be substantially larger than in conventional composting units, raising expenses. Additionally, vermicomposting may not sanitize the wastes, necessitating additional composting.

1.11. Future Perspectives. As previously mentioned, adding compost additives aided in the breakdown of biomass, improved the quality of the compost, and mitigated several problems that can arise with conventional composting. However, there are still several unknowns. As a result, we highlighted a few points of view that will serve as a roadmap for more research (Figure 6).

2. CONCLUSION

Agriculture waste is now a substantial global source of environmental degradation, and the sustained development of agriculture depends on the proper and prompt management of this enormous amount of agricultural waste. However, chemical fertilizer overuse degrades agricultural yield and pollutes. Therefore, the use of organic fertilizer is required in agriculture to produce goods of improved quality without the use of chemicals. Recycling agricultural waste using traditional composting is experiencing protracted composting issues. Because agricultural waste has a high nitrogen concentration, it produces hazardous substances during typical composting, including ammonia (NH_3), nitrous oxide (N_2O), nitric oxide (NO), methane (CH_4), and volatile organic compounds (VOC_s).[230] This review studied the composting of agricultural waste amended with various mineral, organic, and biological additives to enhance the process variables and product quality. Increased soil fertility produces food and fiber, and soil organic matter stores C and mitigates climate change during composting procedures. These compost additives were amended to (1) attain the thermophilic period quickly and shorten the composting period, (2) improve nutrient content retention while decreasing metal mobility, and (3) restrict emissions of odor and GHG. There have been reports of some co-composts having detrimental impacts on plant growth, though. To truly comprehend the additive impacts, more research is needed because their application during composting results in end products with diverse features that affect soil characteristics in various ways. Thus, to improve soil health and reduce environmental concerns, more research is needed to link co-compost characteristics, soil parameters, and plant growth, according to species, and to make the system more cost-effective, and additive quality and quantity must be considered. Consider creating a composting system that is cost-effective. In the process of composting, additives have an impact on the following factors: (1) early compost maturity, (2) increased compost pH, (3) more nutrient retention (Ca, Mg, N, etc.), (4) higher nitrification ratio, (5) stability of humic-like substances, (6) heavy metal passivation (reduces bioavailability), and (7) GHG emission reduction. Before using compost as an organic fertilizer, it is important to determine its maturity. However, it is difficult to standardize the techniques for determining compost maturity due to the variety of conditions, the complexity of the composting material, and process.

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Funding

This work was supported by National Research Foundation of Korea (NRF) grant funded by the Korean Government (MSIT) (NRF-2021R1F1A1055482).

Notes

The authors declare no competing financial interest.

ACKNOWLEDGMENTS

The authors extend their appreciation to National Research Foundation of Korea (NRF) grant funded by the Korean Government (MSIT) (NRF 2021R1F1A1055482). The authors also extend their appreciation to the Deanship of Scientific Research at King Khalid University for support this work through large group Research Project under grant number RGP2/277/44.

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