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# Composting additives and their role in sustainable waste management

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**Abstract**
Aerobic composting is a good way of recycling organic waste. It has a number of benefits: cheap to produce, lower impact on the environment and enhances soil quality. Nevertheless, conventional composting systems are still limited by some issues, including: nitrogen losses, emissions of greenhouse gases, odour, lack of compost maturity, presence of antibiotics, build-up of mineral salts, and the presence of hazardous heavy metals in the final product with high bioavailability. Co-composting with additives like zeolite, lime, rock phosphate, bentonite, biochar and microbial inoculants have been proven to significantly reduce environmental risk and improve the efficiency of the composting process during the treatment of organic waste and hazardous waste. Additives are used to modify the composting process (such as reducing leachate and gaseous emissions, improving the packing, aeration and mixing of the composting piles, accelerating the decomposition of organic matter, increasing the availability of nutrients and the nutrient content of the composted material). The objective of this review is to provide insights into the application of various additives for improving composting performance and compost quality.

**Keywords:** Additives, aerobic composting, bioavailability, co-inoculants, decomposition, organic waste

## Introduction

Composting is a sustainable and environmentally friendly biological process that transforms organic waste materials into a stable, nutrient-rich product known as compost. Through the activity of diverse microorganisms, organic residues are decomposed and converted into humus-like substances that improve soil fertility, structure, and biological activity. Organic solid waste, such as municipal waste, food and agricultural waste, is produced in large amounts in developing countries. These wastes are high in organic matter and key plant nutrients like nitrogen (N), phosphorus (P) and potassium (K). They can, however, also be contaminated with pathogenic microorganisms, hazardous chemicals and heavy metals which have significant impacts on environmental sanitation and public health (Wang *et al*., 2017) [63]. Composting is a well-accepted and a sustainable method for converting the organic solid waste into a value-added product which can be used as a nutrient source for plant growth, supporting green agriculture for an effective waste management strategy (Chen *et al*., 2017) [18].

Despite this, there are a number of problems with composting, such as long composting times, significant losses of nitrogen, greenhouse gas emissions and odours (Lim *et al*., 2016; Turan *et al*., 2018) [34, 56]. The restrictions can diminish the efficiency and profitability of composting, especially when composting heterogeneous feedstocks on large scales. This has led to a growing interest in using various additives to optimize composting performance and improve the quality of the compost product (Guo *et al*., 2021; Huang *et al*., 2013; Mei *et al*., 2022; Shan *et al*., 2021; Wu *et al*., 2017; Yang *et al*., 2022; Zhou *et al*., 2019) [24, 29, 41, 55, 66, 70, 70, 85]. Additives are the substances used in purposefully adding to the composting system to enhance the physicochemical and biological conditions during decomposition. Based on functions and type, additives can be classified into four types: mineral additives, organic additives, microbial inoculants, and nanomaterials (Table 1).

They are commonly employed to enhance composting efficiency, but each additive works differently (Cerda *et al*., 2018; Maulini-Duran *et al*., 2014) [16, 40].

**Table 1:** Types of additives with examples

| Additives categories | | | |
|---|---|---|---|
| **Mineral additives** | **Organic additives** | **Microbial additives** | **Nanomaterials** |
| Medical stones, zeolite, Ca-bentonite, lime, kaolin, dolomite chalk, ashes, biochar, calcium nitrate, potassium dihydrogen phosphate, magnesium sulphate, charcoal, clay, superphosphate, oxalic acid, phosphogypsum and cobalt sulphate (Abdellah *et al*., 2022; Himanen and Hänninen, 2011; Sanchez-Monedero *et al*., 2018) [1, 28, 54] | Remaining straws, mature composts, garbage from green waste compost, grass clippings, biochar, crushed materials made of hardwood, corn stalks, crushed wood pallets, bark, whey and molasses (Akdeniz *et al*., 2019; Doublet *et al*., 2011) [2, 21] | *Alcaligenes*, *Clostridium*, *Enterococcus*, *Lactobacillus*, *Bacillus subtilis*, *Bacillus amyloliquefaciens*, *Bacillus licheniformis*, *Pseudomonas stutzeri*, *Pseudomonas aeruginosa*, Yeast, *Phanerochaete chrysosporium*, *Trichoderma viride*, *Aspergillus oryzae*, white-rot fungi (*Fomes fomentarius*, and *Trametes versicolor*) microorganisms (Awasthi *et al*., 2015; Rastogi *et al*., 2020; Yang *et al*., 2022; Wang *et al*., 2018a) [3, 49, 70, 61] | Nano zero-valent iron, Iron oxide nanoparticles ($Fe_3O_4$, $Fe_2O_3$), Graphene oxide, Carbon nanotubes (CNTs), Nano-biochar, Silica nanoparticles ($SiO_2$), Titanium dioxide nanoparticles ($TiO_2$), Nano-zeolite, Nano-bentonite, Manganese oxide nanoparticles ($MnO_2$) |

Mineral additives such as zeolite, bentonite, and gypsum primarily enhance the physicochemical properties of the composting matrix by improving aeration, moisture retention, pH regulation, and nutrient conservation. Heavy metal adsorption was also performed using zeolite and Ca-bentonite, which are known for their chemical and physical properties and are applied in water purification systems as well as in soils (Awasthi *et al*., 2016b; Wang *et al*., 2016) [7, 60]. Pure mineral additives, such as clay materials from quarries or soils are being used during the composting process to reduce greenhouse gas emissions (Barthod *et al*., 2016) [12]. In addition, it can be beneficial to add calcium superphosphate to the composting process to improve nutrient retention and minimize nitrogen losses (Sagdeeva *et al*., 2018) [52].

Organic additives encompass a wide range of materials, including crop residues, mature compost, vegetative waste, grass clippings, shredded wood materials, crushed wooden pallets, bark and maize stalks. Organic additives provide additional carbon sources, optimize the C:N ratio, improve compost structure, and stimulate microbial growth. The selection of suitable organic additives should consider the initial carbon-to-nitrogen (C/N) ratio of the composting mixture to ensure efficient organic matter degradation and minimize nitrogen losses through leaching during the composting process (Awasthi *et al*., 2016a; Yin *et al*., 2021) [6, 72].

Microbial additives consist of microorganisms that are intentionally inoculated into composting piles to enhance the degradation process. These microorganisms are typically isolated from compost during the thermophilic phase, cultured, and subsequently commercialized as microbial inoculants (Manu *et al*., 2017) [39]. Several well-known cellulolytic bacteria involved in composting include Pseudomonas, Cellulomonas, Bacillus spp. and Thermoactinomycetes. In addition, fungi such as Aspergillus, Sclerotium, Trichoderma and white-rot fungi produce extracellular enzymes responsible for the degradation of cellulose and lignin during composting (Awasthi *et al*., 2015; Rastogi *et al*., 2019) [3, 50]. The proliferation of mesophilic and thermophilic bacterial populations due to microbial inoculation can significantly influence the compost temperature profile and ammonia emissions throughout the composting process (Barthod *et al*., 2018) [11].

Nanomaterials-based additives have been developed to improve composting efficiency, enhance organic matter degradation, minimize nutrient loss and boost compost quality. The catalytic activity, high surface area, and unique physicochemical properties of nanomaterials can stimulate the microbial metabolism, facilitate extracellular electron transfer, enhance enzymatic activities, and improve oxygen diffusion into compost matrices (Gattupalli *et al*., 2023) [22]. In addition, nanomaterials also play a catalytic role in the transformation of organic matter into stable humic substances, so that the compost product produced is better quality (Liu *et al*., 2025) [35].

Some reports also showed that by adding nanomaterials, GHG emissions ($CH_4$ and $N_2O$) can be decreased, ammonia volatilization can be minimized, nutrient retention can be improved and potentially toxic heavy metals can be immobilized, which makes composting systems more environmentally sustainable (Zhang *et al*., 2022) [82]. Different types of nanomaterials have been tested for composting such as nano zero-valent iron (nZVI), iron oxide nanoparticles ($Fe_2O_3$ and $Fe_3O_4$), graphene and graphene oxide (GO), carbon nanotubes (CNTs), nano biochar, $TiO_2$ nanoparticles, silica nanoparticles, manganese oxide nanoparticles, and nano clay material. Of these, the nanoparticles of iron have been found to be very effective in the process of aerobic composting in promoting microbial community activity, organic matter degradation, reducing phytotoxicity, and improving compost maturation (Yang *et al*., 2023) [71]. Nanomaterials additives, therefore, provide a new and sustainable approach for optimizing composting processes, enhancing the nutrient conservation, reducing environmental pollution and consequently, for the production of high-quality organic fertilizers appropriate for sustainable agriculture production.

**Table 2:** Impact of additives on composting process and quality

| Additives | Improvement of process parameters | Compost quality | References |
|---|---|---|---|
| Biochar | Aeration, Temperature (°C), Moisture, pH | Carbon sequestration, Enhance N & P content, reduction of heavy metals | Czekała *et al*., 2016; Waqas *et al*., 2018; Awasthi *et al*., 2017b [20, 64, 9] |
| Organic substrates | Microbial activity, Temperature (°C), pH, Duration | Carbon sequestration | Manu *et al*., 2017 [39] |
| Rock P | Microbial activity, Moisture | Enhance N & P content | Qiu *et al*., 2021; Zhang and Sun, 2017a [47, 77] |
| Red mud, fly ash | Stimulated microbial activity and improved aeration | Improvement of compost and soil health | He *et al*., 2016; Zhou *et al*., 2017 [26, 84] |
| Ligno-cellulolytic Consortium | Enhanced degradation of lignocellulosic materials and reduced electrical conductivity (EC) | Improved compost maturity | Xu *et al*., 2019 [69] |
| White-rot fungi (*Phanerochaete chrysosporium*, *Trametes versicolor* and *Fomes fomentarius*) | C/N ratio reduction, Electrical conductivity, Enzymatic activities, Germination index and pH | Accelerated degradation of solid waste | Heidarzadeh *et al*., 2019; Wang *et al*., 2018b [27, 61] |
| Nano zero-valent iron (nZVI) | Enhanced microbial metabolism, accelerated organic matter degradation, and increased humification rate | Reduced phytotoxicity and improved compost stability | Yang *et al*., 2022; Zhang *et al*., 2018b [70, 81] |
| Iron oxide nanoparticles ($Fe_2O_3$) | Increased enzymatic activity and decomposition rate | Enhanced compost maturity and nutrient transformation | Pan *et al*., 2024 [46] |

## Effects of Additives on Composting Process Dynamics

### The impact of additives on temperature profile during composting

Mineral, biological and organic additives have been shown to enhance microbial activity, thereby initiating the thermophilic phase earlier and prolonging its duration compared to conventional composting (Jiang *et al*., 2015; Morales *et al*., 2016) [31, 43]. During the composting of animal manure, green waste, and food waste, rapid temperature increases were observed following the addition of biochar and other amendments, including mineral and polymer additives such as jaggery, zeolite and polyethylene glycol. The incorporation of biochar into composting systems can increase the internal pile temperature during the thermophilic phase and extend thermophilic microbial activity (Awasthi *et al*., 2017a; Wang *et al*., 2017) [9, 63].

The rapid increase in temperature observed following the addition of these amendments may be attributed to enhanced microbial biomass and metabolic activity (Yang *et al*., 2022) [70]. During the composting process, the microbial inoculant had a significant effect on pile temperature, with the thermophilic stage initiating approximately 2 days earlier and extending for an additional 10 days.

### Additives to stimulate microbial activity

Pile moisture, temperature and aeration are all affected by the additives and can have a significant impact on the compost microbial populations because these additives contain nutrients and sources of readily available carbon. The microbial population has been found to be higher in the composted green waste with jaggery added, which resulted in better decomposition of the cellulose (Barthod *et al*., 2018) [11]. The microbial consortia directly influence the microbial community structure and activity in the composting system, whereas mineral additives have mostly indirect effects. The use of a commercial microbial inoculant changed the average composting temperature and ammonia emissions, compared to a conventional composting system without microbial inoculants, as a result of increased populations of mesophilic and thermophilic bacteria. Thus, the use of such additives can be a useful method for promoting composting (Ngo *et al*., 2013) [44]. Further, the soluble carbohydrates in silage can stimulate the growth and metabolic activity of microorganisms. Moreover, flue gas desulfurization gypsum has high surface reactivity, which is conducive to the growth of microflora during composting process (Wang *et al*., 2021) [62].

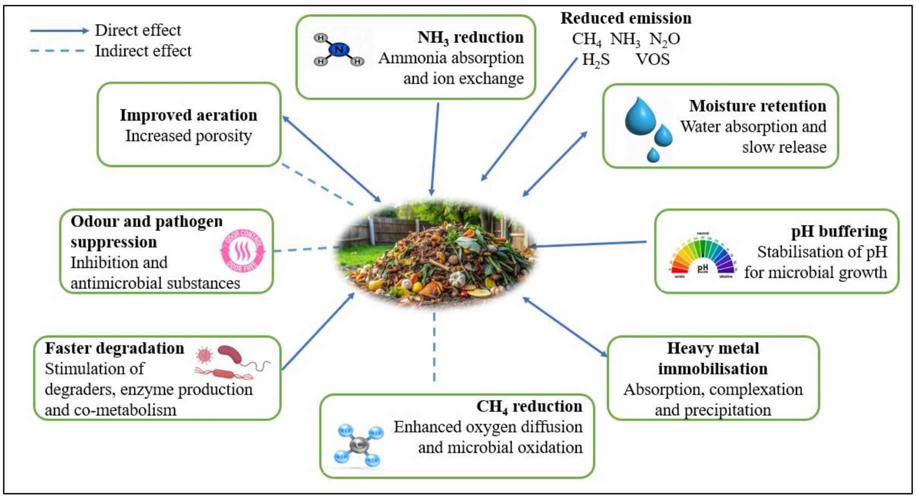


**Fig 1:** Mechanism through which additives enhanced composting

**Additives to improve aeration**

Low aeration rates can cause anaerobic conditions or excessively high aeration rates can prevent thermophilic conditions due to excessive heat loss. Adding bulking agents like biochar, sawdust, wood chips and crushed branches to the compost heap can improve the aeration and porosity of the heap, which will increase the oxygen available and the efficiency of the composting process (Czekala *et al*., 2016) [20].

The different additives decreased the bulk density and increased the water-holding capacity (WHC) of the resulting compost product (Jain *et al*., 2018) [30]. But high WHC can reduce aeration in the compost matrix, and hinder plant growth and development (Zhang and Sun, 2017b) [78]. An important indicator of pore structure, water retention and air permeability of the composting material is the void ratio (VR). High (>67) or low (<40) values of VR can become a problem in the process of organic matter degradation (Zhang and Sun, 2018a) [80]. VR values were improved with adding flue gas desulfurization gypsum and silage. The big surface area of silage can improve the porosity of the compost and the high calcium ion ($Ca^{2}+$) content of flue gas desulfurization gypsum can increase its water adsorption capacity.

**Effect on the compost particle-size distribution and coarseness index**

Particle-size distribution is an important indicator of compost maturity, as it reflects the extent of degradation of complex organic compounds (Zhang and Sun, 2018b) [81]. In addition to improving the physical structure of the composting matrix, the incorporation of sugarcane bagasse (SCB), furfural residue (FR) and maifanite (MF) may provide essential nutrients required for microbial growth, thereby improving the particle-size distribution of the compost (Li *et al*., 2017; Lu *et al*., 2014) [33, 36].

**Moisture content regulation by additives**

During composting, moisture content influences oxygen transfer within the pile, thereby affecting microbial activity and the rate of organic matter degradation. The optimal moisture content for efficient decomposition of organic matter is generally considered to range between 50% and 70% (wet basis; ratio of water weight to total material weight). Excessive moisture levels during composting may promote anaerobic conditions and result in odour generation. To mitigate the adverse effects of high moisture content, fibrous bulking agents are commonly incorporated into composting materials, as they can absorb excess leachate and improve pile aeration (Doublet *et al*., 2011; Zhang *et al*., 2014) [21, 76]. Conversely, excessive water loss during the initial stages of composting may delay the decomposition process and necessitate additional watering. The incorporation of ash or phosphate rock during the composting of green waste has also been reported to enhance the water-holding capacity of the composting material (Zhang and Sun, 2017c) [77].

**pH-buffered additives**

The pH of compost undergoes dynamic changes during the composting process, typically decreasing during the initial stages and increasing during the later stages (Onwosi *et al*., 2017) [45], thereby influencing microbial activity. To improve the composting of acidic feedstocks, such as food waste, various additives are used to elevate pH levels. This increase in pH may be attributed to enhanced biological activity leading to the degradation of organic acids and other organic compounds. Additionally, the use of bulking agents such as bagasse, peanut shells, paper, Ca-bentonite and sawdust has been reported to increase compost pH (Wang *et al*., 2016) [60].

Flue gas desulfurization gypsum (FGDG) and silage may reduce ammonia volatilization and consequently lower the pH of the final compost product, thereby promoting microbial activity (Rastogi *et al*., 2019) [50]. A pH range of 7.0-8.5 is considered optimal for microbial metabolic processes and is therefore favorable for compost development. Variations in pH can alter the surface charge of microbial cell membranes, thereby influencing nutrient uptake efficiency and overall microbial activity (Bai *et al*., 2020) [10].

**Additives impact to humus content**

According to Zhang and Sun (2017), compost was considered mature when the final humus content reached 1.7. During the composting process, microbial activity transforms fulvic acid into humic acid, resulting in a gradual increase in humic acid content over time (Zhou *et al*., 2017) [84]. Humic acid is widely recognized as an important indicator of compost stability and the extent of organic matter decomposition (Wei *et al*., 2016; Meng *et al*., 2018) [65, 42]. Generally, compost products with higher humic acid content are considered more stable and mature. Flue gas desulfurization gypsum (FGDG) has been reported to increase the abundance of benzene- and nitrogen-containing compounds while reducing alkane content, thereby accelerating humic acid synthesis and enhancing the unsaturation and aromatization degree of humic substances (Guo *et al*., 2016) [25]. Furthermore, the high porosity of silage may modify the composting environment in a manner that promotes microbial activity and consequently enhances humus accumulation. Microorganisms were able to rapidly degrade and utilize the organic matter present in rice husk and sugar residue. In contrast, the complex structural composition of tomato straw limited microbial degradation and utilization, resulting in lower humus content after composting (Yang *et al*., 2022) [70].

Rastogi reported that the addition of cellulolytic bacteria during municipal solid waste (MSW) composting significantly influenced the humic properties of the composted material (Rastogi *et al*., 2019) [50]. The study demonstrated that inoculated compost achieved maturity at an earlier stage due to an enhanced degree of humification.

**Impact on compost nutritional content**

In the composting phase, different N compounds such as ammonium nitrate, ammonium hydroxide and ammonia are generated through ammonification, nitrification, denitrification, assimilation and volatilization and all play a part in the stabilization and transformation of nutrients (Zainudin *et al*., 2020) [73]. Livestock manure also has a higher nitrogen content than crop straw (Yang *et al*., 2023) [71] and the degradation of organic substrates during composting results in greater $NH_4^+$-N production.

The nitrification process is generally restricted during the thermophilic phase because high temperature and high ammonia levels halt the growth and activity of nitrifying bacteria leading to comparatively low accumulation of

$NO_3^-$-N during this phase (Xiao *et al*., 2017) [67]. Both silage and bean dregs are a source of minerals and phytochemicals that can improve the nutrient content of the end compost product (Benito *et al*., 2017) [13]. Flue gas desulfurization gypsum (FGDG) has been reported as a promoter for nitrogen retention during composting, due to the promotion of $NH_4^+$-N to $NO_3^-$-N (Wang *et al*., 2021) [62]. Moreover, the processing of tomato straw, sugar residue and rice husk had higher C/N ratio than the control.

**Effect on Electrical Conductivity**

Electrical conductivity (EC) is correlated with the mineralisation rate of compost as well as with soluble salt concentration, which has a direct impact on plant growth and development. Very high values of EC after the use of compost can be phytotoxic to crop plants. The EC value of mature compost is generally under 4 microSiemens per cm (mS/cm) which is suitable for agricultural use (Xie *et al*., 2017) [68].

In general, at the end of the composting process, EC values are stable in the range of 2.5-4.0 mS/cm. EC typically rises during the thermophilic phase, peaks at around 2.5-3.0 mS/cm during the high temp phase and slowly decreases during the cooling phase. In the co-composting of sheep manure, cow manure, mushroom residue and recycled materials, the high inorganic content of mushroom residue had a significant effect on the mineralization rate and caused high EC values in the composting material (Yang *et al*., 2023) [71].

**Green gas reduction and nitrogen loss**

Biochar possesses a high specific surface area, strong adsorption capacity and extensive microporosity (Voběrková *et al*., 2017; Chowdhury *et al*., 2014; Shan *et al*., 2021) [57, 19, 55], enabling it to effectively adsorb $NH_3$/$NH_4^+$ and thereby reduce ammonia emissions during the composting process. Similarly, zeolite exhibits a strong affinity for cations and can retain ions such as $NH_4^+$ through ion-exchange mechanisms. According to Awasthi *et al*. (2017a), the application of zeolite at 10%, 15% and 30% (w/w) enhanced $NH_4^+$ retention in the final compost product more effectively than charcoal applied at 12%. In another study, Awasthi *et al*. (2017c) reported that the addition of biochar to sewage sludge reduced $CH_4$ and $N_2O$ emissions by 92.85-95.34% and 95.14-97.3%, respectively, while increasing humic substance content by 35-42%.

Co-composting municipal solid waste (MSW) with sludge and mixed microbial cultures, including Bacillus casei, Candida rugopelliculosa, Lactobacillus buchneri, Trichoderma and white-rot fungi, significantly reduced nitrogen loss and enhanced the mineralization rate (Awasthi *et al*., 2016c; Rastogi *et al*., 2020) [8, 49]. Various microbial inoculants used in composting systems include nitrifying bacteria (Zeng *et al*., 2014; Zhao *et al*., 2020) [74, 83], Azotobacter (Lu *et al*., 2018) [37], thermophilic ammonium-tolerant bacteria (Kuroda *et al*., 2015) [32] and nitrogen-retaining microbial agents (Qu *et al*., 2020) [48].

**Table 3:** Studies on additives used during composting of different solid waste feedstocks

| Compost feedstock | Additive | Description | Impact on the overall composting process | References |
|---|---|---|---|---|
| Pig manure | Zeolite | Natural aluminosilicate mineral with high cation exchange capacity and adsorption potential | Reduced $NH_3$ volatilization, improved nitrogen retention, accelerated compost maturity, and enhanced fertilizer quality | Awasthi *et al*. (2015) [3] |
| Municipal solid waste | Rock phosphate | Natural phosphate-bearing mineral | Increased phosphorus content and availability in finished compost, improved fertilizer value | Biswas and Narayanasamy (2006) [15] |
| Mushroom substrate waste | Rock phosphate | Naturally occurring phosphate mineral | Increased phosphorus availability and improved nutrient quality of compost | Mahimairaja *et al*. (1994) [38] |
| Pig manure | Biochar | Carbon-rich porous material produced through biomass pyrolysis | Reduced $NH_3$ and GHG emissions, enhanced aeration, improved nitrogen retention, and promoted humification | Sánchez-García *et al*. (2015) [53] |
| Chicken manure | Biochar | Highly porous organic amendment | Reduced ammonia volatilization, increased microbial activity, and improved compost maturity | Wang *et al*. (2013) [58] |
| Sewage sludge | Biochar | Pyrolyzed biomass with high adsorption capacity | Immobilized heavy metals, reduced emissions, and enhanced humification | Godlewska *et al*. (2017) [23] |
| Chicken manure | Rice husk | Agricultural residue used as bulking material | Improved aeration, moisture balance, and degradation efficiency | Chang *et al*. (2010) [17] |
| Wheat straw | Cattle manure | Nitrogen-rich co-substrate | Improved microbial growth and accelerated degradation | Bernal *et al*. (2009) [14] |
| Green waste | Molasses | Readily degradable carbon source | Stimulated microbial activity and increased composting temperature | Huang *et al*. (2013) [29] |
| Green waste | Fungal consortium (Trichoderma + Aspergillus) | Mixed lignocellulose-degrading fungi | Accelerated degradation of woody biomass and improved compost maturity | Ryckeboer *et al*. (2003) [51] |
| Chicken manure + Rice husk | Trichoderma harzianum + Phanerochaete chrysosporium | A synergistic fungal inoculation strategy employing a ligninolytic white-rot fungus and a cellulolytic/ligninolytic fungus | High compost maturity; accelerated organic matter mineralization and humification; promoted beneficial fungal community succession and endophyte abundance | Zhai *et al*. (2025) [75] |
| Chicken manure | Iron oxide nanoparticles ($Fe_2O_3$) | Iron-rich nanoparticles acting as catalytic additives | Enhanced enzymatic activity and accelerated decomposition rate | Yang *et al*. (2023) [71] |
| Agricultural waste compost | Iron oxide nanoparticles ($Fe_2O_3$) | Iron-based nanoparticles | Enhanced microbial abundance, dehydrogenase and urease activities, increased organic matter degradation, and improved compost quality | Zhang *et al*. (2022) [82] |

## Conclusion

The development of advanced composting technologies has significantly reduced the potential environmental risks associated with composting processes. Strategies such as optimizing composting parameters, incorporating chemical, biological and mineral additives, and improving operational practices have been shown to enhance the quality of the final compost product. Most nanomaterial research in composting has focused on iron-based nanoparticles (nZVI, $Fe_3O_4$, $Fe_2O_3$), graphene-based materials, and nano-biochar, primarily because of their ability to enhance microbial activity, facilitate extracellular electron transfer, promote humification, reduce nitrogen losses, and mitigate greenhouse gas emissions. However, compared with mineral additives and microbial inoculants, the application of nanomaterials in composting remains an emerging research area, and large-scale field validation studies are still limited. Appropriate techniques can be selected based on the initial characteristics of the raw materials in order to improve composting efficiency and minimize adverse environmental impacts. Furthermore, the application of advanced composting technologies can effectively reduce greenhouse gas (GHG) emissions, odour generation, ammonia volatilization and the bioavailability of heavy metals during the composting process.

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