

Review

Bio-Based Fertilizers from Chicken Manure Composting: Feedstock Optimization, Odor Mitigation, and Antibiotic Resistance Control

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Abstract

Bio-based fertilizers derived from chicken manure (CM) composting show potential to meet the requirements of current European fertilizing product legislation, provided that the final product satisfies the relevant quality, stability, and hygienization criteria, although technological challenges remain. This review focuses on the critical aspects related to feedstock optimization and mitigation of odor emissions and antimicrobial resistance-related risks, including the occurrence of antibiotic residues, antibiotic-resistant bacteria, and antibiotic resistance genes. Effective CM composting depends on a balanced feedstock formulation, appropriate aeration, moisture control, temperature–time profiles, and maturation conditions. Co-composting with suitable co-substrates can optimize the carbon-to-nitrogen ratio, enhance nutrient retention, minimize nutrient losses, and improve process performance. Two critical challenges (odorous emissions and antibiotic resistance) remain inadequately characterized and regulated, posing potential risks to environmental quality and public health. Although composting typically reduces antibiotic residues and pathogenic bacteria, certain antibiotic resistance genes may persist, depending on feedstock contamination and operational parameters. This persistence highlights the need for further research and targeted mitigation strategies. Future studies should assess modified composting technologies and integrated process strategies to enhance compost maturity, stability, and microbial safety. A life cycle assessment of CM composting should be performed in future work to help identify trade-offs among operational conditions, enabling the optimization of product quality while reducing environmental impacts. Comparative evaluations with conventional inorganic fertilizers across multiple impact categories (e.g., energy demand) can further support sustainable decision-making and foster adoption of climate-resilient organic waste management practices.



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1. Introduction

The agrifood sector has been increasingly adopting ecological and sustainable practices to minimize its ecological and carbon footprints. While the fertilizer industry plays a vital role in ensuring food security, reducing the use of mineral fertilizers is one of the European Union's (EU) key strategies to achieve these goals and lessen its dependence on imports. In fact, the EU Commission's "Farm-to-Fork" and "Biodiversity" strategies, part of the EU

Green Deal, set an ambitious goal for 2030: to reduce nutrient losses from both organic and inorganic fertilization by at least 50% while maintaining soil fertility. This target, along with other objectives such as expanding organic farming to 25% of agricultural land, is expected to drive a reduction in the use of conventional fertilizers. By 2030, the nutrient consumption of nitrogen (N), phosphorus (P), and potassium (K) for agriculture is projected to decline by approximately 4% [1].

In line with that, the implementation of EU Regulation 2019/1009 (Fertilizing Products Regulation) has established a harmonized regulatory framework for all fertilizers across the European market. The Regulation classifies products according to *Product Function Categories* and *Component Material Categories* rather than the origin of the raw materials. This regulation broadens the scope beyond conventional fertilizers to include a wider range of innovative products, including *bio-based* and *waste-derived fertilizers*, thereby supporting sustainable nutrient management. Thus, the transition from a fossil-based to a circular bio-based economy requires the recovery of nutrients from waste streams and redefining waste as a valuable resource [2].

As the global agrifood sector embraces sustainability, *bio-based fertilizers* are emerging as viable and environmentally friendly alternatives to conventional fertilizers, offering significant potential to leverage economies of scale and create new value chains across key market sectors. These circular solutions offer a win-win benefit: reducing the environmental impact of waste while minimizing nutrient losses and decreasing the demand for resource extraction and energy-intensive fertilizer production [3,4]. Although the term *bio-based fertilizer* is widely used in the scientific literature, it is not a formal *Product Function Category* under EU Regulation 2019/1009. In this review, the term refers to fertilizer products derived from renewable biological resources and organic waste streams. It is essential to clarify and differentiate the definition of *bio-based fertilizers* from that of *biofertilizers*, as this distinction is currently ambiguous in the literature. *Bio-based fertilizers* are produced from renewable sources, such as animal manure, agricultural residues, urban organic waste, and sewage sludge, through specific processes, including composting. In the case of *bio-based fertilizers*, they provide nutrients and organic matter (OM) directly to the soil [5]. In contrast, *biofertilizers* contain living microorganisms, such as bacteria and fungi, which colonize the rhizosphere when applied to the soil. These beneficial microbes enhance plant growth through multiple mechanisms, including improving nutrient cycling efficiency by converting nutrients from unavailable forms into plant-accessible compounds via nitrogen fixation, phosphate solubilization, and enzymatic mineralization of OM [6].

In the case of *bio-based fertilizers*, despite the benefits of recycling waste streams to produce them, associated risks remain, including the potential spread of pollutants and pathogens [4,7]. Traditionally, manure has been applied directly to agricultural soils as an organic amendment, often untreated, which can pose serious risks of soil contamination and environmental pollution. Therefore, developing and evaluating treatment processes is crucial to ensure the safe use of waste-derived materials in *bio-based fertilizers*. Such treatments (e.g., composting and anaerobic digestion) should maximize their beneficial properties, such as nutrient content, while minimizing the release of pollutants into the soil, addressing the inherent trade-off between resource recovery and environmental safety. Chicken manure (CM) composting is a key nutrient recovery pathway that converts nutrient-rich organic waste into a stabilized fertilizer product that complies with EU quality and safety requirements. Composting enables the stabilization and hygienization of these nutrients, facilitating their safe recycling into agriculture, reducing dependence on mineral fertilizers, and contributing to nutrient circularity.

In this context, the present study provides a narrative review of the conversion of CM into *bio-based fertilizers* via composting. Contrary to previous review articles, which

primarily focused on individual aspects of CM compost and its agricultural applications, this review adopts an integrated perspective by combining an analysis of the European regulatory framework, market trends, agronomic performance compared with conventional mineral fertilizers, and the technical feasibility of the composting process, with particular emphasis on odor mitigation strategies. In addition, environmental and health-related risks were assessed to provide a holistic understanding of the potential opportunities, challenges, and future perspectives associated with this valorization pathway. This review was primarily based on publications retrieved from the Web of Science database. The literature search was conducted using the keywords “composting” AND “chicken manure” AND “fertilizers” applied to article titles. To identify studies addressing specific environmental concerns, complementary searches were performed using the same keywords combined with “odor emissions” and “antibiotic resistance.” The search covered publications from 2000 to June 2026.

2. European Regulations for Fertilizers

For producing *bio-based fertilizers*, it is essential to determine their classification under the European fertilizer framework, specifically Regulation (EU) 2019/1009 of the European Parliament and of the Council of 5 June 2019 [8].

Regulation (EU) 2019/1009 is a key framework, enabling the EU single market for fertilizer products that were previously outside the scope of harmonized rules. This regulation sets safety, quality, and labeling requirements for these products, including requirements related to the maximum levels of contaminants and pathogens, minimum levels of nutrients, and other relevant characteristics depending on the product category. These limits safeguard soil protection and reduce risks to human health and the environment, while also providing manufacturers with the opportunity to adjust their production to comply with the new standards. Since July 2022, this regulation has replaced and repealed Regulation (EC) 2003/2003, which mainly covered mineral (inorganic) fertilizers [9]. Regulation (EU) 2019/1009 encompasses seven categories of EU fertilizing products (*Product Function Categories*), as illustrated in Figure 1. In the EU context, *Product Function Categories* provide a standardized framework for classifying fertilizing products for CE marking and market placement across Member States. Products are classified according to their function in soil or plant systems. In addition, Regulation (EU) 2019/1009 defines *Component Material Categories*, and any EU fertilizing product, regardless of its function category, must be composed solely of materials that comply with one or more of these categories. Regulation (EU) 2019/1009 designed eleven *Component Material Categories*: (1) virgin material substances and mixtures; (2) plants, plant parts, or plant extracts; (3) compost; (4) fresh crop digestate; (5) digestate other than fresh crop digestate; (6) food industry by-products; (7) microorganisms; (8) nutrient polymers; (9) polymers other than nutrient polymers; (10) derived products within the meaning of Regulation (EC) No 1069/2009; and (11) by-products within the meaning of Directive 2008/98/EC.

Although *bio-based fertilizers* are not an official category in European regulations, if they are produced from CM composting, they can be classified as either *organic fertilizers* or *soil improvers* based on the characteristics summarized in Figure 1. The final product of composting (commonly known as compost) is among these categories. Therefore, when an *organic fertilizer* or *soil improver* is derived from compost, it must comply with the criteria established for *Component Material Category 3* (compost), beyond the general requirements of its product function category (Table 1).

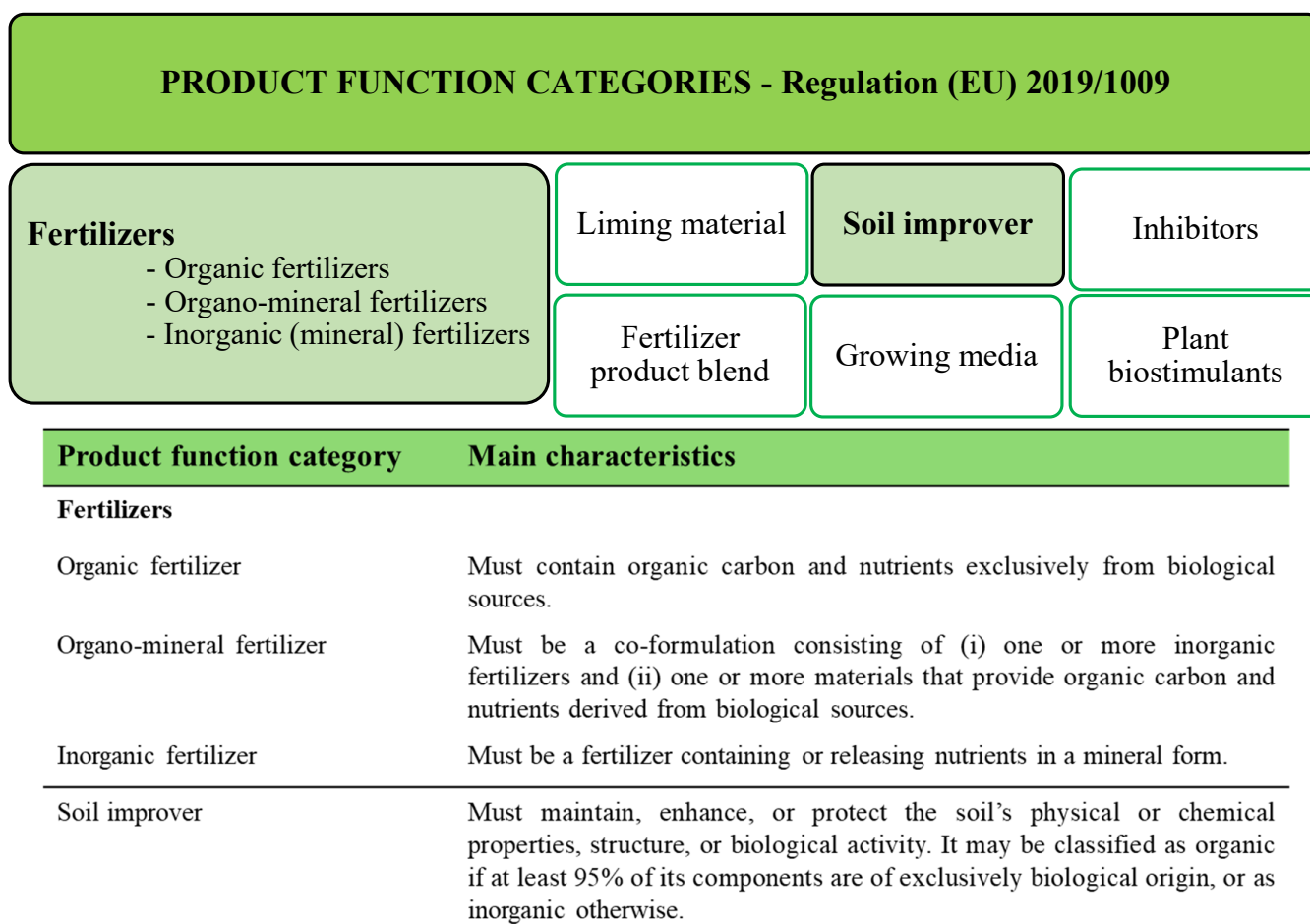


Figure 1. Product function categories according to the Regulation (EU) 2019/1009 for fertilizing.

Given that CM is an animal-derived material, it must also comply with Regulation (EU) 142/2011, which establishes sanitary standards for the processing of animal byproducts. This regulation specifies sanitization requirements, such as minimum temperature, particle size, and residence time, to ensure successful pathogen inactivation during treatment, specifically composting. Simultaneously, Regulation (EU) 2019/1009 specifies standards for EU fertilizing products, including compost-based fertilizers intended for the EU market. In addition to defining the quality and safety criteria for the final product, this regulation also defines composting process requirements, including minimum time-temperature profiles, to ensure proper sanitization. Although both regulations include time-temperature restrictions, they serve distinct functions and apply to various phases of the manufacturing process.

In addition to the criteria listed in Table 1, Regulation (EU) 2019/1009 requires that all materials be exposed to one of the following temperature–time profiles during composting: (i) ≥ 70 °C for at least 3 days; (ii) ≥ 65 °C for at least 5 days; (iii) ≥ 60 °C for at least 7 days; and (iv) ≥ 55 °C for at least 14 days. In addition, Regulation (EU) 142/2011 states that Category 3 materials—including animal-derived products—used as feedstock in a composting facility must meet the following conditions: (i) a maximum particle size of 12 mm, (ii) a minimum material temperature of 70 °C in the reactor, and (iii) a minimum uninterrupted retention time of 60 min.

Table 1. Parameters that must be complied with for a fertilizing product to be classified as an organic fertilizer or soil improver (*Product Function Category*) related to compost (*Component Material Category*) according to the Regulation (EU) 2019/1009.

Parameter	Units (on Dry Basis)	Product Function Category—Regulation (EU) 2019/1009		Compost from CM [10]
		Solid Organic Fertilizer	Organic Soil Improver	
Total N	%	$\geq 2.5^{(1)}$ or $\geq 1^{(2)}$	-	2.66
P ₂ O ₅	%	$\geq 2^{(1)}$ or $\geq 1^{(2)}$	-	3.68
K ₂ O	%	$\geq 2^{(1)}$ or $\geq 1^{(2)}$	-	5.06
TOC	%	≥ 15	≥ 7.5	37
Dry matter (%)	% (as is)	-	≥ 20	75
Cd	mg/kg	1.5	2	0.4
Cr VI	mg/kg	2	2	9.6 *
Hg	mg/kg	1	1	<0.03
Ni	mg/kg	50	50	9.3
Pb	mg/kg	120	120	1.3
As	mg/kg	40	40	-
Cu	mg/kg	300	300	88.2
Zn	mg/kg	800	800	547
<i>Salmonella</i> spp. <i>E. coli</i>	in 25 g (or mL) CFU/g	Absent <1000	Absent <1000	Absent <10
PAH ₁₆	mg/kg	<6	<6	-
Impurities (>2 mm) *	g/kg	<3	<3	<0.01
Impurities (total) *	g/kg	<5	<5	<0.01
OUR	mmol O ₂ /kg OM·h	≤ 25	≤ 25	-
Self-heating factor (Rottegrad)	-	$\geq$ III	$\geq$ III	III

⁽¹⁾ If only one macronutrient is declared; ⁽²⁾ if more than one macronutrient is declared—the sum should be 4%_{db}; * glass, metal, or plastics; TOC—total organic carbon; CFU—colony forming units; PAH—16 polycyclic aromatic hydrocarbons; OUR—oxygen uptake rate; *—measured as Cr total.

3. Market Dynamics and Environmental Impact

As the *bio-based fertilizer* derived from CM compost can be classified as an *organic fertilizer*, it is important to examine its market dynamics in comparison with mineral fertilizers. The global *organic fertilizer* market is set for strong growth, with projections estimating a rise from €10 billion in 2025 to €15 billion by 2030, reflecting a compound annual growth rate (CAGR) of approximately 9% over the forecast period [11]. In Europe, the sector is similarly expanding, with a value of approximately €4 billion in 2025 and expected to reach €5.7 billion by 2030, growing at a CAGR of approximately 8%. This momentum, namely in Europe, is driven by robust policy support, such as the Common Agricultural Policy, European Green Deal, and recent EU Fertilizing Products Regulations, which encourage sustainable and circular nutrient management strategies. Additionally, the global growth of this market is largely driven by the rising demand for organic food, growing environmental awareness, and a global shift toward more sustainable farming practices [12].

According to data from 2022, European agriculture relied almost equally on organic and mineral N sources: approximately 8.4 million tons of N were supplied through livestock-derived organic fertilizers, compared to 9 million tons from mineral fertilization. In the case of P, organic sources delivered 4.5 million tons, more than double the 2.2 million tons from mineral inputs. Similarly, K application from organic sources reached approximately 10 million tons, nearly four times higher than the 2.4 million tons provided

by mineral fertilizers. However, this nutrient distribution is uneven across Europe, with Western countries, particularly France, Germany, Spain, and the United Kingdom, recording the highest rates of *organic fertilizer* usage [13]. In line with the increasing use of *organic fertilizers*, there is a growing need to expand organic farming to meet the objectives of the European Green Deal. The share of EU agricultural land under organic farming grew from 5.9% in 2012 to 10.5% in 2022, reflecting a CAGR of 6% [14]. Achieving the EU's 25% target for organic farming by 2030 will require sustained acceleration in growth. This goal can be supported by scaling up the production of *organic fertilizers*, which also helps strengthen consumer confidence in sustainable agriculture.

Another market, not the primary focus of this work but closely related to organic farming, is the biofertilizer market. The global biofertilizer market is valued at approximately €3 billion in 2025 and is projected to grow to around €5 billion by 2030, representing a CAGR of 9.9%. Market dynamics are evolving as *organic fertilizers* are increasingly integrated into conventional agricultural systems. This transition is driven by environmental concerns, the need for sustainable farming practices, and the implementation of supportive regulatory policies [15].

The growing market for *bio-based fertilizers* highlights the need to examine their environmental impact, as well as their main opportunities and limitations compared to *inorganic fertilizers* (hereafter defined as *mineral fertilizers*).

Figure 2 summarizes the key advantages and disadvantages of using *bio-based fertilizers* compared to conventional *mineral fertilizers*.

Feature	Bio-based fertilizers	Mineral fertilizers
Nutrient concentration	Generally lower nutrient concentration	Generally higher nutrient concentration
Consistency	Nutrients composition may vary depending on feedstock and processing	More consistent and predictable nutrient composition
Commercial use	Bulkier materials: transport and application may be less efficient	Wide range of formulations adapted to different farming systems
Nutrient release	Usually gradual release. May improve nutrient use efficiency	Rapid nutrient availability. May require careful management to reduce losses
Effects on soil	May improve soil organic matter and biological activity when properly stabilize	Do not add organic matter. Impacts depend on management
Environmental aspects	Environmental benefits depend on proper stabilization and management	Environmental impacts depend on fertilizer type and management

Figure 2. Advantages and disadvantages of bio-based fertilizers compared to mineral fertilizers.

Mineral fertilizers are composed of highly soluble compounds, making their nutrients immediately accessible to plants and promoting rapid growth. However, when improperly managed or excessively applied, their high solubility can increase the risk of nutrient loss through leaching and runoff, resulting in significant environmental impacts. Depending on the fertilizer type, soil characteristics, and management practices, a substantial fraction (30–70%) of the applied nutrients from mineral fertilizers may be lost to the environment, contributing not only to water eutrophication but also to air pollution, soil degradation, and broader ecosystem disturbances [2,16]. Despite these concerns, *mineral fertilizers* offer

significant benefits, such as consistent concentrations of macronutrients (and, in some cases, micronutrients) and the need for smaller application rates.

In contrast, *bio-based fertilizers* release nutrients more slowly. Their effectiveness depends on soil microbial activity, which is influenced by soil moisture and temperature. While this slow-release mechanism may reduce nutrient losses and improve soil health, these benefits rely on the degree of stabilization and appropriate application of *bio-based fertilizers*. Nutrient leaching, ammonia and greenhouse gas emissions, salinity, or the spread of pathogens can all be caused by poorly stabilized and improperly applied fertilizers. In addition, their composition can vary owing to inconsistent feedstock sources, making the nutrient content less predictable. Some *bio-based fertilizers* remain at a low technology readiness level. Their development from novel renewable feedstocks often requires extensive R&D, together with product standardization and compliance with regulatory approval processes [2,17]. In addition, *mineral fertilizers* are available in a wide range of packaging sizes and formats, specifically designed to meet the diverse needs of large-scale agricultural operations. This level of packaging variety and convenience is generally absent in *bio-based fertilizers*, which are typically available in fewer formats and often sold in bulk or smaller, non-standardized packages.

4. Composting Chicken Manure to Produce Bio-Based Fertilizers

4.1. Process Optimization

Composting is a nature-inspired technology that relies on the aerobic decomposition of organic materials under controlled conditions to produce a stable, nutrient-rich product that enhances soil fertility and structure. In this way, composting provides an effective method to convert the OM in CM into a valuable product, avoiding the environmental burden associated with its direct disposal. Beneficial mesophilic and thermophilic microorganisms, appropriate conditions for microbiological activity, and nutrient availability are critical for the aerobic composting process [18]. Efficient composting requires careful control of multiple parameters, including temperature, mixture volume, particle size, porosity (or free air space—FAS), pH, moisture, oxygen concentration inside the mixture, carbon-to-nitrogen (C/N) ratio, and the quantity and quality of biodegradable OM [19].

Aerobic composting can be carried out using windrow or in-vessel systems, which are the most common technologies. Windrow composting without aeration is simple and low-cost but requires large land areas, longer processing times, and offers limited control with a higher odor risk. Aerated windrows improve oxygen control and reduce composting time, although they involve higher costs and energy use. In-vessel composting provides the highest level of process control, fastest stabilization, and minimal odors with a small footprint, but it requires high capital investment and skilled operation [18].

The degree of control provided by each composting technology directly influences the ability to maintain optimal operational conditions. Table 2 summarizes the optimal conditions for key composting parameters, including typical values for CM composting, associated challenges, and strategies for their mitigation. Although pH, moisture, and FAS depend on the properties of the feedstock, they vary throughout the process, making them potentially dynamic parameters. In batch composting, pH typically ranges from 6 to 9 over time, and values measured in raw materials or at different maturity stages are not reliable indicators on their own, limiting their usefulness for assessing compost maturity [20]. Deviations in pH outside the optimal range can hinder the transition from the mesophilic to the thermophilic phase, highlighting the need for monitoring and control during composting [21]. Moisture is a key parameter, with an optimal range between 40 and 60%, whereas well-matured and stable compost (final product) typically exhibits a moisture content below 35% [20]. The moisture content of raw CM may be higher than the

upper recommended limit, as shown in Table 2. Therefore, corrective measures should be applied before the composting process (e.g., air drying).

However, the most challenging parameter to adjust within the recommended range during CM composting is the C/N ratio. Table 3 summarizes selected studies on feedstock mixture optimization, highlighting strategies to achieve appropriate values for key composting parameters.

CM has a naturally low C/N ratio (7–15, Table 3) compared with the optimal conditions required for effective composting (see Table 2), indicating the need to optimize the feedstock mixture.

Literature studies summarized in Table 3 indicate that incorporating carbon-rich materials, such as biochar, wood-based materials, or agricultural wastes (e.g., rice straw, cornstalks) as composting additives to CM increases and sustains maximum temperatures relative to control treatments. This temperature increase is generally attributed to the favorable C/N ratio of the designed mixture (which improved microbial activity), but it was also supported by improved porosity from the added materials (bulking agents), which enhanced aeration during composting. Consequently, composting performance improves, leading to longer thermophilic phases, more effective OM breakdown, and ultimately improved compost maturity and stability, as corroborated by other studies [22].

Table 2. Optimal composting conditions, CM characteristics, process challenges, and mitigation strategies.

Parameter	Feedstock Initial Parameters	Process Optimal Conditions	Process Challenges	Mitigation Strategies
pH	6.77 [23]; 7.89 [24]; 7.59 [25]; 7.63 [26]; 7.51 [27]	6.0–9.0	Low pH—↓ microbial activity High pH—↑ NH ₃ volatilization and odors	Buffer with alkaline/acidic amendments depending on conditions
Moisture	78.6 ± 0.12% [23]; 77.3 ± 1.10% [24]; 55.0% [28]; 78.8 ± 0.41 [27]	50–70%	Excess moisture → anaerobic conditions, odors, leachate Low moisture → reduced microbial activity	Add dry bulking agents Add water if needed Continuous monitoring
C/N ratio	29.2 [23]; 11.4 [24]; 12.4 [25]; 13.9 [26]; 8.01 [28]	25–35	High C/N → slow degradation Low C/N → N losses (volatilization/leaching)	Add carbon-rich bulking agents (e.g., straw)
FAS	20% [27]	35–50%	Low FAS → anaerobic conditions High FAS → heat loss, lower temperature	Improve porosity using bulking agents Regular turning to prevent compaction
Temperature	Not applicable	40–70 °C	<40 °C prevents thermophilic phase, slower degradation, and pathogen survival	Improve aeration Ensure sufficient reactor volume Homogenize mixture
Oxygen concentration	Not applicable	≥5 or 10%	O ₂ deficiency → anaerobic conditions, odor emissions, slower decomposition, and nitrogen losses	Forced aeration systems Control moisture and airflow Regular mixing

CM—chicken manure; FAS—free air space.

Table 3. Literature studies of feedstock optimization for chicken manure composting.

Ref.	Feedstock (Optimal Mixture)	Mixture C/N Ratio	Composting Conditions				Main Conclusions
			H (%)	Aeration	Reactor Volume (L)	Duration (d)	
[29]	CM + RS CM + CS CM + WS (1:4 ratio dw)	19.6 ± 1.49 20.2 ± 6.23 30.3 ± 4.11	65	Intermittent forced (1 m ³ /min/m ³ every 30 min)	100	30	- Porosity: CM + RS (0.78) > CM + WS (0.75) > CM + CS (0.62) - CM + RS and CM + WS: ↑ O ₂ diffusion; ↑ microbial activity, prolonged thermophilic phase (>55 °C) - CM + CS: ↓ O ₂ diffusion, unstable temperature
[30]	CM + SMS (2.2:1 ratio dw) plus microbial and commercial inoculum	20–25	60	Forced (12.5 L/min for 8 h a day)	112	13	- Peak temperature: 74 °C with microbial inoculum; >65 °C reached on day 3 - Thermophilic phase: 13 days - Microbial inoculum: ↑ thermophilic temperature (+3–7 °C vs. control)
[26]	CM + SD (4:1 ratio dw) plus RB (0, 3, 5, 10%)	25–30	65	0.1 L/min	-	50	- Biochar: ↑ thermophilic temperature (66–70 °C vs. 60 °C in control) - Thermophilic phase: 7 days, with pathogen inactivation
[31]	CM + CS (4:1 ratio ww) WCB, CSB, and RB mixed separately at 10% of the mixture	-	65	0.27 L/kg·min	60	42	- Biochar: ↓ low-molecular-weight organic acids; ↑ pH stability - Temperature: >50 °C (day 2–14); 70 °C maximum with biochar - CSB treatment: higher temperature

Ref.—reference; CM—chicken manure; RS—rice straw; CS—corn strover; WS—wheat straw; SMS—spent mushroom substrate; SD—sawdust; RB—rice husk biochar; WCB—wood chip biochar; CSB—cornstalk biochar;; dw—dry weight; ww—wet weight; H—moisture.

According to the work developed by [31], at the end of composting, the germination index of the biochar-added treatments was between 70 and 75%, compared to 56% in the control treatment (only CM). These results indicate that biochar can improve the maturity of the control treatment, a significant finding given the potential use of these materials in soil. Typically, the C/N ratio decreases gradually toward values between 10 and 15, as microbial activity converts organic carbon into CO₂.

In summary, adding bulking agents to CM, such as wood chips, sawdust, straw, or biochar, can significantly improve FAS (porosity), aeration, moisture regulation, and organic carbon availability, thereby enabling robust thermophilic microbial activity, effective OM breakdown, and enhanced humification. Nonetheless, producing a high-quality compost requires balancing structural improvement and aeration with appropriate C/N and biodegradability. Indeed, overuse of highly recalcitrant bulking agents may lead to

elevated final C/N ratios or lower humification, even if other maturity indices appear satisfactory [32].

Temperature is a key control parameter and must be continuously monitored during composting to ensure effective sanitization (pathogen inactivation), particularly when processing feedstocks such as manure. In batch systems, including windrow composting, temperature evolution is highly dynamic, as illustrated in Figure 3a [33]. The process typically evolves through four successive stages. The initial mesophilic phase (20–40 °C) is dominated by mesophilic microorganisms (such as bacteria, fungi, and protozoa) that degrade readily biodegradable OM. As microbial activity intensifies, temperatures rise above 40 °C, initiating the thermophilic phase, during which thermophilic microorganisms prevail. This stage is characterized by intense biological activity, fast OM degradation, and increased oxygen consumption. The thermophilic phase is essential for hygienization of the composting mixture, as the elevated temperatures promote the inactivation of pathogenic microorganisms. According to Section 2, the European Legislation specifies minimum time-temperature conditions that must be achieved during the thermophilic phase to ensure effective pathogen reduction. As readily degradable substrates become progressively exhausted, microbial activity declines, and temperatures decrease, leading to a second mesophilic phase. Finally, as the material approaches ambient temperature, the maturation phase begins, during which the compost stabilizes and evolves into a mature and high-quality final product [34]. The oxygen uptake rate (OUR) may be used as an indicator of compost stability, whereas maturity is generally assessed using the self-heating factor, as established in the relevant legislation (Table 1) [34].

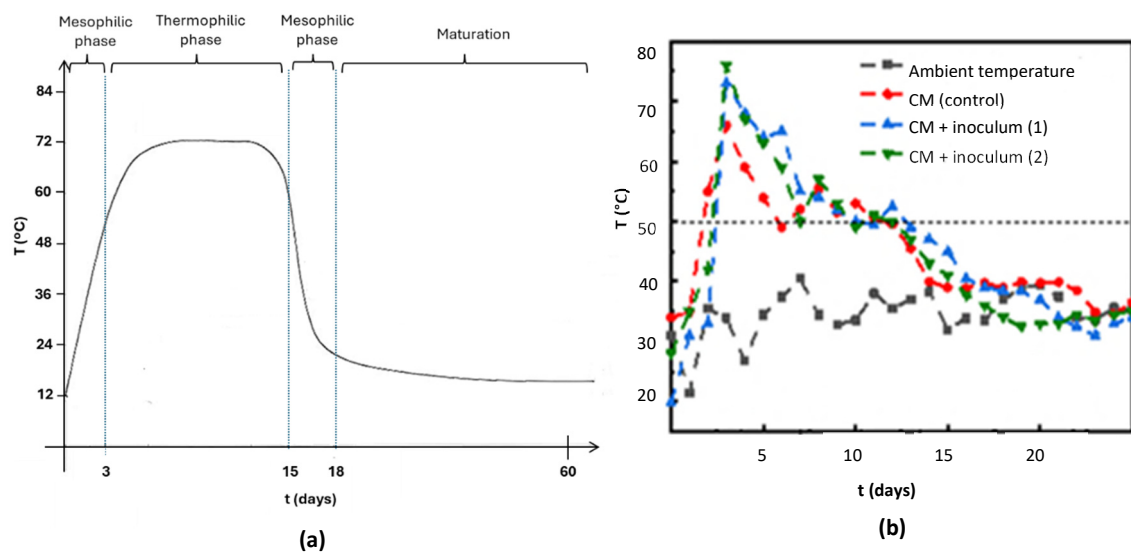


Figure 3. Temperature–time profiles during composting: (a) generic batch process [Adapted from [32]] and (b) chicken manure composting in batch, with and without inoculum [Adapted from [29]].

Figure 3b illustrates a representative temperature–time profile obtained during batch composting using CM as the raw material, with and without the addition of inoculum. According to the results, all three composting treatments exceeded 65 °C by the third day of the process. The inoculum-amended treatments reached thermophilic temperatures approximately 3–7 °C higher than the control. Moreover, the thermophilic phase persisted for around 13 days, a duration that may be sufficient to comply with legislative requirements for effective compost hygienization [30].

Regarding the hygienization of compost, although composting relies on the activity of beneficial microorganisms, CM may also have a wide range of pathogenic bacteria, including *Escherichia coli* and *Salmonella* spp. [35]. Therefore, compost intended for agricultural

use should be free of pathogens at concentrations that may pose a risk to overall health. The composting process can eliminate pathogens loads through a combination of different mechanisms, such as microbial competition, nutrient depletion, the production of inhibitory compounds (e.g., organic acids and ammonia), and, most importantly, thermal inactivation during the thermophilic phase [36–39]. Among these mechanisms, temperature is the primary factor governing pathogen destruction, with microbial inactivation depending on both the temperature reached and the duration of exposure. Consequently, lower temperatures maintained for longer periods may achieve pathogen reductions comparable to those obtained during shorter exposures to higher temperatures [39].

4.2. Environmental and Health Challenges

4.2.1. Soil Benefits and Challenges

The shift from linear nutrient management to nutrient circularity is a key strategy for enhancing the sustainability of agricultural systems. CM composting supports this transition by recycling nutrients and OM into soils, which reduces reliance on synthetic fertilizers and mitigates nutrient losses throughout the agri-food chain. Despite its considerable agronomic potential, the sustainable application of CM compost requires careful management to address several environmental challenges [40]. Nitrogen conservation is a primary concern during composting, since N undergoes transformations such as ammonification, nitrification, immobilization, and denitrification, resulting in a dynamic N pool that includes organic N, ammonium (NH_4^+), and nitrate (NO_3^-). During the thermophilic phase, high temperatures and alkaline pH conditions promote ammonia (NH_3) volatilization, which is often the main pathway for N loss [41]. This volatilization not only reduces the fertilizer value of the compost but also contributes to the formation of atmospheric particulates, acidification, and indirect nitrous oxide (N_2O) emissions.

Preserving N losses enhances the fertilizer value of compost by providing a larger reservoir of both organic and mineral N, which can be gradually released to crops through mineralization. This process improves nutrient-use efficiency and decreases the need for synthetic N fertilizers. Conversely, excessive N losses reduce the nutrient content of the compost, often necessitating higher application rates to meet crop nutrient requirements. After field application, the stabilized organic N fraction supplies slow-release nutrients, lowering the risk of NO_3^- leaching compared to mineral fertilizers. However, inappropriate application rates or poor balance between N release and crop demand can still result in NO_3^- leaching and N_2O emissions from agricultural soils. Therefore, maximizing N retention during composting and implementing site-specific nutrient management strategies are essential for improving crop productivity while minimizing environmental impacts [42–44].

Phosphorus management is also critical for achieving nutrient circularity. Composting facilitates the mineralization of organic P into plant-available orthophosphate, thereby increasing P availability compared to raw CM. This transformation improves fertilizer efficiency and reduces dependence on mineral phosphate fertilizers. Nevertheless, repeated compost applications based on crop N requirements may lead to P accumulation in soil, increasing the risk of P runoff and eutrophication of nearby water bodies. Balanced nutrient management plans that consider both N and P requirements are therefore necessary for long-term sustainability. Stabilized compost typically reduces P mobility compared to fresh CM, as P becomes associated with OM and mineral fractions, resulting in slower nutrient release and improved soil retention [19].

In addition to nutrient losses, CM can introduce other environmental contaminants into agricultural soils, such as potentially toxic metals (e.g., copper and zinc), due to their frequent use as feed additives in poultry diets. While composting does not eliminate these metals, the stabilization of OM may reduce their bioavailability through complexation with

humified organic compounds. Nonetheless, ongoing field application requires periodic monitoring to prevent long-term accumulation in soils [45].

Also, the transformation of OM during composting significantly affects compost quality and long-term soil benefits. Most OM mineralization occurs during the active phase, when microorganisms rapidly degrade biodegradable compounds such as carbohydrates, proteins, lipids, and amino acids. As decomposition progresses, more recalcitrant fractions, including cellulose, hemicellulose, and lignin, become dominant, and humification processes lead to the formation of stable humic-like substances rich in carboxylic, phenolic, and amine functional groups. During the maturation phase, OM becomes increasingly stabilized, resulting in a dark-colored compost with improved physicochemical properties [19,46]. Assessing compost maturity and stability indicators are essential before agricultural application, as immature compost may cause phytotoxicity, N immobilization, oxygen depletion, and poor crop establishment. Common indicators of maturity include temperature stabilization, C/N ratio, ammonium-to-nitrate ratio, respiration activity, oxygen uptake rate, CO₂ evolution, germination index, and humification indices [20].

The long-term effects of CM compost on soil quality are generally beneficial when appropriate application rates are maintained. Repeated applications increase the soil organic carbon pool, enhance aggregate stability, improve water-holding capacity, reduce bulk density, increase cation exchange capacity, and stimulate soil microbial biomass and biodiversity. Several soil studies have shown that CM compost can sustain or increase crop productivity while improving nutrient-use efficiency compared to raw manure or mineral fertilizers alone. Integrated nutrient management strategies that combine compost with mineral fertilizers often achieve higher nutrient-use efficiency than either source alone, while also improving soil fertility over multiple growing seasons. Although crop responses vary with soil type, climate, compost maturity, and management practices, soil experiments consistently demonstrate that CM compost helps maintain soil fertility and reduces dependence on synthetic fertilizers, thereby strengthening nutrient circularity in agricultural systems [47,48].

4.2.2. Odor Issues

Regulations typically do not cover leachates, odors, and gaseous emissions from composting processes. However, during CM composting, significant emissions occur, including NH₃, hydrogen sulfide (H₂S), and total volatile organic compounds (TVOC), representing a particularly critical challenge. These gases not only pollute the surrounding air and endanger human health, but also cause the loss of N, S, and C, which may compromise the product quality [49]. Therefore, it is essential to mitigate these gaseous emissions from an environmental, economic, and social perspective. Several approaches have been reported in the literature, as summarized in Table 4, to mitigate odor emissions, such as the addition of microbial inoculum, controlling the process conditions (e.g., aeration, moisture content), functional additives, and feedstock adjustments.

Zang et al. [49] investigated the use of a functional additive as a microbial inoculum (carbon-based microbial agent—CBMA) in combination with a biotrickling filter to enhance odor removal during the composting process of chicken manure with corn straw. The authors concluded that the release of NH₃ occurs during the early phase of composting. In the treatment with the functional additive, the release duration was limited to 1–4 days, resulting in cumulative emissions of 40,466 ± 37.91 mg. By contrast, the control treatment (CM with corn straw) showed a prolonged release period of 1–11 days and higher cumulative emissions of 50,125 ± 25.63 mg. Overall, the use of the functional additive achieved an approximately 25% reduction in emissions. Regarding H₂S emissions, the release duration was similar in both treatments, possibly due to the high oxygen consumption associated

with microbial activity. However, lower H_2S levels were observed with the CBMA additive, probably because its porous structure enhanced the adsorption of odorous molecules. The cumulative emissions were 7906 ± 20.69 mg with CBMA compared to $10,548 \pm 17.36$ mg in the control treatment. In addition, the combined use of a biotrickling filter and CBMA additive proved to be an attractive solution, achieving removal efficiencies of approximately 90, 96, and 56% for NH_3 , H_2S , and TVOC, respectively. The compost produced with CBMA had a high NO_3^- content, which increased by 36.5% compared to the control. In addition, the total nitrogen retention rate after composting increased by 14.6%, thereby improving the compost quality.

Ma et al. [50] investigated how varying oxygen levels affect H_2S and NH_3 emissions during the composting of CM with cornstalks. Five distinct oxygen levels were evaluated: four intermittent rates (0.05, 0.1, 0.2, and $0.4 \text{ m}^3/\text{h}$, supplied every 30 min) and one continuous rate ($0.1 \text{ m}^3/\text{h}$). During the thermophilic phase, higher aeration enhanced the NH_3 emission rate owing to enhanced convective stripping and mass transfer of volatilized ammonia. However, by the end of the composting period, the highest aeration rate ($0.4 \text{ m}^3/\text{h}$) resulted in the lowest cumulative NH_3 emissions. This was likely due to the high moisture removal, which limited microbial activity and suppressed organic N ammonification. When other factors, such as compost maturity and humification, were considered, the authors found that continuous moderate aeration ($0.1 \text{ m}^3/\text{h}$) minimized H_2S emissions because it maintained sufficient oxygen in the mixture, preventing anaerobic conditions that lead to H_2S formation. According to Ma et al. [50], an aeration of $0.1 \text{ m}^3/\text{h}$ emerges as the optimal condition for composting. This rate is sufficient to ensure effective maturity and humification while minimizing the NH_3 and H_2S emissions. Continuous aeration at this level maintains aerobic conditions and prevents anaerobic zones that generate odorous and harmful gases. Moreover, an aeration rate of $0.1 \text{ m}^3/\text{h}$ promoted humic substance formation and ensured both high environmental performance and compost quality.

Another effective strategy for reducing odor emissions is the incorporation of functional feedstock optimization, as demonstrated in some studies [51,52]. In fact, Li et al. [51] investigated the addition of different volumes of mature compost to the composting of CM with rice husk. The results showed that mature compost (10–30%) not only accelerated the composting process but also supported higher temperatures and improved key maturity indicators, including pH, electrical conductivity (EC), C/N ratio, and germination index. With respect to emissions, the authors found that adding 20% mature compost to the rice husk and CM mixture effectively reduced NH_3 and CH_4 emissions without increasing greenhouse gas (GHG) release. Considering both emissions and final compost quality, 20% mature compost backfilling was the optimal supplementation rate. It enhances microbial diversity and N cycling, suppressing gas losses without external inoculants, and offers a practical way to improve compost quality while reducing emissions [50,53–55].

The study by Liu et al. [52] investigated the use of additives such as biochar, superphosphate, and magnesium sulfate, both individually and in combination. Biochar is an interesting option because it enables the valorization of additional waste streams. However, the authors observed a 16% increase in cumulative NH_3 emissions and a reduction in NH_4^+ content, which is undesirable for N conservation. These effects are likely linked to the high pH and porous structure of biochar, which favors NH_3 volatilization and enhances aeration. In contrast, the porous structure can reduce anaerobic zones and adsorb H_2S , whereas the high pH may inhibit the reduction of sulfate or organic sulfur to sulfide. Therefore, the application of biochar requires balancing compost quality with the management of NH_3 and H_2S emissions, which can be optimized through careful dosage control.

Some studies have reported the use of zeolites as effective additives for mitigating odor emissions from CM. Their effectiveness is mainly attributed to their high cation-

exchange capacity and adsorption properties, which enable the capture of NH_3 and other volatile compounds responsible for unpleasant odors. Moreover, zeolite can contribute to N retention during CM storage and composting, improving the agronomic value of the final product while reducing environmental impacts [55,56].

Overall, no single odor mitigation strategy can simultaneously minimize gaseous emissions while preserving compost quality and nutrient content. Operational parameters, including aeration, moisture content, and C/N ratio, play crucial roles in odor control. However, optimizing these parameters often involves tradeoffs. For example, increasing aeration effectively suppresses anaerobic conditions and reduces H_2S emissions, but excessive aeration may enhance NH_3 volatilization, accelerate moisture loss, increase energy consumption, and negatively affect compost stabilization. Similarly, amendments such as mature compost, biochar, microbial inoculants, and biotrickling filters have shown potential for odor mitigation through mechanisms such as adsorption, microbial competition, and biofiltration. Nevertheless, their effectiveness is strongly influenced by feedstock characteristics, operational conditions, application rates, and economic feasibility, resulting in variable outcomes. Therefore, future composting strategies should adopt an integrated approach that simultaneously considers odor mitigation, nutrient conservation, GHG emissions, compost maturity, and economic viability rather than optimizing individual parameters.

Table 4. Literature studies exploring odor emissions during chicken manure composting.

Ref.	Study Aim	Experiment Setup and Materials	Main Conclusions
[50]	Investigate the impact of the biotrickling filter and insertion of a carbon-based microbial agent (CBMA) on odor emissions during CM composting.	Feedstock: Fresh CM, CS, and CBMA Treatments: T1—CM:CS (2:1 ww); T2—CM + CS + 10% CBMA Moisture content: 65% Aeration: Forced airflow at 4 L/min Reactor volume: 50 L Duration: 30 days Sampling: days 0, 5, 10, 15, 20, 25, and 30	- CBMA (T2): ↓ 25% NH_3 and H_2S ; ↓ 20% TVOC (vs. control) - Biotrickling filter: 90% of NH_3 , 96% of H_2S , and 56% of TVOC emissions removal.
[48]	Investigate the effects of different doses of a Bacillus-based inoculum on NH_3 and H_2S emissions during CM and sawdust composting.	Feedstock: CM + SD (5:1 ww); C/N ratio of 14 Bacillus inoculum: <i>Bacillus subtilis</i> , <i>Bacillus licheniformis</i> , <i>Bacillus amylolyticus</i> , and <i>Bacillus lateosporus</i> at a mass ratio of 1:1:1:1 Treatments: Bacillus inoculum—0.05, 0.1, and 0.2% Aeration: 4 L/min·kg Reactor volume: 30 L Sampling: days 0, 1, 4, 7, 10, 14, 21, and 28	- NH_3 emissions: Bacillus inoculum (0.05%) > control. - Bacillus inoculum: ↑ H_2S emissions (vs. control).
[51]	Investigate the influence of five oxygen levels on odor (H_2S and NH_3) emissions during CM composting with cornstalks (CS).	Feedstock: CM:CS (85:15 ww) Moisture content: 65% Aeration: 0.1 m^3/h (continuous) + intermittent aeration (every 30 min): 0.05, 0.1, 0.2, and 0.4 Reactor volume: 60 L Duration: 35 days	- NH_3 emissions: ↑ in the first 2 weeks; ↑ temperature; ↑ aeration rate (during thermophilic phase) - H_2S emissions: ↑ first 10 days; ↑ aeration > 0.2 m^3/h . - Continuous moderate aeration at 0.1 m^3/h led to the lowest cumulative H_2S emissions.

Table 4. Cont.

Ref.	Study Aim	Experiment Setup and Materials	Main Conclusions
[54]	Investigate the effect of two thermophilic microbial agents (TMA) on the inhibition of NH ₃ , H ₂ S, CH ₄ , and N ₂ O emissions during CM + wheat straw (WS) composting	Feedstock: CM:WS (4:1 ww); C/N ratio 16 Treatments: (T1) CM + WS; (T2) CM + WS + TMA (4% dw), and 108-spore/kg dw of thermophilic fungal agent Moisture content: 60% Aeration: continuous at 0.3 m ³ /h (0–14 days) and at 0.2 m ³ /h (15–35 days) Reactor volume: 60 L Duration: 35 days; turning on days 6, 15, and 26	- NH ₃ emissions: ↑ initial (0–10 days; >60 °C); ↓ with thermophilic microbial agents (weak effect for bacteria) - H ₂ S emissions: ↓ 25% (bacteria) and ↓ 34% (fungi) vs. control - CH ₄ emissions: ↓ with fungal agent
[52]	Investigate the mechanisms of mitigating gaseous pollutants during co-composting of fresh CM with rice husk (RH) and mature compost (MC).	Feedstock: Mature compost produced with CM + RH for 35 days of open-air composting Treatments: (control) 30% CM + 70% RH; (T1) 30% CM + 60% RH + 10% MC; (T2) 30% CM + 50% RH + 20% MC; (T3) 30% CM + 40% RH + 30% MC; Bacterial inoculants added at 0.2% dw Moisture content: 60% Aeration: intermittent aeration every 30 min at 0.2 L/(kg _{dw} ·min) Reactor volume: 60 L Duration: 30 days composting; turning on day 0, 2, 6, 10, 15, 22, and 30 Sampling: days 0, 2, 10, and 30	- CH ₄ emissions: ↓ in T2 (−41%) and T3 (−62%) vs. control - N ₂ O emissions: ↑ with MC dosage (T3 > T2 > T1 > control) - Total GHG emissions: ↓ in T2 (−2.58%) - NH ₃ emissions: ↓ in T1 (−32%), T2 (−34%), T3 (−56%) vs. control
[53]	Investigate the individual cornstalks (CS) and the combined effect of biochar (BC), superphosphate (SP), and magnesium sulfate (MS) on emissions of malodorous substances during CM composting.	Feedstock: BC produced from cornstalks (2–4 cm size); CM:BC (85:15 ww) Treatments: (control) CM + CS; (T1) CM + CS + 10%BC; (T2) CM + CS + SP (15% of initial N content); (T3) CM + CS + SP + MS (15% of initial N content); (T4) CM + CS + BC + SP + MS Reactor volume: 60 L Aeration: continuous at 0.2 L/kg·min (1–14 days) and at 0.1 L/kg·min (15–35 days) Duration: 35 days	- VSC: 8 compounds detected; H ₂ S, (CH ₃) ₂ S, (CH ₃) ₂ S ₂ dominant - H ₂ S emissions: ↓ in T1 (−31%) and T4 (35%) vs. control - (CH ₃) ₂ S and (CH ₃) ₂ S ₂ : ↑ mainly in the first 7 days, like H ₂ S pattern - Total sulfur odor compounds emissions: ↓ in T4 (−72%) > T1 (−65%) > T3 (−60%) > T2 (−51%)

Ref.—reference; CM—chicken manure; H—moisture content; ww—wet weight basis; TVOC—total volatile organic compounds; CS—cornstalks; CBMA—carbon-based microbial agent; SD—sawdust. T—temperature; ww—wet weight basis; dw—dry weight basis.

4.2.3. Antibiotic Contamination and Prevalence of Antibiotic Resistance Genes

Antibiotic resistance is a multifaceted environmental and public health challenge that involves several interconnected yet distinct concepts [57,58]. Antibiotic residues are pharmaceutical compounds that persist in environmental matrices after administration and excretion. Although these residues are not themselves resistant, they exert selective pressure on microbial communities, promoting the persistence and proliferation of antibiotic-resistant bacteria (ARB). Resistance is conferred by antibiotic-resistance genes (ARG), which can disseminate among bacterial populations via mobile genetic elements [59]. The collective presence of all ARG within a specific environment is referred to as the resistome. Although not all resistant bacteria are pathogenic, the transfer of ARG to pathogenic microorganisms poses a significant threat to both the environment and public health.

The chicken industry often relies on antibiotics to control and prevent infectious diseases, ensure animal health, and boost operational efficiency. However, the excessive use of these antibiotics and poor metabolism can lead to accumulation in manure. The most common classes of antibiotics used in food-producing animals, such as the chicken industry, are tetracyclines, penicillin, and sulfonamides [58]. The fixation and sorption of various antibiotics in soil are influenced by its specific physicochemical properties, climate conditions, and soil characteristics [56]. This aspect is not covered by European Legislation.

Table 5 summarizes selected studies regarding the prevalence of antibiotic residues, ARB, and ARG during the composting of CM.

Chen et al. [56] conducted a study in which CM from different farms was collected for seven consecutive days, starting one day before the administration of oxytetracycline. CM from chickens without antibiotic administration was used as a control. In addition, CM samples after composting were also collected for comparison purposes. The selected farms administer antibiotics exclusively for infection treatment and for limited durations. Antibiotic residues were present in CM samples during the administration period, but no residues were detected by the second day after the end of the antibiotic treatment. The authors suggest that antibiotic residues disappear rapidly after post-treatment due to metabolism and degradation in the chicken's body or microbial degradation, adsorption, or transformation in the manure matrix [60].

The tetracycline administration did not alter the proportion of ARB in the CM compared to the control sample (manure without antibiotic administration). However, Chen et al. [56] verified that composting increased ARB from 18 to 49% compared to the control sample. This result is likely due to the proliferation of antibiotic-tolerant microbes, indicating a potential risk of ARB dissemination. In addition, antibiotic use and composting significantly reduced bacterial diversity in CM, with the greatest decrease observed during antibiotic administration [56].

A recent study by Jia et al. [60] reached contrary conclusions regarding the effectiveness of CM composting in reducing ARG abundance and mobility. This study analyzed ARG profiles, their mobility potential, and the risk associated with the antibiotic resistance (collection of all ARGs in a specific microbiome or environment), under varying feedstock, moisture, and aeration rate. Results showed that feedstock and aeration rate had no significant effect ($p > 0.05$) on ARG abundance reduction compared to the control (60% moisture content, 0.12 L/(min.kg)). In contrast, moisture content was the most influential factor ($p < 0.05$). The treatments with 50% of moisture content showed poorer ARG removal rates and a significant rebound in ARG abundance from day 30 onward (maturation phase). On the contrary, moisture levels of 60–65% effectively mitigated ARG rebound, likely due to an extended mesophilic and thermophilic phase [60].

Jia et al. [60] noted that composting alters ARG profiles and mobility through changes in physicochemical properties, antibiotic residues, heavy metals bioavailability, and microbial composition. Correlation analysis showed that key factors influencing ARG classes shifted from the active phase (temperature, pH, EC, and moisture content) to the maturation phase (moisture content and total organic carbon). During the composting active phase, microbial growth raised the temperature and reduced moisture, helping lower ARG abundance via heat sterilization and microbial water use. In the maturation phase, lower moisture levels favored dry-tolerant microbes like *Firmicutes*, which became the main ARG hosts. For pathogenic ARB, ARG abundance decreased from 9.7–21.6% on day 0 to 2.7–6.6% after composting. Overall, composting is effective at reducing ARG, but its efficiency depends largely on moisture management [44], consistent with other studies [61–63].

Wu et al. [64] explored microbial inoculation to enhance ARG removal during CM with rice husk composting. The authors noted that while composting can reduce ARG, it is not always efficient and rapid. As an alternative, inoculation with *Bacillus subtilis* can extend the thermophilic phase, accelerate maturation, eliminate pathogens, and enhance ARG reduction. Combining *Bacillus subtilis* with biochar offers further benefits, as biochar regulates microbial growth, limits antibiotic availability, and constrains horizontal gene transfer, supporting ARG mitigation in both compost and soil [64].

Table 5. Literature studies exploring the prevalence of antibiotic residues, antibiotic-resistant bacteria, and antibiotic-resistance genes during composting of chicken manure.

Ref.	Study Aim	Experiment Setup and Materials	Main Conclusions
[60]	Investigate how oxytetracycline and composting (in a pile) change bacterial diversity, resistance patterns, and metabolic functions in CM	- CM from 40 days stage (control) - CM from chicken fed with tetracycline for 3 days - CM after 30 days of composting Antibiotic: Oxytetracycline (30 mg/kg)	- Antibiotic residues in CM were detected only during the administration period: 2–10 mg/g on day 1 and 15 mg/g on day 3. - Oxytetracycline treatment did not alter ARB levels compared to the control. - After composting, ARB increased from 18 to 49% relative to the control. - Antibiotic administration and composting: ↓ bacterial community diversity in CM.
[61]	Investigate the effect of moisture content, composting amendments, and aeration rates on the elimination of ARG during CM composting in a greenhouse for 45 days.	Feedstock: CM + mushroom residues (MR); initial C/N ratio 20 Treatments: biochar and calcium magnesium phosphate—0, 5, and 10% Moisture content: 50, 60, and 65% Aeration: 0.08, 0.12, and 0.20 L/(min.kg) Reactor volume: 400 L (open vessel) Sampling: days 0, 3, 8, 30, and 45	- A total of 708 ARG from 27 antibiotic resistance classes were identified across all compost samples. - ARG: ↓ 29.4–82.4% during the process. - During the maturation phase, a lower initial moisture content (50%) led to a rebound in ARG abundance. - Moisture content: the strongest controlling factor.
[62]	Investigate the effect of heavy metals passivation, ARG degradation, and rebound effect in the combined application of reactor and static composting.	Feedstock: CM Reactor composting plus static Duration: 8 days (reactor) plus 24 days (static composting) Sampling: days 0, 8, 24 (2 samples—middle and top of the pile), 32.	- Reduction in the total abundance of ARG during the composting process compared to the control (day 0). - About 72.9% of ARGs were reduced during composting in the reactor, with a total of around 84% after 24 days in a static pile.
[63]	Investigate the interaction among bacterial communities, nutrients, heavy metals, antibiotics, and ARG during the composting process and in soil after fertilization.	- 10 samples of fresh CM - 13 samples of compost CM (after thermophilic phase in reactor, 15 days) - 25 samples of compost CM (after maturing phase in pile, 30 days) - 10 samples of fertilized soil with compost for three years Treatment: Compost of CM:bagasse:corn cob (5:3:2 v/v), with C/N ratio of 26 and a moisture content of 55%	- <i>Firmicutes</i> were the most abundant phylum during the composting process, increasing from 38.6% in the reactor phase to 80.1% in the pile phase. - The abundance of potential pathogenic bacteria decreased sharply from fresh CM (37.2%) to final compost (3.43%). - <i>Bacteroides</i> and <i>Pseudomonas</i> were the most abundant pathogenic bacteria in the fresh CM.
[64]	Investigate the combination of <i>B. subtilis</i> inoculation with biochar and rice husk (RH) to enhance ARG reduction and product quality during CM composting.	Treatments: (1) composting of CM + RH + 0.5% of <i>B. subtilis</i> ; (2) composting of CM + RH + 6% biochar + 0.5% of <i>B. subtilis</i> ; (3) control—composting of CM with RH. Reactor volume: 165 L Sampling: days 0, 2 (warming phase), 4 (high-temperature stage), 10 (cooling phase), and 31 (maturation stage)	- <i>B. subtilis</i> affects the bacterial community structure in the high-temperature stage. - <i>Firmicutes</i>, <i>Actinobacteria</i>, <i>Proteobacteria</i>, and <i>Bacteroidota</i> were the most dominant. - <i>Firmicutes</i> were the most abundant bacteria on day 0 and on day 10 in all three treatments. - The treatment with <i>B. subtilis</i> and biochar achieved 97% of ARG removal efficiency.

Ref.—reference; CM—chicken manure; ARB—antibiotic-resistant bacteria; ARG—antibiotic-resistance genes; avg.—average.

The results indicate that the relative abundance of ARG decreased markedly after the high-temperature phase of the composting and continued to decline over time. By the end of composting, ARG were reduced by about 93 and 97% in the treatment with *Bacillus*

subtilis alone and with *Bacillus subtilis* plus biochar, respectively. The rapid growth of *Bacillus subtilis* during the thermophilic phase likely helped suppress resistant host bacteria, while biochar favored non-resistant microorganisms, making the combination effective for ARG reduction [64]. Considering that the addition of external agents can enhance ARG mitigation, several studies have explored other additives, including mineral materials (diatomite and bentonite) [47], chitosan [48], microbial inoculum with ferric chloride [23], and biochar [49].

Overall, the literature indicates that ARG persistence during composting is governed by multiple interacting factors rather than temperature alone. Moisture content strongly influences microbial activity and determines whether ARG rebound occurs during the maturation phase. Adequate aeration promotes aerobic degradation but may also alter microbial succession. Likewise, prolonged thermophilic conditions generally enhance ARG reduction through pathogen inactivation, whereas the recolonization of compost by drought-tolerant microorganisms during maturation may contribute to ARG persistence or rebound. Heavy metals may exert co-selection pressure, while mobile genetic elements facilitate horizontal gene transfer and ARG dissemination even after antibiotic residues have declined. Consequently, ARG mitigation depends on the combined effects of process conditions, microbial community dynamics, and compost maturation.

5. Insights and Perspectives on Future Studies

Despite the considerable progress achieved in CM composting, several scientific and technological challenges remain insufficiently addressed. Current research is largely focused on optimizing individual process parameters under controlled experimental conditions, whereas fewer studies evaluate integrated composting systems, long-term agro-economic performance, and environmental sustainability under practical operating conditions. Addressing these gaps is essential to improve the efficiency, safety, and large-scale implementation of CM composting.

One important research gap concerns the development of integrated and modified composting strategies capable of producing consistently high-quality compost. Although several studies have investigated specific amendments, microbial inoculants, or aeration strategies, the synergistic effects of combining different composting approaches remain poorly understood [45,49–51]. Future research should therefore evaluate hybrid systems, such as reactor composting followed by conventional windrow or pile maturation, to improve compost maturity, stability, nutrient conservation, and pathogen reduction while maintaining economic feasibility. Likewise, integrated resource recovery approaches, particularly those combining anaerobic digestion with composting, deserve further investigation because they offer the potential to simultaneously recover renewable energy and produce high-quality organic fertilizers within a circular bioeconomy framework [52–54].

Another major limitation identified in the literature is the scarcity of real-time monitoring and process automation, particularly for industrial-scale composting facilities. Most studies rely on periodic measurements of physicochemical parameters, which provide limited information for dynamic process control. The implementation of sensor-based monitoring systems, coupled with automated aeration and moisture management, could significantly improve process performance, reduce nutrient losses and gaseous emissions, and ensure more consistent compost quality. The integration of digital technologies and precision composting tools therefore represents an important direction for future research, especially considering the increasing demand for efficient nutrient recycling within circular economy strategies.

Environmental emissions also remain one of the principal barriers to sustainable CM composting. Although numerous mitigation strategies have been proposed, includ-

ing optimized aeration, bulking agents, microbial inoculation, and physical covers, these approaches are generally evaluated independently. Future studies should investigate integrated emission-control systems capable of simultaneously reducing ammonia, GHG, volatile organic compounds, and odor emissions while preserving compost quality. Comparative evaluations under standardized operating conditions are particularly needed to determine the most effective combinations of mitigation technologies.

From an agronomic perspective, there is still limited evidence regarding the long-term performance of CM compost under field conditions. Most available studies are based on laboratory or greenhouse experiments, while relatively few evaluate crop productivity, soil health, and nutrient dynamics under real agricultural conditions. Future research should prioritize long-term field trials to validate the agronomic performance of CM-derived biofertilizers across different crops, soil types, and management practices. Such studies should simultaneously assess contamination risks associated with heavy metals, antibiotics, antimicrobial resistance, and pathogen persistence, as well as their environmental mobility and potential uptake by plants. Comparative assessments with conventional mineral fertilizers are also needed to determine the capacity of CM compost to partially replace inorganic fertilizers without compromising crop yield or soil fertility.

As future work, optimization of CM composting should be integrated with holistic life cycle assessment (LCA) to identify conditions that maximize compost quality while reducing environmental impacts. Evaluating the carbon footprint of CM composting and comparing its performance with conventional inorganic fertilizers is crucial for informed decision-making [54–56]. A literature review examined LCA and techno-economic evaluations of livestock manure, including chicken manure, under different treatment strategies [57]. These approaches enable a systematic assessment of livestock manure utilization options, highlighting their advantages and limitations, as well as the various processes involved in resource recovery. The main conclusions indicate that the environmental impacts of CM management depend largely on the treatment strategy applied. LCA studies show that optimized valorization options, such as composting or bioenergy production, can reduce environmental burdens by enabling nutrient and energy recovery. However, LCA outcomes are highly sensitive to methodological choices, including the definition of the functional unit, system boundaries, allocation procedures, and selected impact categories. Consequently, differences in these assumptions can substantially influence both the results and their interpretation [57].

Finally, technological advances alone will not ensure the wider adoption of CM composting. Future studies should also investigate the policy, regulatory, and socio-economic factors influencing compost implementation. The development of harmonized quality standards, clear guidelines for compost application, incentive mechanisms, and training programs for producers and farmers will be fundamental to facilitate the safe and effective use of CM compost in agriculture. Integrating these technical, environmental, economic, and policy dimensions will contribute to the transition from waste management to a truly circular nutrient management strategy.

6. Conclusions

This literature review highlights key conclusions on CM composting for bio-based fertilizer production. Under current European legislation, compost-based products are eligible for use as fertilizing products, supporting the use of composted CM as a *bio-based fertilizer*.

Regarding operating conditions, optimizing process efficiency and nutrient retention requires careful refinement of the feedstock mixture. This involves testing different combinations of CM with bulking agents or co-substrates (e.g., straw, biochar, agricultural

residues) to balance the C/N ratio, enhance compost dynamics, and minimize nutrient losses in the final product.

However, two major issues remain under-regulated in current legislation: odorous emissions and the potential presence and dissemination of ARB and ARG. Odor emissions and N volatilization losses can be mitigated through several strategies, such as microbial inoculation, co-composting with other residues or bulking agents, and optimized operating conditions (e.g., aeration). Regarding ARB, ARG, and microbial safety, evidence indicates that composting of CM substantially reduces antibiotic residues and pathogenic bacteria, lowering (but not necessarily eliminating) associated risks of CM-derived compost. Nevertheless, some ARG and resistance markers may persist depending on the feedstock and composting conditions. Thus, it is necessary to monitor ARG fate under different composting regimes, assess mitigation strategies, and ensure the safety of final compost for agricultural use.

Overall, integrating optimized CM management strategies with robust LCA frameworks and agronomic trials is essential in future work to support sustainable, environmentally responsible, and resource-efficient practices in the sector. Such integrated assessments can guide policymakers, farmers, and waste managers toward more sustainable and climate-resilient organic waste management.

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List of Abbreviations

ARB	antibiotic-resistant bacteria
ARG	antibiotic resistance genes
BC	biochar
CAGR	compound annual growth rate
CBMA	carbon-based microbial agent
CFU	colony-forming units
CM	chicken manure
CS	corn stover
CSB	cornstalk biochar
dw	dry weight
EC	electrical conductivity
EU	European Union
FAS	free air space
GHG	greenhouse gases
H	moisture

LCA	life cycle assessment
MC	mature compost
MR	mushroom residue
MS	magnesium sulfate
OM	organic matter
OUR	oxygen uptake rate
PAH	16 polycyclic aromatic hydrocarbons
RB	rice husk biochar
RS	rice straw
SD	sawdust
SMS	spent mushroom substrate
SP	superphosphate
TMA	thermophilic microbial agents
TOC	total organic carbon
TVOC	total volatile organic compounds
WCB	wood chip biochar
WS	wheat straw
ww	wet weight

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