

Review Article

Bulking Agents and Composting Methods Influence the Physicochemical Quality of Aerobic Chicken Manure Compost: A Comprehensive Review

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ABSTRACT

The aerobic composting of chicken manure (CM) has developed through continuous research and experimentation to optimise compost quality while concurrently improving environmental safety and public perception. Successful composting often requires a suitable carbon-to-nitrogen ratio (C/N) in a balanced combination of feedstock and bulking agent for effective microbial degradation. Despite numerous trials using different bulking agents, a comprehensive review of the aspect of practicality and effectiveness on physicochemical quality parameters remains unclear in current studies. Hence, this study investigates the influence of distinct bulking agent categories and composting methods of CM on key physicochemical parameters, which include C/N, pH, electrical conductivity (EC), nitrogen, phosphorus (P), potassium (K), bulk density (BD), moisture content (MC) and composting duration (CD). Plant-derived materials and livestock manure serve as the primary bulking agents, which significantly affect C/N, EC, K, BD and CD. The windrow method

provided better retention of P and K contents, while the in-vessel method improved C/N, EC, BD, MC and CD. These reviews highlight the importance of selecting suitable bulking agents and composting methods, as their interactions directly influence CM compost quality.

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INTRODUCTION

Chicken manure (CM) is recognised as one of the most produced livestock waste globally, primarily due to its intensive production worldwide to meet the demand for animal protein (Food and Agriculture Organisation [FAO], 2023). Farmers have historically favoured CM as a soil amendment over other livestock manures due to its well-known high concentration of macronutrients, which has proven to yield better agricultural harvests (Oagile & Namasiku, 2010; Warman, 1986). Aerobic composting, which involves the breakdown of organic matter in the presence of oxygen, has emerged as a popular treatment option due to its cost-effectiveness, requiring less mechanisation, and applicability for both urban and rural settings (Congilosi & Aga, 2021). Feedstock refers to the raw organic materials in the compost pile, which significantly influence both the nature of the compost and the composting process itself, often more than any other factors (Rynk et al., 2022). Additional feedstock introduced during composting, besides the primary feedstock, is also referred to interchangeably as a bulking agent (Manish et al., 2013). In this review, CM is the primary feedstock utilised, which can be composted solely or co-composted with a bulking agent. The benefits of bulking agent include the conditioning of initial composting composition, enhancing density, providing inter-particle gaps and air space, regulating moisture levels and serving as a carbon source for microorganisms (Chang et al., 2022; Chowdhury et al., 2014; Oshins et al., 2022; Santos et al., 2016; Yang et al., 2013).

The type and amount of bulking agent utilised in composting could largely influence the compost maturation time, emissions of gases, and overall compost quality (Li et al., 2018; Zhu, 2007). Common examples of bulking agents include wood chips, wood shavings, sawdust, dry leaves, food waste, shredded landscape waste, shredded paper, shredded cardboard, and animal bedding (Manish et al., 2013). Although these bulking agents are often considered waste materials, discarding them without fully utilising their abundant nutrient content would be inefficient. Composting not only mitigates pollution but also effectively reutilises the residual energy and nutrient resources (Grisey & Aleya, 2015; Paredes et al., 1996).

Moreover, the daily mass production of waste has given rise to several environmental challenges. Leaching of excess nutrients into waterways, which leads to eutrophication and the production of greenhouse gases caused by large volumes of waste storage, is among the factors that contribute to the contentious issue of climate change (Fernando, 2019; Kaza et al., 2018; Mehta et al., 2015). Subsequently, an ideal feedstock combination is critical to ensure optimal composting procedures in producing high-quality and sustainable compost products. Chai et al. (2013) and Rynk et al. (2022) have emphasised that farmers and researchers have been experimenting with various compositions and bulking agents when composting chicken manure to achieve the best outcomes. The methods applied during CM composting also play a vital role in determining the final quality of the compost.

Popular methods consist of static pile, vermicomposting, bokashi, windrow and in-vessel methods. The choice of composting method is influenced by various factors, including the type of feedstock, operational scale, financial considerations, regulatory requirements, and the degree of community sensitivity (Oshins et al., 2022). Since the most widely adopted methods are in-vessel and windrow composting systems (Kim et al., 2008; Manyapu et al., 2017; Zhou et al., 2022), this review will particularly focus on analysing the impact of in-vessel and windrow composting systems on compost physicochemical parameters.

The objectives of this review are to (a) analyse the effect of different bulking agents on compost physicochemical parameters (carbon-to-nitrogen ratio, pH, electrical conductivity, nitrogen, phosphorus, potassium, bulk density, moisture content), and composting duration; (b) investigate the effects of composting methods (in-vessel and windrow) on physicochemical parameters and composting duration; and (c) identify significant correlations among the physicochemical parameters during aerobic composting of CM. Due to the wide variations of bulking agents used in CM composting, this paper aims to unravel the complex relationship between bulking agents, composting methods, and the physicochemical quality of the resulting compost.

MATERIALS AND METHODS

Literature Search

The literature search utilised various online research databases, including Science Direct, Elsevier, MDPI, PLOS One, ResearchGate, Wiley Online Library, Scopus, Taylor & Francis, Springer, and Frontiers in Microbiology were used in the literature search. A total of 79 research articles which focus on assessing physicochemical parameters during aerobic composting of CM were selected in this review. The chosen studies were mostly published regarding either in-vessel or windrow composting systems between 2014 to 2023. Hence, this review covered 125 distinct compost samples. The methodological approach of this review draws from a broad and reputable range of article databases, a focused ten-year window, and a substantial set of 125 distinct compost samples that lend strong credibility and robustness to this comprehensive review.

Data Analysis

Microsoft Excel was implemented in this review for data management and descriptive analysis. Data collected from different studies were standardised into consistent units to facilitate comparison. The dataset was then classified based on authors, publication year, continent, composting method and duration. Comparative analysis was conducted on physicochemical parameters like carbon-to-nitrogen ratio (C/N), pH, electrical conductivity (EC), nitrogen (N), phosphorus (P), potassium (K), bulk density (BD), and moisture content (MC), along with composting duration (CD).

OVERVIEW OF THE SELECTED LITERATURE

The review compiled global studies on the physicochemical quality parameters of aerobic composting of CM across nine continents, which were Far East Asia, Southeast Asia, South Asia, North America, South America, Africa, Australia, Europe and the Middle East. The regional data distribution based on individual treatments collected from the selected studies was illustrated in Figure 1.

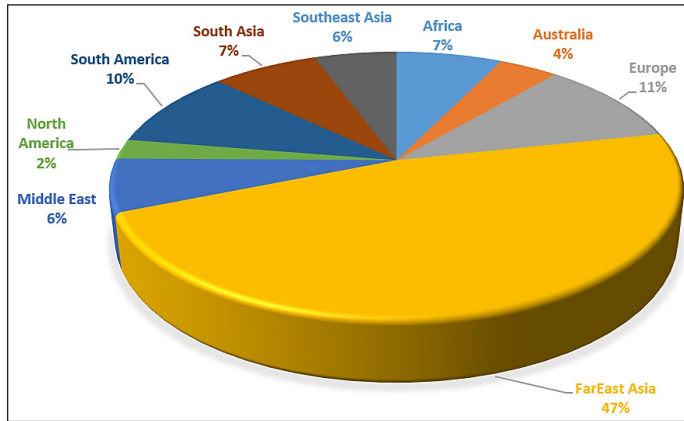


Figure 1. Regions explained with the number of data, Southeast Asia (n = 7), South Asia (n = 9), Far-east Asia (n = 59), North America (n = 3), South America (n = 12), Africa (n = 9), Australia (n = 5), Europe (n = 13), Middle East (n = 8), all regions (n = 125)

Fareast Asia contributes almost half (47%) of the total studies conducted on physicochemical quality parameters of CM composting, primarily from China. This shows their contribution in managing extensive waste production and developing better compost quality. Furthermore, China ranks as the third-largest global chicken producer, after the United States and Brazil (Shahbandeh, 2023; Wen et al., 2019). Other continents contributed approximately equal percentages of studies to this review, with the lowest percentage of 2% from North America.

OPTIMAL PHYSICOCHEMICAL COMPOSTING CONDITIONS

The optimal composting conditions outlined in this section serve as benchmarks for evaluating compost quality parameters and providing references for subsequent discussions. The key physicochemical parameters reviewed in this study were C/N, pH, EC, N, P, K, BD and MC. C/N ratio determines the stability and maturity of compost (Oshins et al., 2022). Carbon serves as the primary energy source for microbial growth, while N is necessary for microbial development and reproduction through protein synthesis (Sweeten, 2008). The ideal final C/N falls within the range of 20:1 to 30:1, as microbes require 20 to 30 parts of carbon per unit of N for optimal microbial activity (Estévez-Schwarz et al., 2012; Guo et

al., 2022 ; Ogunwande, 2008; Rynk et al., 1992). Compost pH reflected the hydrogen ion activity, which was influenced by mixing and concentrations of cations and anions in the composting system (Butterly et al., 2013; Smith & Doran, 2015). Most composts tend to maintain a neutral to slightly alkaline pH, with the optimal pH range between 6.5 and 8.0 (Ho et al., 2022; Oshins et al., 2022).

Compost salinity was assessed by measuring the EC of its water extract (Thompson et al., 2002). High levels of salt concentrations negatively affect plant tissues and reduce their root capacity for water adoption from the soil compost (Gondek et al., 2020). EC values lower than 4 dS m⁻¹ are generally considered ideal and non-phytotoxic (Awasthi et al., 2016; Manyapu et al., 2017). Higher macronutrient concentrations are often assumed to improve soil fertility and crop performance. However, recommended compost quality standards suggest a range of 1.0 - 3.5% for N, <1.0% for P, and 1.0 -3.0% for K (Nyi et al., 2017; Heyman et al., 2019). BD represents the ratio of a material's mass to its occupied volume, which is considered the key indicator of aeration within the composting mix (Calisti et al., 2020 ; Oshins et al., 2022). Practically, BD ranging from 400-600 kg/m³ is advisable (Oshins et al., 2022) to enhance permeability, adequate air space, oxygen utilisation efficiency and heat transfer. Due to moisture-filled pores or denser piles, excessively high BD occurred and led to a decrease in porosity and limited aeration. In contrast, extremely low BD can cause unnecessary substrate aeration and reduced water availability (Azim et al., 2018).

Moisture content was widely recognised as the second most important factor in influencing the rate of decomposition, after the C/N ratio (Choi, 1999; Sharma & Reynnells, 2018). Effective composting requires careful monitoring of moisture or humidity levels, ideally maintaining them between 40-60% by weight (Singh & Kalamdhad, 2015 ; Oshins et al., 2022). Microorganisms require water for transporting nutrients and energy elements through their cell membrane; thus, regulating moisture levels becomes critical for successful composting. Inadequate moisture levels can restrict the growth and survival of microorganisms within the compost (Sharma & Reynnells, 2016). Nevertheless, it is important to acknowledge that an ideal compost is a combination of multiple factors highly influenced by the environment and ambient conditions, and there is no universally "ideal" compost; rather, there are several types, each designed for specific purposes.

Composting consists of three commonly identified phases: the mesophilic (moderate-temperature phase), which lasts for a couple of days, the thermophilic (high-temperature phase), which lasts for a few days to a few weeks, and the long maturation (cooling) phase (Pace et al., 1995; Wong et al., 2017). The composting process begins as soon as the raw materials are combined. In the initial stage, microbes rapidly consume oxygen and easily degradable components of the source materials. As active composting slows down, the temperature gradually decreases until the compost reaches ambient air temperature. The active composting phase is followed by a curing phase, where the components will break

down progressively. This continues until the final degradable raw materials are utilised by the remaining microbes. At this stage, the compost becomes less odorous, free of pathogens, reduced in volume, easier to manage, and relatively stable (Wang et al., 2016; Wong et al., 2017). The general perception is that composting phases are time-consuming; shorter compost maturation durations are preferred.

DIFFERENT BULKING AGENTS USED IN CHICKEN MANURE COMPOSTING

Most of the bulking agents were selected due to their production as by-products and being commonly perceived as agricultural wastes. Co-composting them with CM concurrently addresses the waste management issue for both parties. Another general reason is that these incorporated materials help to compensate for the shortcomings of CM, thereby enhancing various aspects of the composting process, including structural, biological, and chemical parameters, ultimately improving the quality of the final compost. The effect of various bulking agent categories used in CM composting will be investigated by analysing individual treatments ($n = 125$) in studies conducted between 2014 and 2023. They are classified into different categories, including plant-derived, livestock manure, organic waste, animal by-product, rock, industrial by-product, animal, and bio-surfactants (Table 1). Discussion will focus on bulking agent categories with more than three treatments ($n > 3$), namely plant-derived material and livestock manure.

Plant-Derived Material as Bulking Agent

This review has found that bulking agents derived from plants are the preferred choice for composting CM. This preference may be attributed to the high-carbon compounds found in plant wastes, constituting up to 30% of total organic carbon (Azim et al., 2018; Vallini et al., 1993). Bulking agents rich in carbon compounds are essential to attain optimal C/N of 20:1 -30:1, especially considering the high N content in CM (Nahm, 2003). This balance enhances optimal microbial activity during the composting process, making the addition of plant-derived materials as bulking agents crucial for this purpose. Additionally, the lignocellulosic properties in plants also contribute to the structural degradation and biochemical enhancement of the composting process and the resulting compost product (Hubbe et al., 2010). Watermelon waste serves as an effective bulking agent, significantly enhancing the organic matter, N, K, dry matter, moisture content, bulk density, and pH on the final compost (Nurin et al., 2024).

Livestock Manure Bulking Agent

Co-composting with two or more distinct livestock manures is a popular disposal method aimed at optimising the priming effect and antagonistic reactions among the vast

Table 1
Categorisation of bulking agent types

Bulking Agent Category and Definition	List of Materials
Plant-derived is coming entirely from plants, plant-derived materials, or plant by-products.	(1) sugarcane waste, (2) rice husk, (3) gamal leaves, (4) agricultural lime, (5) molasses, (6) <i>Catha edulis</i> leaf wastes, (7) farm wastes, (8) wheat straw, (9) rice straw, (10) mushroom dreg, (11) rice bran, (12) banana peels, (13) sawdust, (14) rice hull, (15) biochar, (16) barley straw, (17) <i>Caragana microphylla</i> straw, (18) rice husk biochar, (19) bagasse, (20) <i>Eucalyptus</i> sp. sawdust, (21) coir pith, (22) vegetable waste, (23) coffee husk, (24) pod husk mixed with topsoil, (25) pine sawdust, (26) macadamia nutshell biochar, (27) hardwood shavings biochar, (28) olive leaves and pruning, (29) alperujo cereal straw, (30) exhausted grape marc, (31) gorse forest shrub, (32) bamboo charcoal, (33) tomato stalk, (34) peat bog, (35) fruit and vegetable residue, (36) oil palm empty fruit bunch biochar, (37) corn stalk, (38) straw pellets, (39) green algae, (40) olive mill wastewaters, (41) olive pomace, (42) corn straw, (43) rapeseed meal, (44) green waste, (45) greenhouse tomato (1) swine manure, (2) poultry litter, (3) dairy manure, (4) chicken litter biochar, (5) horse manure compost (1) market organic waste, (2) household organic waste, (3) sewage sludge (1) urea, (2) beef rumen content, (3) meat meal (1) pumice, (2) chabazite, (3) dolomitic limestone, (4) zeolite, (5) diatomite, (6) bentonite (1) sugar filter cake waste (1) black soldier fly larvae (BSFL), (2) larva inocula, (3) <i>B. subtilis</i> BSF-CL, (4) dead birds (1) Rhamnolipid, (2) Tween-80
Animal Manure refers to solid, semisolid, and liquid waste generated by livestock animals or their derived materials	
Organic Waste refers to organic materials derived from living organisms or their metabolic processes	
Animal by-product refers to materials of animal origin that are inedible	
Rocks refer to a solid collection of mineral grains that possess a high amount of carbon	
Industrial by-product refers to residual material generated from an industrial or commercial operation that is not the primary product of that operation	
Animal refers to bulking agents coming entirely from animal and animal-derived materials	
Bio-surfactants are produced by bacteria, yeasts, and filamentous fungi, which have low toxicity, high biodegradability, and remain active at extreme pH and salinity	

microorganisms, nutrient compositions, and physicochemical conditions derived from the combination of multiple types of manure in the compost mix (Huang et al., 2017; Neher et al., 2020). Nurin et al. (2025) reported that application of sawdust as bulking agent improved the overall quality in co-composting of CM with horse manure. This approach helps in enhancing organic matter degradation and elevating nutrient conservation, thereby improving compost quality and mitigating potential environmental effects associated with the mass production of livestock manures (Hwang et al., 2020; Song et al., 2014).

This review identified several livestock manures previously utilised as bulking agents in aerobic composting of CM, including swine manure, chicken litter, dairy manure, chicken litter biochar, and horse manure compost (Table 1). Co-composting chicken with swine manures was found to significantly increase the quantity of xylan-degrading bacteria and reduce the number of human pathogens (Song et al., 2014). However, Hwang et al. (2020) revealed that co-composting CM with swine manure released 4.1 times more NH_3 emissions compared with dealing with CM alone. Co-composting CM with dairy manure increases lignin, cellulose, and hemicellulose degradation, leading to higher organic mass reduction by the end of the composting period (Rehman et al., 2017). Since chicken, swine, and cattle manures are high in N, their incorporation often results in very low C/N and significant N loss through ammonia volatilisation during composting (Biala et al., 2016).

The utilisation of manure biochar, produced through pyrolysis, is increasingly common as a bulking agent during composting. The application brings several advantages, including providing a high carbon source contributing to optimal microbial activity, being lighter and thus more cost-effective for transport, emitting less odour, and offering beneficial soil amendment properties. Moreover, it has been proven to enhance the composting process by promoting the nitrification process, reducing methane emissions, and eliminating pathogens (Agyarko-Mintah et al., 2017; nase et al., 2014). Liu et al. (2018) conducted a study on co-composting CM with mature horse compost. They reported that sodium content dilution and microbial activity were enhanced, resulting in optimal compost temperature and better maturity indices compared to composting CM with vegetable or food waste. Livestock manure as a bulking agent has long been applied in CM composting, and its incorporation has brought various benefits to the entire composting process.

EFFECTS OF DIFFERENT BULKING AGENT CATEGORIES ON COMPOST PHYSICOCHEMICAL PARAMETERS

CM was composted without bulking agent (WO) (n = 20) and co-composted with the following bulking agent categories; plant-derived materials (n = 79), livestock manure (n = 5), livestock manure and plant-derived (n = 5), animal (n = 2), organic waste (n = 2), rock (n = 2), animal by-product (n = 1), animal and plant-derived (n = 1), industrial by-product (n = 1), plant-derived and industrial by-product (n = 1), plant-derived and

bio-surfactants ($n = 2$), rock and plant-derived ($n = 2$), rock and animal ($n = 1$), animal by-product and plant-derived ($n = 1$). This review focuses on the effect of bulking agent categories on compost physicochemical parameters with more than three treatments ($n > 3$), which include CM composted without a bulking agent (CM-WO), CM co-composted with plant-derived materials (CM-P), CM co-composted with animal manure (CM-M), and CM co-composted with animal manure and plant-derived materials (CM-MP). Summary statistics of the physicochemical parameters of the final CM compost; comparisons between bulking agent categories are presented in Table 2.

Carbon-to-Nitrogen Ratio

C/N is a crucial parameter in composting, signifying the balance between carbon-rich and nitrogen-rich materials for optimal microbial activity (Khan et al., 2014). The C/N for each bulking agent category fall below the ideal range of 20:1 to 30:1. CM-MP shows the highest average value (19.6), followed by CM-P (17.8), CM-M (14.6), and CM-WO (12.9). CM-MP nearly approaches the optimal C/N range. This review highlights that the incorporation of CM solely with plant-derived materials (CM-P) or livestock manures (CM-M) does not improve the final C/N to the same extent as the combination of both materials does. This signifies limitations of each bulking agent category, and the application of both materials as bulking agents during the composting of CM is recommended to achieve better C/N in the final compost. Comparatively, Liu et al. (2018) found that co-composting CM with livestock manure was more efficient in degradation rate as compared to using plant-derived material as a bulking agent. Additionally, CM-WO has the lowest C/N, emphasising that composting CM without any bulking agent is not advisable. The imbalance in organic matter composition resulting from the absence of a bulking agent will consequently lead to immature C/N in the final compost.

pH and Electrical Conductivity

Compost pH plays a significant role in plant growth as it impacts various soil parameters such as nutrient availability, heavy metals toxicity, soil microbial composition, and activity, as well as cation exchange capacity (Oshins et al., 2022; Zhang et al., 2021). In this review, the average pH values for each bulking agent category were found to be within an acceptable range when compared with the ideal range of 6.5 -8.0 (Ho et al., 2022; Oshins et al., 2022). The results span from CM-WO (7.7) to CM-P (8.1), showing a very narrow variance between the bulking agent categories, suggesting that each of them did not have a significant negative effect on the final pH value in CM composting.

The electrical conductivity value reflects the total concentration of dissolved salts and ions in compost, directly impacting nutrient availability, microbial activity, and overall compost quality. As shown in Table 2, there is a considerable variation in EC values, ranging

Table 2
 Summary statistics of the physicochemical parameters of final chicken manure compost; comparisons between bulking agent categories

Bulking Agent Category	Physicochemical Parameter											CD (day)
	C/N	pH	EC (dS m ⁻¹)	N (%)	P (%)	K (%)	PS (cm)	BD (kg/m ³)	MC (%)			
Without a Bulking Agent (CM-WO)	Mean	7.7 ± 0.8 (n = 19)	6.6 ± 9.1 (n = 9)	2.4 ± 1.2 (n = 20)	1.4 ± 0.7 (n = 15)	2.3 ± 1.5 (n = 14)	0.4 ± 0.1 (n = 2)	521.8 ± 223.7 (n = 5)	42.5 ± 24.8 (n = 11)	98.7 ± 90.7 (n = 15)		
	± SD	6.4	0.2	0.3	0.00004	0.5	0.3	250	15	9		
	Min	37.2	9.2	29.1	4.3	2.8	0.5	810	88.4	365		
	Max	17.8 ± 7.8 (n = 73)	8.1 ± 0.9 (n = 71)	3.8 ± 2.9 (n = 41)	1.8 ± 1 (n = 48)	1.5 ± 2.1 (n = 36)	0.8 ± 0.5 (n = 5)	401.3 ± 127.9 (n = 8)	47.8 ± 15.8 (n = 43)	80.7 ± 81 (n = 74)		
Plant-derived (CM-P)	Mean	2.2	6	0.003	0.1	0.0002	0.03	260	11.9	0.9		
	± SD	43.1	11	11.7	5.0	11.3	1.5	570	67.6	600		
	Min	14.6 ± 7.7 (n = 5)	7.8 ± 1 (n = 5)	2.0 ± 2.5 (n = 2)	2.3 ± 1.3 (n = 5)	1.2 ± 0.2 (n = 4)	-	-	56.6 ± 21.5 (n = 5)	65.3 ± 39.5 (n = 3)		
	Max	9.8	6.7	0.2	0.2	1.0	-	-	34.0	20		
Animal Manure (CM-M)	Mean	28	9.2	3.8	3.7	1.4	-	-	88.9	92		
	± SD	19.6 ± 9.8 (n = 5)	7.9 ± 0.8 (n = 5)	5.2 ± 3.5 (n = 5)	2.1 ± 0.7 (n = 4)	11.8 ± 2.2 (n = 2)	-	-	52.5 ± 10.2 (n = 3)	81 ± 45 (n = 5)		
	Min	10.2	7.3	3.0	1.5	10.3	-	-	40.9	30		
	Max	35.7	9.0	11.4	3.0	13.4	-	-	60	126		

Note. CM-WO, chicken manure composted without bulking agent; CM-P, chicken manure co-composted with plant-derived materials; CM-M, chicken manure co-composted with livestock manure; CM-MP, chicken manure co-composted with livestock manure and plant-derived materials; SD, standard deviation; C/N, carbon-to-nitrogen ratio; EC, electrical conductivity; N, nitrogen; P, phosphorus; K, potassium; PS, particle size; BD, bulk density; MC, moisture content; CD, composting duration. Number of data reviewed for this analysis, n = 101

from the lowest value in CM-M (2.0 dS m^{-1}), followed by CM-P (3.8 dS m^{-1}), CM-MP (5.2 dS m^{-1}), to the highest in CM-WO (6.6 dS m^{-1}). Both CM-M and CM-P fall within the optimal EC range below 4 dS m^{-1} , indicating an adequate concentration of dissolved salts that creates optimal conditions for plant nutrient uptake efficiency (Gondek et al., 2020). The high EC value in CM-MP may be attributed to the microbial dynamics and high nutrient content resulting from the combination of both plant-derived material and livestock manure (Lauber et al., 2009; Zhang et al., 2018). The extremely high EC value observed in CM-WO could be attributed to its low C/N, which accelerates mineralisation, producing more N compounds such as ammonium, nitrates, and organic nitrogen. These organic compounds contain electrolytes that contribute to the high EC value (Carmo et al., 2016). This indicates the importance of selecting compatible feedstock and bulking agents to maintain suitable pH and EC levels as well as minimising the risk of phytotoxic effects on plant growth and productivity.

Macronutrient Contents

This review focuses on the primary macronutrients essential for optimal compost quality, which were N, P and K (Sánchez et al., 2017). Previous studies have highlighted a significant correlation between feedstock composition and the rate of nutrient mineralisation (Silva et al., 2014; Wang et al., 2019). Hence, this review determined the variations in macronutrient contents across different types of bulking agent, indicating their effects on nutrient dynamics of composting. The average N values in increasing order were observed in CM-P (1.8%), CM-MP (2.1%), CM-M (2.3%) and CM-WO (2.4%). The lowest N content recorded in CM-P is likely due to the high carbon content presented in plant-derived materials. This creates a higher initial C/N ratio, which can reduce N mineralisation during the composting process and consequently the final concentration (Oshins et al., 2022). However, no significant difference in N content was found among the other bulking agent categories. The highest N content in CM-WO may be owing to the high net mineralisation resulting from a low initial C/N ratio (Eckhardt et al., 2018). In addition, all bulking agent categories exhibited N levels within the acceptable range defined by established compost quality standards recommended by Nyi et al. (2017) and Heyman et al. (2019).

The contrasting trends observed in P and K contents among the various bulking agent categories emphasise their contradictory impacts on nutrient composition. CM is well-known for its highest P content among other organic wastes, requiring an optimised mode of composting to maximise P reutilisation (Wei et al., 2015). The variation of P between the bulking agent categories is very narrow, ranging from 1.2% - 1.5%. This suggests that every category retains a relatively high concentration of P in the compost, implying that feedstock composition does not significantly affect P content in the composting of CM. Instead, Takahashi et al. (2016) reported that P mineralisation was influenced by factors

such as particle size and moisture content of compost, with increasing moisture levels leading to increased P bioavailability.

Contrastingly, there are significant variations in K values, with the maximum value in CM-WO (2.3%), followed by CM-M (1.9%), CM-P (1.8%), and CM-MP (0.08%). While CM-WO, CM-M, and CM-P show considerably high K content, CM-MP demonstrates exceptionally low K content. This does seem to depend on the combination of plant-derived materials and livestock manure as bulking agents, which induces a substantial increase in organic matter availability and creates gaps between compost particles. It is important to highlight the fact that K is not bonded to organic matter (Marschner, 1995), thus contributing to leaching between the particle gaps due to its high water solubility (Chang et al., 2022; Eghball et al., 2002; Santos et al., 2016). Additionally, Kutu and Masowa (2018) discovered that different initial composting feedstock reveals significantly different net K mineralisation rates. These reviews emphasise that the role of bulking agents extends beyond achieving an optimal C/N, also influencing the specific nutrient composition of compost with the objective of meeting plant requirements.

Bulk Density and Moisture Content

The structural characteristics of compost are determined by its bulk density, with the suggested target being to maintain BD below 400 kg/m³ for optimal results. However, BD data are not commonly recorded in the selected composting studies; hence, only CM-WO and CM-P generated sufficient data for comparison. The results show that an average BD of 521.8 kg/m³ and 401.3 kg/m³ for CM-WO and CM-P, respectively. The higher BD value observed in CM-WO is attributed to the absence of a bulking agent during composting. The consequences include reduced particle gaps and poor pile aeration, thus contributing to a slower decomposition process (Azim et al., 2018). Maintaining control over BD is crucial for creating a conducive environment for microbial decomposition and the transformation of organic matter into a nutrient-rich compost.

Optimal moisture content maintains a thin water film on particle surfaces, acting as the main site for microbial activity (Azim et al., 2018). The MC of all bulking agent categories falls within the ideal range of 40-60%, indicating that MC is not significantly affected by feedstock composition but rather by an external force, particularly the manual addition of water during the composting process (Azim et al., 2018). The control of MC during the composting process is pivotal to providing an adequate microbial site for optimal degradation.

Composting Duration

Composting often perceived as a time-consuming process, which drives preference for shorter maturation periods (Wong et al., 2017). The discrepancy in CD among different

bulking agent categories is shown in Table 2, with CM-M exhibiting the shortest duration (65.3 days), followed by CM-P (80.7 days), CM-MP (81 days), and CM-WO (98.7 days). The prolonged CD observed in CM-WO can be attributed to the negative effects of composting without a bulking agent, resulting in slower decomposition of organic matter and delayed maturation. This mainly happens due to an unfavourable C/N balance, which disrupts the sufficiency of primary nutrients required by composting microbes for a shorter maturation period (Haug, 2018 ; Zhou, 2014). In contrast, the short CD of CM-M could be well justified by the existing nutrient and microbial variations in the manure substrates, which benefit from the co-composting of multiple types of manure (Risberg et al., 2017; Sun et al., 2015). Additionally, the combination of CM with other manures may be favourable to microbial activity that produces heat (Hwang et al., 2020), which successfully accounts for the rapid degradation process and faster maturation reach (Bonanomi et al., 2016; Das et al., 2017). The choice of bulking agent significantly affects compost maturation time.

AEROBIC COMPOSTING METHODS OF CHICKEN MANURE COMPOSTING

There are different methods used for composting; the most adapted ones are in-vessel and windrow systems. This section will reveal the operation, advantages, and challenges, as well as the economic considerations of in-vessel and windrow systems in the aerobic composting of CM.

Windrow Composting Method

Windrow composting is the process of piling biodegradable organic matter into long, trapezoidal-shaped rows (Gould et al., 2013) of a certain length, height, and width depending on the available space and resources in that specific area (Andersen et al., 2010; Vergara & Silver, 2019). Windrow composting is classified into three types: turned windrow system (TWS), passively aerated windrow system (PAWS), and forced aerated static windrow (FASW) (Dincă et al., 2019). For TWS, a turning machine is typically employed to enhance oxygen flow and porosity, decrease moisture content, disperse hotter and colder areas of the pile, and boost microbial activity (Kong et al., 2018 ; Manyapu et al., 2017). This procedure does not require complicated technology and is cost-effective, but it demands labour, difficulty in maintaining moisture and temperature as well and substantial N loss was discovered (Manyapu et al., 2017; Ekinci et al., 2022). In PAWS, the pile must be a homogenous, low-density mixture (Michel et al., 2022a) with perforated pipes installed at the bottom of the windrow to ensure convective aeration throughout the pile (Lynch & Cherry, 1996; Patwa et al., 2020). The piles are not turned, and no forced aeration equipment is utilised, removing much of the capital and running costs associated with the previous method (Dincă et al., 2019). In contrast, FASW systems applied air

blowers connected to perforated pipes to force aeration, allowing airflow to be regulated through controlled frequency and duration of the blowers (Michel et al., 2022b). FASW is a well-established technology that allows higher and more uniform oxygen levels, removes excess heat and reduces greenhouse gas emissions (Michel et al., 2022b; Ekinci et al., 2022). In contrast, the common drawbacks of FASW are excessive drying of piles and difficulties in regulating moisture levels.

In-Vessel Composting Method

Composting technologies have undergone long-term improvements from static heaps and windrow composting to artificial intelligence-assisted in-vessel composting systems (Zhou et al., 2022). In-vessel composting can be applied regardless of the seasonal variation and geographical region, as the compost pile is fully controlled artificially within an enclosed system, such as in a building, container, or vessel. Different types of in-vessel systems have been built using fixed, agitated, or rotating bioreactors, which could accommodate either solid or liquid-state compost materials. This controlled composting system is getting exponentially increasing interest as mature composts could be produced more efficiently within a short time (Ajmal et al., 2020a). Besides, simultaneous handling of waste with minimal space could be employed with the production of high-quality mature compost containing fewer pathogenic concerns and lesser greenhouse gas emissions (Cekmecelioglu et al., 2005; Mu et al., 2017; Pandey et al., 2016). During composting, regulating temperature, moisture, and oxygen levels is vital in ensuring microbial degradation efficiency (Ajmal et al., 2020a; Oazana et al., 2018), which could be easily monitored via in-vessel systems. However, constant heating under temperature-controlled conditions may result in increased temperature for an extended length of time, reducing the nutritional content of compost (Ajmal et al., 2020b). Another downside of in-vessel composting is the high mechanical energy consumption that necessitates a large budget (Alkoaik et al., 2018; Mu et al., 2017).

Effects of Windrow and In-Vessel Composting Methods on Compost Physicochemical Parameters

Windrow and in-vessel composting methods have been widely applied across different continents, as depicted in Figure 2, which integrates data from 125 individual treatments spanning from the year 2014 to 2023 on the aerobic composting methods of CM. Fareast Asia stands out with the highest number of studies compared to the other continents, with 46 studies employing the in-vessel method and only 13 utilizing the windrow method. Similarly, the trend is observed across other continents, indicating a preference for the in-vessel approach over the windrow method, except for North America. In North America, two studies applied the windrow method, while only one employed the in-vessel method.

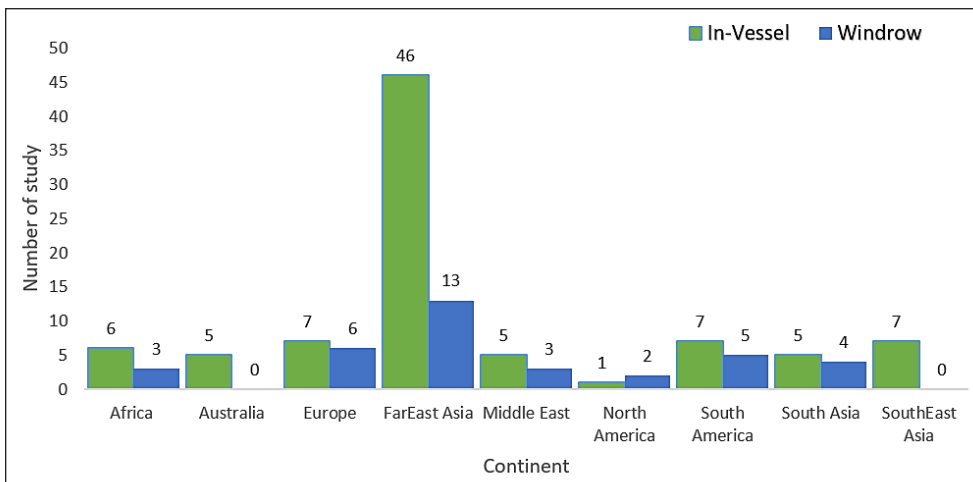


Figure 2. In-vessel and windrow composting systems of CM aerobic composting practised in different continents (n = 125)

The summary statistics for physicochemical parameters of final CM compost; comparison between in-vessel and windrow composting methods are presented in Table 3. Only two bulking agent categories, CM-WO and CM-P, which have more than three treatments ($n > 3$) each for both in-vessel and windrow systems, will be considered for comparison and further discussion. The in-vessel method applied for both CM-WO and CM-P exhibits a closer to ideal C/N than the windrow method. This discrepancy may be due to the capacity of the in-vessel method to control temperature within the compost pile, which is consistent with the findings of Ajmal et al. (2020b), who found that temperature is a significant factor influencing C/N of final compost. Aeration and moisture are other factors influencing the C/N of compost, which are feasible to control during in-vessel composting systems. Lack of aeration within the compost pile will result in anaerobic conditions, hindering the microbial degradation process, which induces negative net mineralisation (Gondek et al., 2020). Additionally, aeration may also be hindered when the moisture level exceeds 65%, as the thick moisture film surrounding the particles slows down oxygen transfer (Oshins et al., 2022). In contrast, the windrow method applied for CM-P shows a significantly higher average EC value (5.8 dS m^{-1}) compared to the ideal range, while the EC for the in-vessel method was superior (2.9 dS m^{-1}). This proved that the in-vessel method produced a better EC value in compost, which may result from the frequent pile turning and homogeneous distribution of salts. Furthermore, effective control of aeration, temperature, and moisture during the in-vessel process could also contribute to improved EC value of the final compost.

The in-vessel and windrow methods for CM-WO show inconsistent results for N content, whereas P and K contents show consistent patterns for both methods. The average P and K values

Table 3
Variable summary statistics for physicochemical parameters of final CM compost; comparison between in-vessel and windrow composting methods

Bulking Agent Category	Composting Method	Summary statistics	Physicochemical Parameter										
			C/N	pH	EC (dS m ⁻¹)	N (%)	P (%)	K (%)	PS (cm)	BD (kg/m ³)	MC (%)	CD (day)	
None (n = 14)	In-Vessel (CM-WO-IV)	Mean ± SD	13.9 ± 9.4 (n = 9)	7.4 ± 0.4 (n = 9)	2.6 ± 1.9 (n = 5)	2.5 ± 0.9 (n = 9)	1.2 ± 0.6 (n = 6)	1.2 ± 0.7 (n = 5)	0.5 (n = 1)	450 ± 282.8 (n = 2)	41.5 ± 21.6 (n = 8)	110.1 ± 106.7 (n = 9)	
		Min	6.3	6.4	0.3	1.0	0.6	0.5	0.5	250	15	9	
		Max	37.2	8.0	5.4	4.0	2.2	1.9		650	70	365	
		Mean ± SD	13.5 ± 4.7 (n = 5)	8.0 ± 0.9 (n = 5)	14.7 ± 20.4 (n = 2)	2.2 ± 1.8 (n = 5)	1.4 ± 1.0 (n = 4)	4.4 ± 1.3 (n = 3)		675 ± 191 (n = 2)	88.4 (n = 1)	107.3 ± 66.5 (n = 4)	
Plant-derived (n = 73)	In-Vessel (CM-P-IV)	Min	7.6	6.6	0.2	0.3	0.00004	3.5		539.9	88.4	56	
		Max	18.1	8.9	29.1	4.3	2.3	5.9		810	205	205	
		Mean ± SD	18.6 ± 7.9 (n = 51)	8.2 ± 0.9 (n = 52)	2.9 ± 1.9 (n = 27)	1.6 ± 1.0 (n = 29)	1.6 ± 2.4 (n = 21)	1.6 ± 1.9 (n = 19)	0.9 ± 0.6 (n = 4)	396.8 ± 114.8 (n = 6)	50.7 ± 14.1 (n = 27)	66.5 ± 39.1 (n = 53)	
		Min	2.2	6.4	0.003	0.2	0.01	0.001	0.03	260	18.8	0.9	
Windrow (CM-P-W)	Windrow (CM-P-W)	Max	43.1	11.0	8.5	5.0	11.3	8.5	1.5	500	67	168	
		Mean ± SD	15.1 ± 5.3 (n = 19)	8.0 ± 0.9 (n = 17)	5.8 ± 3.7 (n = 13)	2.1 ± 1.0 (n = 17)	1.7 ± 1.7 (n = 13)	2.4 ± 1.9 (n = 13)	0.6 (n = 1)	415 ± 219.2 (n = 2)	43.2 ± 16.5 (n = 13)	123.2 ± 139.8 (n = 19)	
		Min	6.9	6.0	0.1	0.1	0.0002	0.02	0.6	260	17.5	20	
		Max	24.8	9.1	11.7	4.0	5.6	4.6		570	67.6	600	

Note. CM-WO-IV, chicken manure composted without bulking agent using in-vessel method; CM-WO-W, chicken manure composted without bulking agent using windrow method; CM-P-IV, chicken manure co-composted with plant-derived materials using in-vessel method; CM-P-W, chicken manure co-composted with plant-derived materials using windrow method; SD, standard deviation; C/N, carbon-to-nitrogen ratio; EC, electrical conductivity; N, nitrogen; P, phosphorus; K, potassium; PS, particle size; BD, bulk density; MC, moisture content; CD, composting duration. Number of data reviewed for this analysis, n = 87

from the in-vessel method applied to CM-WO and CM-P are both lower than those from the windrow method, with K values showing a significantly higher difference between the two methods. Specifically, the K value for CM-WO-W is higher by 3.2% than CM-WO-IV, while CM-P-W is higher by 0.8% than CM-P-IV. Iyengar and Bhave (2006) discovered that in-vessel composting produced composts with low K levels; thus, they proposed that an external source of K be added to increase the quality of compost. The reduced nutrient levels could be attributed to the downside of K, which could be easily drained as leachate. Similarly, Hu et al. (2009) found that the reduced concentrations of P and K at the end of in-vessel composting do appear to be associated with leaching, as these elements are non-volatile. Therefore, it is advisable to reintroduce leachate from in-vessel composting back into the compost pile (Iyengar & Bhave, 2006). The observed nutrient variations emphasise the importance of considering the composting method to achieve compost with adequate plant-available nutrients.

The in-vessel composting methods for both CM-WO and CM-P exhibit superior BD values when compared with the windrow method. The variation in BD arises from factors such as moisture content and particle size. The in-vessel system excels as it provides consistent regulation in pile moisture levels, and particle size screening is often conducted before the composting process begins. Larger particles tend to degrade more slowly due to their lower surface area available for microbial activity (Truong & Marschner, 2018). In contrast, the windrow composting method is typically conducted in large batches without particle size screening and pile moisture control. This may cause uneven compaction over time, making turning operations more challenging and less effective.

The average CD of CM-WO, either using the in-vessel or windrow method, does not show a significant difference (110.1 and 107.3 days, respectively), while the average CD for CM-P shows a remarkable difference with CM-P-IV (66.5 days) and CM-P-W (123.2 days). In-vessel composting is more active in organic matter breakdown and reaches maturity faster than windrow composting. The duration of the composting process is determined by the inherent nature of the decomposed organic matter, and the process efficiency is determined by the amount of aeration and agitation (Ajmal et al., 2020a). Accordingly, the aeration homogeneity provided by frequent turning equipped with in-vessel composting technology contributed to a shorter CD. In addition, moisture is also necessary to support the metabolic processes of the microbes. Both methods exhibited optimal MC; however, it is worth noting that higher MC was recorded in CM-P-IV (49.1%) than in CM-P-W (43.2%)

Active composting will change depending on the amount of natural moisture or water added to the compost. Since moisture control is more easily adaptable with the in-vessel method compared to the windrow method, this approach demonstrates improved moisture levels and shorter composting duration. In summary, aeration rate, temperature, and moisture content are the important parameters that affect the composting duration and ultimately affect the quality of the compost product.

CORRELATION BETWEEN THE PHYSICOCHEMICAL PARAMETERS OF COMPOST

The interactions of physicochemical parameter dynamics were proven to have significant effects on one another in numerous prior studies (Ho et al., 2022; Ogunwande et al., 2008; Shi et al., 2020). For that reason, the correlation between the physicochemical parameters will be further discussed by reviewing data from Tables 2 and 3. From Table 2, CM-WO has the lowest average C/N (12.9) and the highest average K (2.3 %), and vice versa for CM-MP. Table 3 also shows the same pattern, where both higher C/N in CM-WO and CM-P retain lower K content in the compost pile. Therefore, it was observed that C/N exhibited a notable antagonistic correlation with K content. This review aligns with studies conducted by Zhou (2017) and Khalid et al. (2014). Zhou (2017) found that a compost pile with low C/N has higher K concentrations throughout the composting process of pig manure and edible fungus residue. This could be attributed to the increased mineralisation rate at low C/N, consequently increasing the amount of K in the compost pile. The increase in K mineralisation might also be related to acid production by microbes at low C/N (Garg et al., 2006 ; Dume et al., 2023). Ogunwande et al. (2008) have also found that C/N has a significant effect on K content during the composting process. The porosity of the compost pile could also be indicative of this negative correlation. Lack of bulking agent in CM-WO has resulted in low porosity, thus less K leaching as it is highly soluble in water (Chang et al., 2022; Santos et al., 2016).

The increase in N mineralisation was observed to cause a significant decline in pH value, as shown in Table 2, where N concentration for CM-P (the highest pH) is significantly lower than the other bulking agent categories. Azim et al. (2018) reviewed that the same outcome was found in several studies, which could be attributable to the high amount of hydrogen ions released due to increased nitrification, creating an acidic environment (Fang & Wong, 1999; McKinley & Vestal, 1985). Shi et al. (2020) stated that this antagonistic correlation indicates an imbalance in the transfer of protons and electrons during the biochemical process of composting. Furthermore, the elevated pH value suggests a significant presence of ammonia, which also hinders the nitrification process and leads to increased N losses (Chen et al., 2011 ; Wang et al., 2015). Cáceres et al. (2018) mentioned that nitrification can be inhibited due to extreme pH values (below 5 or above 8); similarly, this study also showed that pH values that stay below 8.0 corresponded to higher N values at the end of composting.

The present study confirmed previous results on how compost particle size is associated with bulk density values (Głąb et al., 2020; Ho et al., 2022). Khater (2015) studied the porosity and bulk density of cattle manure and sugar cane residues and found that sugar cane has higher porosity and lower bulk density than cattle manure. This affirms that materials with high porosity generally display low bulk density values, consequently influencing compost pile density. Table 2 illustrates that CM-P has a higher average

particle size, resulting in a lower and better average BD value than CM-WO. Therefore, it can be concluded that the high porosity of plant-derived materials in CM-P contributed to better BD values compared to CM-WO, which lacks the incorporation of a bulking agent. Shorter CD is associated with higher MC, as illustrated in Table 2, where the highest MC in CM-WO had the longest CD, and vice versa for the lowest MC in CM-M. Similarly, Nada (2015) reported that MC has an insignificant effect on the physicochemical quality parameters of compost. Changes in MC are closely related to aeration and temperature levels within the compost pile. Past studies have indicated that approximately 90 % of heat dissipation can be attributed to water evaporation in an aerated static pile system (Sasaay et al., 1997). The lack of bulking agent incorporation in CM-WO has resulted in inadequate space between the compost particles, thus preventing proper aeration within the composting pile. This influences the presence of oxygen for aerobic microbial activity and explains the long average CD of 98.7 days in CM-WO. Adequate pore spaces are crucial as they allow for proper aeration and prevent compaction within the compost pile for a more efficient composting process.

CONCLUSION

The comprehensive review provides insights into the recent developments in the aerobic composting of CM, particularly focusing on the effects of different bulking agents and composting methods on the physicochemical parameters. Plant-derived materials and livestock manure emerged as the most commonly utilised bulking agents in CM composting, playing crucial roles for optimising C/N, EC, K, BD and CD. The windrow method provides better retention of P and K, while the in-vessel method performed well in improving C/N ratio, EC, BD, MC and CD. Negative correlations were observed between C/N ratio and N, K and pH values, respectively, as well as between BD and particle size. A positive correlation was observed between CD and MC. These reviews highlight the importance of selecting suitable bulking agents and composting methods, as their interactions directly influence CM compost quality.

LIMITATIONS

This comprehensive review provides valuable insights into the effects of different bulking agents and composting methods. However, several limitations should be acknowledged. First, the review did not account for variations in composting duration, turning frequency, or ambient climatic conditions across the selected studies. Such heterogeneity may constrain the direct comparability of results among different experimental setups. Second, the analysis only focused on physicochemical parameters, without consideration of microbiological dynamics (e.g., pathogen reduction, microbial community succession) or gaseous emissions (e.g., ammonia, greenhouse gases). These factors are essential for a holistic evaluation of

composting performance and environmental impact. Third, the majority of the included studies were conducted under controlled or pilot-scale conditions, which may not fully represent the operational challenges and feedstock variability inherent in full-scale, real-world composting facilities.

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