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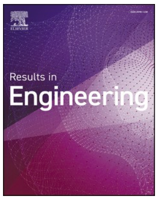

Review article

Biochar-amended food waste compost: A review of properties

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ABSTRACT

The attention towards managing food waste (FW) and transforming it into compost has significantly increased in recent years, driven by the potential advantages it offers for sustainable agriculture and waste reduction. Biochar, a carbon-rich amendment derived from biomass through pyrolysis, has gained significant attention due to its potential benefits to enhance compost quality. This systematic review analyzed 11 studies to assess the role of biochar in optimizing FW composting. Studies revealed several benefits of biochar addition, including shortening of the time to reach the thermophilic stage and an increase in composting temperature. Biochar also improved compost quality by maintaining nitrogen content, reducing ammonia emissions, and promoting a favorable pH for microbial activities. Its porous structure created a suitable habitat for microbes, potentially accelerating organic matter degradation. Additionally, biochar's high cation exchange capacity (CEC) helped immobilize potentially toxic metals, reducing their availability in the final compost. However, our knowledge of biochar's benefits in improving compost quality remains incomplete. The reviewed studies neglected to evaluate the microbial quality of the resulting compost and the cost-effectiveness of biochar application. Future research should prioritize long-term studies to assess plant uptake from soils amended with biochar. Additionally, investigations into the optimal biochar-to-compost ratio, as well as the most effective timing and methods for land application, should be undertaken. Addressing these knowledge gaps is crucial for optimizing the utilization of biochar in FW composting, thereby leading to sustainable waste management practices and enhanced soil fertility.

1. Introduction

The world's growing population, coupled with changes in lifestyles, has resulted in a significant rise in waste production in recent years. Projections indicate that this trend will persist, with waste production expected to reach 3.4 billion tons by 2050. This represents a significant rise from the 2.1 billion tons recorded in 2016 [1]. Food waste (FW) constitutes the largest bio-waste in the world [2], which is estimated at 1.3 billion tons produced per year [3]. This waste has substantial economic implications, costing between 9 and 23 billion dollars annually [4].

A substantial portion of FW ends up in landfills without proper treatment [5]. In the European community, FW constitutes approximately 45 % of all biological waste, while this figure rises to a staggering 55 % in developing countries [2]. Organic matter (OM) decomposes in landfills, producing methane (CH_4), a potent greenhouse gas that contributes to climate change [5]. Moreover, disposal of FW in landfills generates unpleasant odors and produces harmful leachate. As landfill capacity shrinks and finding suitable sites becomes increasingly difficult in metropolitan areas, many cities are implementing policies to limit waste disposal and promote alternative solutions like biological treatment [6].

FW offers a promising resource for various applications due to its rich composition, including carbohydrates, proteins, and lipids [2]. Technologies including anaerobic digestion, direct combustion, biodiesel production, and ethanol production have also been developed for the conversion of waste materials into recoverable resources [7,8]. However, composting remains the most widely used method globally for recovering OM due to its simplicity [9]. This environmentally friendly approach involves converting FW into valuable products for soil amendment, as well as producing CH_4 through biological processes [10]. Notably, countries like the Netherlands (24 %), Spain (33 %), and France (14 %) achieved significant success in composting a portion of their total waste [11].

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Compost improves soil properties such as apparent density and water holding capacity [12]. It also acts as a natural agent against plant diseases transmitted from the soil. In recent years, composting has been studied for the bioremediation of soils contaminated with potentially toxic metals and organic pollutants [13]. Although a fraction of some pathogens, including viruses and protozoa, may survive high temperatures during composting, most pathogens are destroyed due to the high temperature of the composting process (50–60 °C) [14,15]. In addition, the quality of compost is influenced by a range of factors. These factors include the types and ratios of raw materials used in the composting process, the rate of aeration, the moisture content (MC), and other relevant parameters. Consequently, it is essential to prioritize the optimization of composting conditions to produce a final product that is both stabilized and sanitized, without any chemical or microbial hazards [16,17]. To ensure the long-term, safe agronomic application of compost, standardized processing protocols are essential for mitigating potential risks.

To overcome the limitations and improve the physical structure of compost, various studies have explored the use of additives and bulking agents [2]. These include chemicals (hormones), decomposing microbes, bulking agents (straw and leaves), natural minerals (zeolites) and biochar produced from biomass [18–23].

Natural zeolites and biochar have garnered increased attention due to their unique physicochemical characteristics [11]. Biochar is a carbon-rich material produced from organic feedstock under certain thermal combustion with limited oxygen [24,25]. The unique physicochemical properties of biochar, including its high specific surface area, porous structure, functional groups, and mineral content, render it a versatile material. Its applications span diverse fields, such as environmental remediation through adsorption of pollutants, catalysis for processes like tar removal and biodiesel synthesis, and soil improvement. Furthermore, emerging research explores its potential in energy storage devices like fuel cells and supercapacitors [16,26–30]. Different types of biochar are produced from various raw materials, including agricultural residues, forestry byproducts, animal manures, sewage sludge, and municipal solid waste, using different pyrolysis conditions to evaluate their properties [31]. The use of biochar as a renewable compost amendment has received a lot of attention in recent years, and several studies have reported its effect on compost and subsequently soil characteristics [30,32–34].

In order to assess the viability of biochar-amended composting as a sustainable solution for FW management, this study conducted a systematic review of existing literature on the topic. The review focused on several key aspects: (i) presenting the diverse characteristics of biochar employed in previous studies, (ii) detailing the impact of biochar amendment on the physical and chemical properties of FW compost, and (iii) discussing potential gaps and limitations associated with the use of biochar-amended FW compost.

2. Materials and methods

This systematic review of the effects of biochar amendment on FW compost was compiled according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) method. A systematic Boolean search of electronic databases (Web of Science, Scopus, and PubMed) was conducted to identify relevant studies published up to July

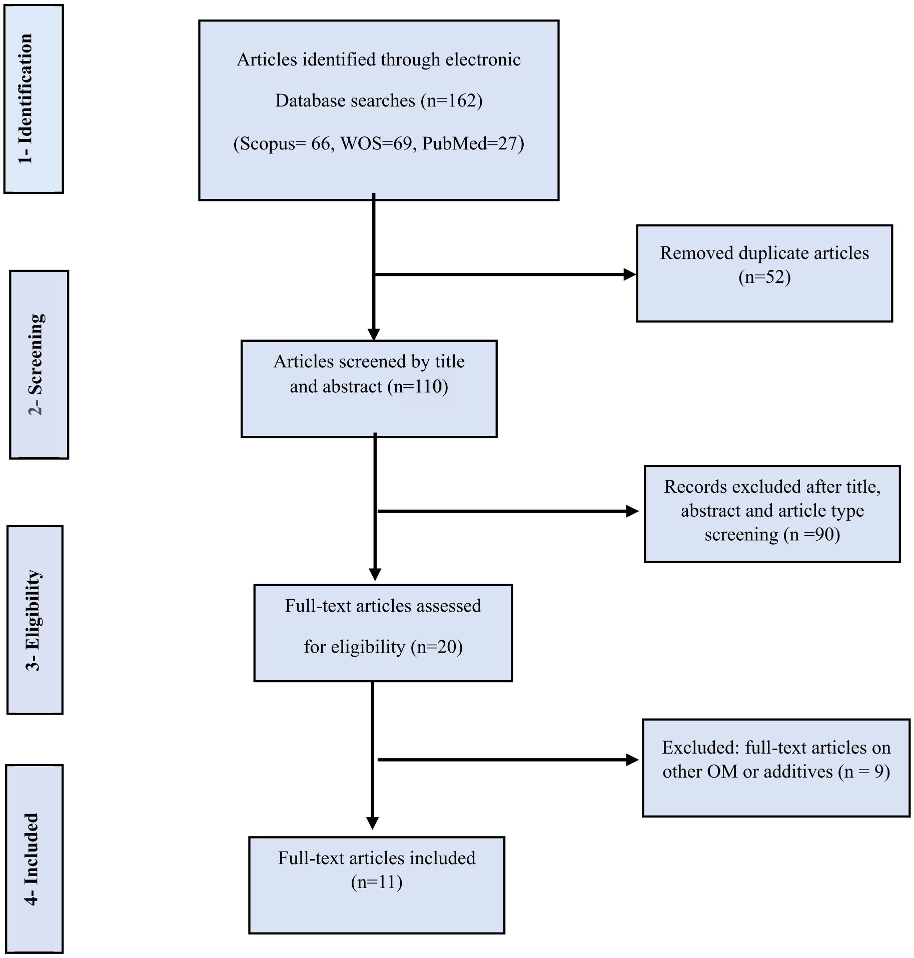

Fig. 1. The PRISMA flow diagram for conducting a systematic review.

24, 2023. Keywords used included "biochar," "composting," "co-composting," "food waste," and "kitchen waste," combined using AND and OR operators. After removing duplicates, the initial 162 articles (Fig. 1) were reduced to 110. To further refine the focus, only original studies exclusively on FW compost and biochar were included. Non-English language articles, review articles, conference abstracts, news articles, and posters were excluded. Studies focusing on other organic matters, such as manure, sewage sludge, and mixed municipal solid wastes, as well as those investigating other compost additives like zeolites, were also excluded. Following title, abstract, and full-text screening, 11 articles clearly presenting the methods used and results were retained for inclusion in the study (Fig. 1).

3. Results and discussion

3.1. Biochar production

3.1.1. The effect of raw materials on biochar

Pyrolysis temperature and biomass source significantly affect biochar properties [35]. Wood and non-wood biomass are the two main categories used for biochar production (Table 1). Wood biomass, such as remnants from forests and trees, typically has low moisture, ash, and porosity, and high calorific value and density [36]. In contrast, non-wood biomass, including agricultural and forestry residues, industrial by-products, and municipal wastes, encompasses diverse materials with varying properties [31]. These non-wood materials often contain higher ash content due to their mineral composition [37,38]. Studies suggest that the choice of raw materials significantly impacts biochar properties [39]. Wood biomass generally has higher lignin content, while non-wood sources like leaves and reeds are richer in cellulose and hemicellulose. Lignin content positively affects biochar production efficiency compared to cellulose and hemicellulose [31,40]. Therefore, using raw materials with higher lignin content, like wood, can increase biochar yield due to due to lignin's higher heat resistance [40]. Additionally, wood-derived biochar typically has higher carbon content, lower ash content, and lower levels of nutrients compared to non-wood biochars like manure or leaves [38,41]. In contrast, biochars derived from industrial by-products, municipal waste, and non-conventional materials often have higher ash content, mineral composition, MC, and lower energy value [31,36]. For example, chicken manure biochar has high levels of potassium (K^+), calcium (Ca^{2+}), magnesium (Mg^{2+}), and sodium (Na^+), while paper waste biochar has high calcium (Ca^{2+}) content [42].

The choice of biomass feedstock significantly impacts the properties of the resulting biochar, influencing its suitability for various applications. Wood-based biochar is generally preferred for soil amendments due to its low ash content and higher carbon content [38]. However, biochars derived from other materials can have valuable nutrient content. Manure biochar can act as both soil amendment and an organic fertilizer, as proven by increased nitrogen, phosphorus, and K^+ uptake, a positive liming effect, and high soil nutrient availability (both organic and mineral) [51]. Sewage sludge biochar can improve soil properties and phosphorus availability [52]. Nevertheless, it is important to consider the potential risks associated with some non-wood biochars, such as the release of potentially toxic metals from sludge-derived biochar [53]. Choosing the appropriate biochar for a specific purpose requires careful consideration of its properties and potential environmental impacts.

Table 1
Characteristics of biochar used in the included studies.

Biochar feedstock	Biochar size (mm)	Biochar production temperature (°C)	Reference
Rice husk	2–5	500–600	[43]
Green waste	NR[a]	350 & 450	[44]
Beachwood	4	400	[11]
Rice husk	2–5	NR	[45]
River Redgum *(Eucalyptus camaldulensis)*	0.5–12	500–600	[46]
Pine tree Poplar plant Wetland plant Yard waste	0.5	500	[47]
Prosopis juliflora (woody biomass*)*	NR	400–500	[48]
Bagasse	NR	350	[49]
The combination of biosolid and green waste (2:1)	NR	650	[50]

[a] Not reported.

3.1.2. The effect of pyrolysis temperature on biochar production

The effect of pyrolysis temperature on biochar production is shown by the varying temperatures used in the studies listed in Table 1. The lowest temperature used was 350 °C for bagasse and lawn waste biochar [44,49], while the highest was 650 °C for biochar produced from a biosolids and green waste combination [50]. It has been reported that elevated pyrolysis temperatures correlate with decreased biochar yield and acidic functional group abundance, while conversely enhancing basic functional group content, ash content, pH, and carbon stability [40,54,55].

Biochar production methods like slow and fast pyrolysis differ in temperature, heating rate, biomass particle size, and steam retention time [50]. Slow pyrolysis typically occurs between 300 °C and 700 °C, with biomass retention times ranging from hours to days [56]. In contrast, fast pyrolysis uses high temperatures and rapidly heats small biomass particles in seconds or minutes, without oxygen [57]. Studies have shown that pyrolysis temperature directly affects biochar yield, which is typically calculated as the mass ratio of the resulting biochar to the initial biomass (based on dry weight) multiplied by 100 [44]. Examining lawn waste biochar produced at 350 °C and 450 °C demonstrated this effect [44]. Generally, biochar yield decreases with increasing temperature e.g., an average yield of 32 % at 400 °C, 29 % at 500 °C, and 25 % at 600 °C has been reported [40]. Conversely, the amount of ash produced increases significantly with rising temperature [54]. Waqas et al. (2018) used X-ray diffraction (XRD) analysis to show that increasing lawn waste biochar synthesis temperature from 350 °C to 450 °C affects its structure and chemical composition [44]. As the temperature rises, the content of macromolecules like hemicellulose, cellulose, lignin, and protein decreases in the solid residue, while aromatic rings begin to form [57], leading to the creation of stable aromatic structures in biochar [58]. Over 80 % of the unstable biomass carbon is converted to these resistant structures at temperatures between 400 °C and 600 °C [40]. This is why 650 °C with a 40-min residence time was chosen as the optimal condition for producing biochar from a biosolids and green waste combination, aiming for a high surface area and abundant aromatic rings [50].

Pyrolysis temperature affects biochar pH due to two factors: (i) the formation of biochar ash containing alkaline minerals at higher temperatures, and (ii) the presence of more acidic functional groups (phenolic and carboxylic) in biochars produced at lower temperatures [55]. Waqas et al. (2018) confirmed this by observing higher pH values in lawn waste biochar produced at 450 °C compared to 350 °C [44]. Additionally, biochar obtained from biomasses like algal biomass and poultry litter, which naturally contain more ash, exhibit higher pH values [36].

Finally, pyrolysis temperature plays a crucial role in biochar stability. Higher temperatures lead to the formation of more stable aromatic structures, increasing the overall carbon content [57]. Biochar produced above 500 °C typically boasts longer half-lives exceeding 1000 years [39]. For example, oak biochar produced at 650 °C had a significantly higher half-life (1074 years) compared to that produced at 250 °C (840 years) [57].

3.1.3. Biochar size

Studies investigating biochar particle size for compost amendment show variation, with sizes ranging from 0.5 mm to 12 mm (Table 1). While no single optimal size exists [59], particle size significantly impacts properties of biochar and effectiveness in compost. Larger biochar particles (around 5 mm, as used in several studies) offer advantages [59, 60]. They are less prone to breakage [61] and have lower density [62], improving aeration within the compost pile [63]. Additionally, larger particles act as bulking agents, enhancing heat transfer, but may be less effective in eliminating pathogens due to lower overall temperature [64]. However, producing large biochar requires less energy and time compared to smaller particles. Smaller biochar particles (e.g., 0.5 mm) offer a different set of benefits. They distribute more uniformly throughout the compost [59] and provide a larger surface area for microbial activity, potentially increasing OM degradation [65]. A study comparing powder (<1 mm) and granule (4 mm-1cm) biochar amendments demonstrated this effect: powder-amended compost showed increased CH_4 emissions, while granule-amended compost exhibited a decrease [66]. Similarly, another study suggests that granular biochar (4 mm–8mm) promotes aerobic conditions, reducing CH_4 emissions, while powdered biochar facilitates ammonia (NH_3) reduction through its larger surface area [67]. This aligns with findings by Ottani et al. (2023) who observed reduced nitrous oxide (N_2O) and CH_4 emissions with coarse biochar, while small biochar lowered NH_3 release, potentially due to NH_3 adsorption on its larger surface area [65].

Biochar particle size also influences antibiotic and antibiotic resistance gene (ARG) removal. A review by Tong et al. (2023) showed that small biochar with a larger surface area (49.16 m^2/g) outperformed coarse biochar (4 m^2/g) in removing these contaminants during pig manure composting [68]. Additionally, the finer biochar particles may contribute slightly more thermal energy to the compost due to their increased surface area [69]. The choice of biochar particle size for compost amendment depends on the desired outcome. Larger particles improve aeration and act as bulking agents, while smaller particles enhance surface area and potentially reduce emissions. Considering these factors alongside production costs can help determine the most suitable biochar particle size for a specific composting application.

3.2. Effects of biochar addition on FW compost

3.2.1. Temperature

Temperature is a crucial factor influencing the performance and rate of composting, as it directly affects microbial activity. During composting, OM degradation by microorganisms generates heat, raising the compost temperature. This rise in temperature is followed by a decrease as microbial activity slows down [44,49]. Maintaining optimal temperature is essential to accelerate the composting process and ensure proper microbial growth [45].

Studies have shown that biochar addition can significantly increase compost temperature. Ravindran et al. (2022) observed that adding 10 % rice husk biochar to compost significantly extended the thermophilic stage, with the highest temperature recorded in this treatment [43]. This increase in temperature during the early stages is likely due to biochar's large surface area, providing favorable conditions for microbial degradation of OM. Similarly, Malinowski et al. (2019) found that incorporating 5 % biochar shortened the time needed to reach the thermophilic stage [70]. Biochar's porous and complex structure allows it to hold oxygen, water, dissolved organic matter, gases, and nutrients, creating a suitable habitat for microorganisms and enhancing their activity [71–73]. This accelerated microbial activity leads to faster OM degradation and heat generation, ultimately shortening the time to reach the thermophilic stage [44–46]. Waqas et al. (2018) demonstrated this effect, observing a rapid temperature increase in biochar-amended compost bioreactors compared to the control [44].

Maintaining a high enough temperature (above 55 °C for at least three consecutive days) is crucial for eliminating pathogens in compost and ensuring its safety for agricultural use [74]. Qin et al. (2021) reported that all biochar-amended composts maintained a temperature above 50 °C for at least 10 days, demonstrating the potential of biochar to facilitate pathogen inactivation [49]. Furthermore, Chaher et al. (2020) observed that the treatment containing 20 % biochar reached the thermophilic stage faster and maintained a higher maximum temperature compared to the control, potentially enhancing pathogen elimination [11]. Similar findings were reported by Castro-Herrera et al. (2022), who observed a significantly higher temperature in cow dung compost amended with biochar compared to the control [46]. However, it is important to note that excessively high temperatures (above 60°C–65 °C) can kill most microorganisms and hinder the composting process [73].

3.2.2. pH

Compost pH is a critical characteristic, although a wide range (pH 3–11) can support composting [6]. Initially, pH decreases due to organic acid formation, hindering microbial activity [16,75]. However, as these acids are consumed and NH_3 forms, the pH typically becomes neutral, which is optimal for most microorganisms [44,76].

Biochar addition can be an effective method to adjust compost pH (Table 2). Studies have shown that biochar can increase compost pH. Ravindran et al. (2022) observed that the treatment with 10 % biochar had a relatively higher final pH (8.73 ± 0.17) compared to the control group (pH = 8) [43]. This increase is attributed to OM degradation, ammonification, and the inherent alkalinity of biochar [43,44]. Similar findings were reported by Waqas et al. (2018) who observed higher pH values in biochar-amended treatments compared to the control throughout the composting process [44]. The increase in pH can be attributed to several factors. Biochar itself has a basic pH and is rich in basic cations like K^+, Na^+, Mg^{2+}, Ca^{2+}, hydroxide (OH^-), and carbonate (CO_3^{2-}), which have a strong capacity to exchange hydrogen ions (H^+). Chaher et al. (2020) observed a final pH of 9.12 in compost amended with 20 % biochar, compared to a final pH of 7.8 in the control group [11]. Similarly, adding rice husk biochar to pig manure and FW compost increased the final pH to 8.0–8.5, compared to lower pH values in treatments without biochar [45]. Slightly alkaline compost is often preferred for soil application due to its ability to buffer soil acidity. Many plants thrive in slightly alkaline conditions, and the addition of alkaline compost can help to neutralize acidic soils, improving nutrient availability and overall soil health [77,78].

However, some studies have reported a decrease in pH with biochar addition. Khan et al. (2019) observed a higher final pH in the control group compared to vermicompost amended with different biochar types [47]. The combined activities of earthworms and microorganisms during vermicomposting appear to contribute to a decrease in pH, likely due to the production of organic acids and carbon dioxide (CO_2) [80,81]. This contradicts the findings of Ameen and Al-Homaidan [79] who suggest that microbial activity increases pH through OM mineralization. Further investigation is needed to clarify the specific effects of biochar type and composting process on pH changes.

3.2.3. Carbon-to-nitrogen ratio (C/N)

The C/N ratio is a crucial indicator of compost stability, maturity, and quality [11]. A C/N ratio between 25 and 30 is considered optimal for microbial activity during composting [72,82]. Microorganisms utilize carbon for energy and nitrogen for protein synthesis [83]. When the C/N ratio is too low, it can lead to nitrogen loss through NH_3 volatilization, reducing the fertilizer value of the compost [70]. Conversely, a high C/N ratio can limit microbial activity due to insufficient nitrogen availability [6,72].

Biochar addition can positively impact compost C/N ratio. Studies have shown that biochar, as a carbon source, can help maintain a more balanced C/N ratio throughout the composting process [43,70]. Ravindran et al. (2022) observed that the C/N ratio in their treatments with rice husk biochar remained within the optimal range throughout

Table 2
Characteristics of biochar amended food waste compost.

Study No.	First author (Year)	Country (City)	Waste type (ratio) or Compost Material	Biochar Dose (%)	Compost time (days)	pH	Max-Temp (Compost)	C/N (Initial)	C/N (Final)	MC[a] (%) Final	EC Final (mS/cm)	OM (%) Final	TKN (%) final	NO_3-N (mg/kg) Final	Heavy Metals
1	Ravindran [43]	South Korea (Suwon)	Poultry and Food waste and Sawdust (2:2:1), C/N:25.3 ± 0.76	0	50	8	49	25.3	24.4	NR[b]	2.3–2.87	NR	NR	NR	NR
				0		8.3	52	25.3	24.1						
				3		8.3	55	26	24.4						
				5		8.5	55	26.2	21						
				10		8.7	60	29.3	19.7						
2	Waqas (2017) [44]	Saudi Arabia (Jeddah)	Food waste	0	90	8.6	NR	NR	NR	54	2	64.2	NR	37.9	NR
				10 (350)		7	NR			36.7	3.4	54.2		82.2	
				10 (450)		7.9	NR			43.2	3.1	55.7		93	
				15 (350)		7.5	53.6			34.7	3.5	55.7		112	
				15 (450)		8	60			39.3	3.3	56.8		117.9	
3	Chaher [11]	Germany (Rostock)	Food waste, Wheat straw, Mature compost	0	32	7.8	61	20.7	11.6	56.3	7.5	NR	NR	2.9[c]	Decrease (Pb, Cu,Zn,Ni,Cd, Cr,As,Hg)
				10		8	66	27	15	49.7	6.1			3.4[c]	
				20		9.1	72	29.7	19.3	43.7	5.3			3.9[c]	
4	Ravindran [45]	South Korea (Suwon)	Food wastes, Swine manure, Sawdust (2:2:1)	0	50	8–8.5	50–60	NR	57 * MAX decreased	NR	3	NR	NR	45* MAX Increase	NR
				0							2.75				
				2							2.64				
				4							2.52				
				6							2.24				
				8							2.25				
				10							2.25				
5	Castro-Herrera (2021) [46]	Germany	Cattle manure, Vegetable scraps, Teff straw, Sawdust	0	185	8	62.1	41.4	14.6	63.3	3.8	62.6	NR	NR	NR
			Cattle manure, Vegetable scraps, Teff straw, Sawdust	19		8.6	65.9	49.8	22.2	60.6	3.1	60.6			
			Humanure, Vegetable scraps, Teff straw, Sawdust	0		7.4	65.1	32.3	25.1	63.1	4.5	70.9			
			Humanure, Vegetable scraps, Teff straw, Sawdust	19		7.9	64.2	50.2	37.5	59.8	4.3	68.8			
6	Ameen [79]	Saudi Arabia (Riyadh)	Eisenia fetida	NR	90	NR	NR	NR	NR	NR	NR	NR	0.5	NR	Decrease (Pb, Cu,Zn,Ni,Cd, Cr)
			Cow-dung,Eisenia fetida, fungi (Acrophialophora jodhpurensis)	NR									1		
			Cow-dung,Eisenia fetida, fungi (Talaromyces diversus)	NR									1.5		
			Cow-dung, Eisenia fetida, Fungi (Acremonium potronii)	NR									0.7		
			Cow-dung, Eisenia fetida	NR									2		
7	Khan [47]	China (Hangzhou)	Sewage sludge, Kitchen waste (70;30), Eisenia fetida	0	46	7.3	NR	NR	12.2	NR	NR	415[d]	NR	NR	Decrease (Pb, Cu,Zn,Mn,Cd, Cr)
				10		7.1			NR			384[d]			
				10		7.1			7.4			381[d]			
				10		7.2			NR			394[d]			
				10		7.1			NR			387[d]			
8	Paul (2019) [48]	India (Guwahati)	Vegetable waste, Cow dung, Saw-dust (5:4:1)	0	60	NR	NR	NR	NR	NR	NR	NR	2.8	630	Increase (Pb, Cu,Zn,Ni,Cd, Cr)
				2.5									2.97	753	
				5									3.1	890	
				10									2.7	920	

(continued on next page)

Table 2 (*continued*)

Study No.	First author (Year)	Country (City)	Waste type (ratio) or Compost Material	Biochar Dose (%)	Compost time (days)	pH	Max-Temp (Compost)	C/N (Initial)	C/N (Final)	MC[a] (%) Final	EC Final (mS/cm)	OM (%) Final	TKN (%) final	NO_3-N (mg/kg) Final	Heavy Metals
9	Qin [49]	China (Guilin)	Excess sludge, Food waste (1:1)	5	40	NR	54.9	NR	NR	50.7	NR	57.3	NR	NR	NR
			Excess sludge, Food waste (2:1)				59.7			54.3		54.2			
			Excess sludge, Food waste (4:1)				58.4			56.2		52.4			
10	Kaudal (2018) [50]	Australia (Melbourne)	Food waste, Sawdust (19:1)	0	77	8.5	60	NR	NR	NR	3.5	NR	NR	NR	Decrease (Fe, Al, Mn, Pb, Ni, Zn) (g/kg)
			Food waste, Sawdust (17:1)	10		8.1	NR				2.2				
11	Voběrková (2020) [75]	Czech Republic (Brno)	Food waste, Microorganisms (Acidulo™)	0	63	NR	79	NR	20	NR	5–6.0	NR	NR	NR	NR
			Food waste, Microorganisms (Acidulo™), saw dust	0		4.8	53.3		58		0.8–1				
			Food waste, Microorganisms (Acidulo™)	20		NR	56.3		38		2.5–3				

[a] %.
[b] not-reported.
[c] mg/L.
[d] g/k.

composting, while the control group C/N ratio dropped below 20, an indicator of excessive nitrogen loss [43]. This suggests that biochar can help retain nitrogen in the compost. Biochar's high carbon stability can also contribute to a mature compost with a suitable C/N ratio. Chaher et al. (2020) reported that the C/N ratio in their treatment with 20 % biochar remained closer to 20 at the end of composting compared to the control group, which experienced a significant decrease [11]. This indicates that the addition of biochar can promote compost maturity. Several studies have observed a decrease in the C/N ratio of biochar-amended composts by the end of the process, suggesting faster OM decomposition [45,74]. However, the final C/N ratio typically remains within the acceptable range for mature compost (less than 20) [74].

3.2.4. *Electrical conductivity (EC)*

Electrical conductivity (EC) reflects the compost salt content and OM decomposition, potentially impacting plant toxicity [72,84]. It can also indicate changes in organic and inorganic ions throughout composting (Table 2). Generally, EC values below 4.00 mS/cm are suitable for agricultural use. Studies have shown that biochar addition can influence compost EC [44].

The influence of biochar addition on compost EC is complex and varies across studies. While some research has shown an initial decrease in EC followed by an increase in the final product [46,84], other studies have reported lower EC values in biochar-amended compost compared to controls [11,43,45,75,85]. These discrepancies can be attributed to factors such as biochar type, application rate, and compost composition.

The porous structure of biochar provides a large surface area for the adsorption of various molecules, including salts and ions which may lead to decreased EC [86]. On the other hand, it can increase EC by releasing soluble compounds [11,72]. Biochar characteristics, primarily determined by feedstock and pyrolysis conditions, significantly impact its influence on EC. Higher pyrolysis temperatures generally lead to increased EC due to the concentration of inorganic residues (ash). Additionally, the inherent mineral content of the feedstock plays a role, with biochars derived from wood and paper waste typically exhibiting lower EC compared to those from manure [86].

3.2.5. *Optimal moisture content (MC)*

Moisture content (MC) is the level of water in a compost pile that balances the needs of microbial activity with sufficient oxygen availability [87]. High MC in OM, especially FW, can lead to leachate production, reduced porosity, and hinder biological activity [45,88]. Additionally, higher MC results in a higher compost weight, making it difficult to handle and transport (Table 2). The optimal MC range is generally considered to be 50–60 % [64]. If MC drops below 30 %, microbial activity is significantly reduced. Biochar's porous structure can absorb moisture and provide a suitable habitat for microorganisms, leading to increased activity, temperature rise, and ultimately, greater water evaporation from the compost pile [11,44]. Qin et al. (2021) investigated MC in excess sludge and FW compost with 5 % bagasse biochar. The lowest final MC (52.41 %) was observed in the 1:1 excess sludge and FW mixture [49]. Waqas et al. (2018) found that biochar addition (15 %) to FW compost resulted in a decrease in final MC, bringing it within the desired range, whereas the control group exceeded the recommended limit (50 %) [44]. Chaher et al. (2020) observed a decrease in MC from 67.4 % to 43.7 % in FW, wheat straw, and mature compost amended with 20 % biochar, compared to 56.3 % in the control group (above the optimal range) [11].

3.2.6. *Organic matter (OM)*

In the composting process, a complex series of biochemical reactions occurs. OM undergoes degradation and transformation under aerobic conditions, resulting in the creation of a well-stabilized product. A portion of the OM is mineralized into CO_2 through oxidative processes, while the remaining part is converted into humic substances, which are more resistant to microbial decomposition due to their recalcitrant structure. The composition of the organic matter being composted significantly influences the rates of these processes and the final product characteristics. For example, materials high in lignocellulose, a complex polymer composed of cellulose, hemicellulose, and lignin, tend to decompose slowly and produce more humified substances due to their slower rate of biodegradation [89]. Studies suggest that biochar can increase microbial activity due to its high cation exchange capacity (CEC) and porosity, which in turn enhances the decomposition of OM components like lignin, cellulose, hemicellulose, and proteins [48,90,91]. Waqas et al. (2018) observed a higher rate of OM decomposition in FW compost amended with biochar compared to the control. The final OM content in the compost with 15 % biochar was significantly lower than the initial value [44]. However, rapid degradation of OM in the early stages of composting may occur, leading to a decrease in pH due to the production of organic acids, ultimately hindering microbial activity [75]. Biochar's microporous structure provides a favorable environment for microbes to breakdown OM and can also increase the substrate's pH [16,44]. Li et al. (2013) reported an increased rate of OM degradation (from 14.8 % to 29.6 %) in corn stalk compost amended with biochar compared to the control group [88]. Several studies have shown that biochar addition can accelerate OM decomposition and shorten composting time [89,90]. For example, Khan et al. (2019) observed faster breakdown of OM in sewage sludge and kitchen waste compost amended with biochar [47]. Similarly, Liu et al. (2017) reported increased microbial decomposition of OM in chicken manure and wheat straw compost with biochar addition [92]. However, not all studies agree on the impact of biochar on OM decomposition. Jindo et al. (2011) and López-Cano et al. (2015) found no significant effect of biochar on the total amount or degradation pattern of OM in chicken manure compost [93,94].

3.2.7. *Nitrogen dynamics*

Nitrogen content is crucial for the agricultural value and quality of compost [45]. Nitrogen loss through NH_3 volatilization is a major limitation, reducing the fertilizer value of the final product and contributing to air pollution [49]. Studies suggest that biochar addition can improve nitrogen dynamics in compost. López-Cano et al. (2015) found that even a small amount (4 %) of biochar effectively reduced nitrogen loss through volatilization and enhanced nitrification, leading to more efficient nitrogen conversion during composting [93]. Several studies have reported a positive effect of biochar on total Kjeldahl nitrogen (TKN) content in compost (Table 2). The increase in TKN may be due to faster microbial decomposition facilitated by biochar's biocatalytic properties [48,75]. Chen et al. (2010) observed that adding biochar to pig manure compost significantly reduced TKN loss. They found that the TKN content in the final product increased with increasing biochar dosage [95]. This is likely because biochar, similar to activated carbon, has a large specific surface area and abundant pores that can absorb NH_3 gas, preventing nitrogen loss. Ravindran et al. (2022) investigated the effect of rice husk biochar on poultry manure, FW, and sawdust compost [43]. They observed an increase in nitrate nitrogen (NO_3-N) concentration and a decrease in ammonium nitrogen (NH_4^+-N) in the final product with increasing biochar content. This could be attributed to biochar's absorption characteristics, high-temperature NH_3 volatilization, rapid mineralization, and an increase in nitrifying bacteria. While Waqas et al. (2018) and Chaher et al. (2020) also reported an increase in NO_3^- levels in biochar-amended compost compared to the control [11,44], their studies differed from Rabindran et al. (2022) in terms of NH_4^+ levels [43]. This discrepancy might be due to variations in compost maturity, initial organic matter composition, or environmental conditions during the composting process. For example, higher initial pH levels in the studies by Waqas et al. (2018) and Chaher et al. (2020) might have favored nitrification, leading to increased NH_3 conversion to NH_4^+ and ultimately higher NO_3^- concentrations. These studies suggest that biochar can reduce NH_3 volatilization and enhance NH_4^+ absorption due to its CEC, thereby preventing nitrogen loss [11,44]. Additionally, biochar may create favorable conditions for microbial activities related to nitrification and ammonification [11]. Improved aeration due to biochar may further promote the nitrification process, as nitrifying bacteria are aerobic [89,92].

3.2.8. *Potentially toxic metals*

Compost can contain small amounts of potentially toxic metals that are essential for plant growth, but excessive levels can be detrimental [11,47,79]. These metals can also accumulate in the food chain, ultimately affecting human and animal health [96]. The mobility and potential for plant toxicity of metals are primarily determined by their bioavailability in the compost [97]. Composting is an eco-friendly process that can biomineralize soluble metals, reducing their toxicity and environmental risk [72,79]. Several studies have shown that biochar addition can reduce the availability of potentially toxic metals in the final compost product (Table 2). This is attributed to biochar's ability to limit heavy metal (HM) bioavailability [11].

Biochar addition can increase compost pH due to the presence of alkaline elements like phosphorus, K^+, Ca^{2+}, and Mg^{2+} [97]. This increases the negative charge of the compost, enhancing electrostatic attraction between potentially toxic metals and the compost particles [98]. Additionally, biochar's high CEC, abundant carboxylic groups, hydroxyls, and alcohols facilitate the formation of complexes with potentially toxic metals, further reducing their bioavailability [99].

Studies have demonstrated the effectiveness of biochar in reducing potentially toxic metals bioavailability. A study investigating the combined effect of bacterial cultures and biochar on pig manure composting found that this combination effectively reduced the bioavailability of copper and zinc [2]. Biochar physicochemical properties, including high porosity, low density, and high adsorption capacity, can improve aeration during composting, modify the microbial community, and consequently, reduce potentially toxic metals mobility [45]. Paul et al. (2020) examined the effect of biochar on vermicompost made from vegetable waste, cow dung, sawdust, and biochar. They observed that while potentially toxic metals concentrations increased after OM decomposition, bioaccumulation in earthworm tissues reduced potentially toxic metals availability [48,79]. This was attributed to improved earthworm metabolism and increased secretion of excess polymeric material by the earthworms due to biochar addition. Although potentially toxic metals cannot be entirely eliminated from compost, their leachability and mobility can be significantly reduced. This helps to minimize the entry of potentially toxic metals into the environment and food chain [100].

3.3. *Knowledge gaps and future directions*

(1) Microbial quality

Despite evaluating various physical and chemical properties of FW compost amended with biochar, the included studies overlooked microbial quality and pathogen presence in the produced composts. While composting temperatures typically inactivate most microorganisms, and mature compost boasts a reduced microbial population, certain pathogens can resist the thermal inactivation. Furthermore, the potential for pathogen reactivation and regrowth during storage adds another layer of concern [15]. To ensure the true sustainability of compost land application, a crucial gap in our knowledge on microbial contamination and its associated public health and environmental risks should be addressed. Compost-grown vegetables, especially those eaten raw, pose a particular concern for human health [101,102]. Additionally, workers handling compost during land application face the potential risk of accidental ingestion of pathogens through contaminated soil [15,102]. To mitigate these potential hazards, future studies must prioritize comprehensive risk assessments of microbial risks associated with land application of FW compost.

(2) Scale

A critical analysis of the existing literature reveals a significant disparity between laboratory and field-scale studies on FW composting. While nine investigations were conducted under controlled laboratory conditions (studies 1–4, 6–9 and 11, Table 2), only two studies (studies 5 & 10, Table 2) explored the process in field scale. Laboratory-scale experiments offer precise control over composting parameters, enabling detailed examination of specific variables. However, the artificial nature of these conditions limits the extrapolation of findings to full-scale composting systems. Field-scale studies, though fewer in number, provide invaluable insights into the practical challenges and complexities of composting institutional FW under dynamic environmental conditions. The limited availability of field-scale data hinders a comprehensive understanding of the applicability of biochar-amended composting processes under real conditions and the impact of environmental factors on these processes.

(3) Carbon loss

While most research has focused on accelerating composting, reducing greenhouse gas emissions, and producing stable compost for agriculture, the critical issue of carbon loss during this process has been largely overlooked. To enhance carbon sequestration through organic waste management, a carbon-centric composting approach is required.

A key step is developing a maturity-based method for evaluating carbon loss. Currently, various maturity indicators exist (e.g., C/N ratio, humic substances, nitrogen forms, seed germination), but their relationship to carbon loss is unclear [103]. Identifying the most suitable indicator for carbon loss assessment is essential. Subsequent systematic review and meta-analysis on biochar amended composts can identify optimal biochar properties, mitigation strategies, and innovative composting techniques to minimize carbon emissions. Further research is needed to explore additional carbon reduction methods and to gain a deeper understanding of organic carbon dynamics throughout the composting process.

A more targeted composting approach that balances carbon sequestration with end-product utilization is desirable. For instance, producing compost with specific maturity levels for different applications can optimize both carbon storage and product quality [103]. A comprehensive life cycle assessment of various composting systems is essential for a complete understanding of their carbon footprint.

(4) *Phytotoxicity*

Phytotoxicity testing, such as seed germination tests, remains crucial for compost safety even when biochar is added. While biochar is theorized to reduce compost toxicity by limiting the availability of pollutants like potentially toxic metals, its actual impact can be complex. This is evident in the reviewed studies, where Kaudal and Weatherley (2018) and Castro-Herrera et al. (2022) observed improved germination in compost amended with 10 % and 19 % biochar, respectively, compared to the control [46,50], but Voběrková et al. (2020) reported significant phytotoxicity (no germination) in FW compost amended with 20 % biochar [75]. This discrepancy highlights the potential for negative effects depending on factors like biochar quality and application rate. Therefore, rigorous phytotoxicity testing is still necessary to ensure the safety and effectiveness of biochar-amended compost.

(5) Cost-benefit analyses

There is a significant knowledge gap when it comes to assessing the cost-effectiveness of biochar-amended FW compost. While biochar has demonstrated potential in enhancing compost quality, a crucial question remains unanswered: are the benefits worth the additional costs? Composting is a well-established and cost-effective waste management strategy. However, incorporating biochar might pose a challenge, particularly in low-income regions. The cost of biochar production is highly variable and depends on several factors. In-situ methods, which produce biochar directly in the soil, can indeed be very cost-effective as they often leverage existing agricultural practices and waste products. However, large-scale industrial biochar production typically involves energy-intensive processes like pyrolysis, which can increase costs. Factors such as feedstock type, production method, and the scale of operation all contribute to the overall cost of biochar [104]. It is essential for future studies to conduct comprehensive cost-benefit analyses that consider the entire life cycle of biochar, including production, transportation, and application costs. Moreover, these analyses should also account for potential economic benefits associated with improved compost quality, such as increased crop yields, reduced fertilizer requirements, and enhanced soil health. By carefully evaluating all costs and benefits, researchers can determine whether the inclusion of biochar is a worthwhile investment, thereby promoting sustainable and economically viable composting practices, especially in resource-constrained settings.

4. Conclusions

This systematic review investigated the impact of biochar amendment on FW compost properties using 11 original articles. The findings emphasize the significance of both biochar characteristics and application parameters. The conditions under which pyrolysis takes place and the choice of raw materials exert a substantial influence on the properties of the resulting biochar, subsequently impacting the final FW compost. Furthermore, the ratio of biochar to FW and the particle size of biochar can have a notable influence on compost properties. Biochar addition emerges as a promising strategy for FW compost management. It can effectively manage C/N ratio, promoting nitrogen retention and reducing NH_3 emissions. Furthermore, biochar's porous structure facilitates moisture retention and provides a suitable habitat for microorganisms. This can lead to increased microbial activity, temperature rise during composting, and ultimately, enhanced water evaporation from the compost pile, potentially leading to faster maturation. However, knowledge gaps remain regarding the potential health risks associated with biochar-amended composts, their phytotoxicity properties, and a comprehensive cost-benefit analysis. Long-term studies are warranted to assess the plant uptake of elements from soils amended with these composts. Additionally, future research should investigate the optimal FW compost-to-soil application ratio, along with the most effective timing and methods for land application.

CRediT authorship contribution statement

Mehdi Ebrahimi: Writing – original draft, Investigation, Conceptualization. **Sahar Gholipour:** Writing – original draft, Conceptualization. **Gholamreza Mostafaii:** Supervision. **Fatemeh Yousefian:** Writing – review & editing, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

The data that has been used is confidential.

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