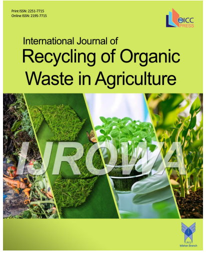

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The effects of compost application on soil properties: Agricultural and environmental benefits

Farida Iraji[1]*, Raimundo Jiménez-Ballesta[2], Jorge Mongil-Manso[3],
Graciela Pellejero[4], David Miguélez[5], Payam Najafi[1],
Juan Manuel Trujillo González[6]

[1] *Water Studies Research Center, Isf.C., Islamic Azad University, Isfahan, Iran.*
[2] *Autónoma University of Madrid, Spain.*
[3] *Forest, Water & Soil Research Group., Catholic University of Ávila, Spain.*
[4] *CURZA-Universidad Nacional del Comahue, Río Negro, 8500 Viedma, Argentina.*
[5] *Grupo Ibérico de Anillamiento, Madrid, Spain.*
[6] *Universidad de los Llanos, Villavicencio, Colombia.*

*__Corresponding author:__ f.iraji@khuisf.ac.ir

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Abstract:

Purpose: Human activities generate substantial waste, often relegated to landfills or incineration. Composting offers a valuable alternative, transforming waste into organic fertilizers that can improve soil health. This review examines the multifaceted influences of compost application on soil properties, the associated agricultural and environmental benefits.
Method: A comprehensive literature review was conducted, analyzing numerous research articles focused on compost application in agricultural soils. The review prioritized studies investigating the direct and indirect effects of varying compost application rates on a range of soil properties. The search encompassed databases and scientific journals related to soil science, environmental science, and agriculture.
Results: The reviewed literature consistently demonstrated that compost incorporation positively influences several key soil properties. Compost application generally led to a reduction in bulk density, indicating improved soil structure. Furthermore, it enhanced water infiltration and hydraulic conductivity, promoting better water management. Compost also increased soil water content and the availability of plant-available water, benefiting plant growth. The review highlighted that compost application generally has positive effects on agricultural and environmental soils.
Conclusion: Composting offers a sustainable waste management strategy with significant potential for soil improvement. The reviewed evidence supports the widespread use of compost as a soil amendment to enhance soil physical properties, water relations, and potentially other soil chemical and biological properties. These improvements contribute to enhanced soil health, sustainable agriculture, and environmental protection, particularly in the context of degraded soil remediation. Further research is encouraged to optimize compost application rates for different soil types and cropping systems.

Keywords: Composting; Waste management; Soil improvement; Sustainable agriculture

1. Introduction

Compost is a stabilized and sanitized product of organic decomposition that resembles humic substances (Bernal et al., 2009). This transformation occurs through controlled aerobic and thermophilic biological processes (Haug, 1993; Paulin and O'Malley, 2008), converting diverse organic wastes (plants, animals, and anthropogenic materials) into nutrient-rich humus (Fig.. 1). While the sanitizing effect of thermophilic phases (> 45 °C) is well-documented for pathogen destruction, recent studies note that some heat-resistant pathogens (e.g., Clostridium spores) may survive

Figure 1. Schematic diagram of the composting process.

if temperature thresholds are not uniformly maintained (Pottipati and Kalamdhad, 2022; Insam et al., 2023).

The composting process typically reduces waste volume by $40-60\%$ while stabilizing organic matter (Oviedo-Ocaña et al., 2023). However, the degree of stabilization varies significantly by feedstock - lignin-rich materials like wood chips require longer processing times than food waste (Oshins et al., 2022). This variability impacts end-product quality, with immature compost potentially causing nitrogen immobilization or phytotoxicity (Pellejero et al., 2020; Moral et al., 2009). Although compost application generally improves soil properties (e.g., reduced bulk density, increased porosity and nutrient content) (Wang et al., 2024), Bass et al. (2016) observed that these increases did not always translate to improved fruit yield, highlighting the need for application rate optimization. These context-dependent outcomes underscore the importance of matching compost characteristics to specific agricultural needs (Meddich et al., 2020; Antil et al., 2014).

Beyond its benefits for soil structure, compost's effectiveness as a fertilizer replacement presents nuanced tradeoffs. Full substitution often results in yield penalties of $15-20\%$ compared to conventional fertilization (Hernández et al., 2014). Its stress mitigation potential, particularly for salinity, appears promising but highly variable. This variability depends on the presence of specific microbial consortia (e.g., *Bacillus* spp.) and shows crop-specific responses (Elbagory, 2023).

This review has two primary objectives: (1) to synthesize current knowledge on compost production processes and their variability across different organic waste streams, and (2) to systematically evaluate both the direct and indirect effects of compost application on soil physicochemical and biological properties, while assessing its agricultural and environmental benefits.

2. Methodology

The data for this study were derived from a systematic review of peer-reviewed scientific literature and research reports retrieved from reputable academic databases, including ScienceDirect, Springer, PubMed, and Scopus, which provide extensive coverage of multidisciplinary scholarly literature. Furthermore, academic search engines such as Google Scholar and ResearchGate were employed to identify high-quality scientific articles and relevant studies.

This rigorous search strategy was implemented to ensure that the analysis and discussion were grounded in current, peer-reviewed evidence, with a particular focus on composting research.

Studies were selected based on:

Peer-reviewed status (excluding preprints to ensure quality).

Relevance (experimental or meta-analyses of compost's soil impacts).

Methodological rigor (clear reporting of compost type, application rates, and soil metrics).

However, the emphasis on high-impact journals may overlook valuable field studies published in local agricultural reports. For example, small-scale farm trials in sub-Saharan Africa (Azim et al., 2017) often appear in gray literature but provide critical insights into low-tech composting.

A targeted literature search was conducted using a combination of controlled search terms (e.g., keywords: ("compost" AND "soil properties") OR ("organic amendment" AND "crop yield"), and Boolean operators (AND, OR, NOT) to refine document retrieval. Despite these refinements, semantic variability in composting terminology (e.g., "biofertilizer" vs. "compost") may have excluded relevant studies. We addressed this by iteratively testing search terms during preliminary screening. Additionally, citation tracking and reference mining techniques were applied to identify seminal works and emerging trends in the field. However, this method inherently favors highly cited works, potentially amplifying publication bias toward positive results. To counterbalance, we included some studies with null findings (e.g., Glab et al. (2008), which found no significant effect of compost amendment on soil saturated hydraulic conductivity) from niche journals.

3. Sources of compostable substances

Composting has emerged as a pivotal strategy in organic waste (OW) management, offering dual benefits of waste reduction and soil enrichment. However, the selection and processing of compostable materials significantly influence the efficiency and sustainability of composting systems. While a wide array of organic wastes including yard waste (leaves, grass clippings, twigs), food scraps (fruit and vegetable peels, coffee grounds, eggshells), agricultural residues (manure, straw, corn cobs), and even certain paper products are viable for composting (Pellejero et al., 2017; Pellejero et al., 2024), their decomposition dynamics vary considerably based on carbon to nitrogen (C: N) ratios, moisture content, and microbial activity.

Agricultural activities, in particular, generate substantial quantities of OW (Azim et al., 2017; Azim et al., 2018), making them a critical source of compostable material. Fig. 2 illustrates diverse feedstocks, ranging from cattle manure and pruning waste to household organic waste and even unconventional inputs like dead fish or plant residues. While such materials contribute to nutrient cycling, their inclusion in composting systems must be carefully managed to avoid imbalances in pH, potential pathogens (e.g., from animal manure), or toxic compounds (e.g., pesticide residues in crop waste).

Aerobic composting, facilitated by microbial activity in the presence of oxygen, is a widely adopted method for converting food waste into nutrient-dense compost (Pace et al., 2018). However, despite its environmental advantages such as carbon sequestration and reduced landfill dependency composting is not without challenges. Operational costs for site preparation, equipment, and maintenance pose economic barriers, particularly for large-scale operations. Additionally, the extended treatment period required for complete decomposition can hinder efficiency, while environmental nuisances like odor emissions, dust, and pest attraction raise concerns for urban or densely populated areas.

In conclusion, while composting presents a sustainable pathway for organic waste valorization, its success hinges on optimizing feedstock selection, mitigating operational constraints, and addressing environmental externalities. Future research should focus on cost-effective technologies, accelerated decomposition methods, and odor/pest control measures to enhance the feasibility of composting as a mainstream waste management solution.

4. Benefits of using compost

One of the advantages of compost production is that it involves the elimination and recycling of many types of waste, thus solving the problems that would be caused by dumping this waste; it is also useful agronomically, since it increases the similarity between the organic matter of the waste and the humus of the soil. Compost production offers a dual

Figure 2. Some sources of compostable substances.

environmental-agronomic advantage:
It diverts organic waste from landfills, mitigating methane emissions and soil contamination risks associated with improper disposal (Boldrin et al., 2009).
Through humification processes, it transforms labile organic matter into stable soil humus fractions (Stevenson, 1994), thereby closing nutrient loops in agroecosystems.
The physical benefits of compost are well-documented: organic matter acts as a binding agent, enhancing aggregate stability by $20-35\%$ in degraded soils (Bronick and Lal, 2005). This structural improvement concurrently optimizes hydraulic conductivity (reducing compaction by $15-25\%$) and water-holding capacity (up to 30% increase in sandy soils), addressing permeability-retention trade-offs (Blanco-Canqui and Lal, 2007).
Chemically, compost provides both immediate and long-term benefits:
Its macronutrients (N, P, K) exhibit slower mineralization rates than synthetic fertilizers, reducing leaching risks by $40-60\%$ (Diacono and Montemurro, 2011).
Its humic acids elevate cation exchange capacity (CEC) by $2-5$ cmol$^+$/kg (Weber et al., 2007).
Biologically, compost serves as a microbial inoculant (Bernal et al., 2017), though its effectiveness depends on feedstock composition and maturation time. The beneficial effects of compost on soil are shown in Table 1.

5. Effects of compost on soil properties

Composting is frequently framed as a dual-benefit solution-reducing waste-related environmental burdens while enhancing soil health. However, a critical examination of the literature reveals that these benefits are often overstated or contingent on specific conditions. While studies (Fichtner et al., 2004; Aggelides and Londra, 2000; Hargreaves et al., 2008) broadly affirm compost's positive influence on soil physical, chemical, and biological properties, many of these findings derive from controlled experiments rather than real-world field conditions. Bernal et al. (2017) emphasize that improperly managed composting can lead to significant emissions of ammonia (NH_3), nitrous oxide (N_2O), and methane (CH_4). Claims that compost universally benefits both agricultural and urban soils (Gómez-Brandón et al., 2008; Azim et al., 2017) overlook critical variables such as feedstock composition, climatic factors, and soil pre-existing conditions—raising questions about the generalizability of these conclusions.

Table 1. Scientifically documented effects of compost on soil properties.

Soil properties	Soil Property Improvement	Supporting References
Physical	Reduction of thermal oscillations	(Ozores-Hampton et al., 2011)
	Increasing and improving of structural stability	(Diacono and Montemurro, 2011)
	Increasing of water and gas permeability	(Aggelides and Londra, 2000)
	Facilitating of drainage causing less waterlogged soils	(Larney and Angers, 2012)
	Reduction of potential erosion	(Tejada and Gonzalez, 2007)
	Improving of water balance	(Evanylo et al., 2008)
	Reduction of bulk density	(Celik et al., 2004)
Chemical	pH buffering capacity	(Whalen et al., 2000)
	Increasing of cation exchange capacity (CEC)	(Paradelo et al., 2011)
	Promotes cation exchange	(Hargreaves et al., 2008)
	Nutrient chelation	(Walker et al., 2004)
	Provides N, P and S reserves	(Eghball et al., 2004)
Biological	Root respiration enhancement	(Marschner et al., 2004)
	Increasing of Seed germination rate	(Zucconi et al., 1981)
	Promotes rhizosphere health	(Bonanomi et al., 2010)
	Regulates microbial activity	(Ros et al., 2006)
	A source of energy Heterotrophic metabolism	(Fontaine et al., 2003)
	The CO_2 released promotes the solubilization of mineral compounds	(Kuzyakov, 2006)
	Enhancement of nutrient level Improves mineral nutrition	(Sullivan and Miller, 2001)
	Enhanced Disease Suppression	(Hoitink and Boehm, 1999)

The assertion that compost "maintains soil quality" (Amlinger et al., 2007) relies heavily on its nutrient-supplying capacity, yet this characterization neglects key limitations. Unlike mineral fertilizers, compost's nutrient release is slow and inconsistent (Kluge, 2006; Oueld Lhaj et al., 2024), potentially limiting its efficacy in high-demand cropping systems. Furthermore, while mature composts are praised for their stable carbon content and superior organic matter retention (Adugna, 2016; Manirakiza and Seker, 2020), the literature often fails to address trade-offs, such as the risk of presence of pathogens in compost (Soobhany et al., 2017). Scholars, such as Azim et al. (2017), have emphasized that composting offers the dual benefit of enhancing soil fertility and facilitating soil carbon sequestration. In a comparative analysis of synthetic fertilizers and organic compost on broccoli crop yields, Aouass and Kenny (2023) concluded that compost acts as a slow-release source of nutrients, significantly improving nitrogen use efficiency in crops over time. Pergola et al. (2018) highlight that compost application offers numerous benefits, such as enhancing soil fertility, increasing soil organic carbon sequestration (CS), improving nutrient availability for crops, and mitigating salt stress.

Table 2 synthesizes empirical evidence from 38 peer-reviewed studies (1996 – 2025) examining diverse compost amendments' effects on soil properties.

While the data compiled in the table convincingly demonstrate the benefits of compost application in improving soil physicochemical and biological properties, a critical interpretation of these findings necessitates several important caveats. Firstly, the predominant focus of the included studies is on short- to medium-term outcomes (typically 2 to 4 years); the long-term sustainability of these benefits particularly concerning carbon sequestration remains less certain due to the dynamic nature of soil organic matter decomposition and requires longer-duration studies for validation. Secondly, potential risks associated with variable compost quality, especially from sources like municipal solid waste or sewage sludge, cannot be overlooked. These materials may introduce undesirable concentrations of salts, heavy metals, or persistent organic pollutants, which could threaten long-term soil health and food safety. Thirdly, the systematic tendency of compost to elevate soil pH though beneficial in acidic soils can in alkaline conditions reduce the solubility and bioavailability of essential micronutrients such as iron and zinc, underscoring the necessity for context-specific management strategies based on initial soil conditions. Finally, as most of these studies were conducted under controlled experimental plots, the generalizability of these results to large-scale, real-world farming systems under practical management requires careful consideration and further validation. Therefore, although compost holds significant promise as a soil amendment, its full and safe potential can only be realized through an intelligent management approach that includes quality monitoring, application rates tailored to specific soil contexts, and long-term environmental oversight.

5.1 Effects of compost on physical soil properties

Compost application is widely recognized as an effective practice for enhancing the physical properties of agricultural soils (Bauduin et al., 1987; Stratton et al., 1995; Tejada and Gonzalez, 2008; Tejada et al., 2009). Although most studies focus on agricultural systems, Kranz et al. (2020) have demonstrated its broader applicability by providing a comprehensive analysis of compost's impact on urban soils. Key physical improvements attributed to compost include increased soil porosity, enhanced water retention, and improved hydraulic conductivity (Hargreaves et al., 2008; Ramos, 2017). However, the extent of these benefits shows substantial system dependence. For instance, sandy soils typically exhibit $30-50\%$ increases in hydraulic conductivity, whereas in clay soils, bulk density reductions plateau at application rates exceeding 20 Mg/ha due to pore occlusion (Kranz et al., 2020; Tejada et al., 2009). These physical improvements peak $2-3$ years after application before gradually declining, necessitating reapplication to sustain the effects (Gioacchini et al., 2024).

Effects of compost addition on bulk density

Numerous studies have established that compost application effectively reduces soil bulk density across various soil types and agricultural management systems (Brown and Cotton, 2013; Logsdon et al., 2017; Somerville et al., 2018). This effect is particularly pronounced in degraded soils, where Curtis and Claassen (2009) documented significant bulk density reductions following compost incorporation across four distinct disturbed soil types, underscoring its rehabilitative potential for compromised topsoils. Similar improvements have been reported by Aggelides and Londra (2000) in both clay and loam soils, and by Somerville et al. (2018) in coarse-textured soils (loamy sands and sandy loams), confirming the efficacy of compost across diverse textural classes.

The magnitude of bulk density reduction depends critically on three factors: compost composition, application depth, and intrinsic soil properties. Cogger et al. (2008) demonstrated that surface layer amendments ($0-20$ cm depth) exerted minimal influence on subsoil bulk density, revealing important vertical stratification effects. Temporal patterns further modulate outcomes; for instance, Noor et al. (2023) observed significant reductions in bulk density within just two growing seasons, demonstrating the potential for rapid physical soil modification.

Several constraints merit consideration: first, the transient nature of organic matter decomposition may gradually diminish bulk density improvements Diacono and Montemurro (2011); second, shallow applications are frequently inadequate for mitigating subsoil compaction, particularly for deep- rooted species; and third, the generalized 1.4 g/cm^3 threshold (Schjønning et al., 2015) requires crop- and soil-specific calibration. Consequently, while compost application consistently lowers bulk density, optimal long-term outcomes necessitate tailored implementation strategies accounting for local edaphic conditions and management objectives.

Table 2. A review of studies investigating the effects of compost application on soil physicochemical and biological properties.

Type	Key Effects on soil	Duration	Sample Size	Bias Risk	Reference
Sesame Stalk Compost	-Improved Soil Physical Properties: -Reduced bulk density (1.34 vs. 1.38) -Lower penetration resistance (630 vs. 720 kPa) -Enhanced Soil Chemical Properties: -Increased soil organic carbon (6.30 g/kg) and SOC stock (11.8 Mg/ha) -Neutralized acidic soil pH (6.8 to 7.2) Higher available N, P, and K	4 yrs	Adequate (long-term multi-season data)	Low (Controlled design, quantitative metrics)	Sangeetha et al. (2025)
Stable and mature compost	-Increased organic matter: 27.8% (Site A) and 58.1% (Site B) -Reduced bulk density (10.5-15.7%) -Enhanced aggregate stability (6-30%) -Higher saturated water content: 5.3-11% -Improved hydraulic conductivity (28.6% at Site B) -Elevated pH and electrical conductivity	2023 and 2024 growing seasons	Adequate (For a field experiment: Two large parcels per locality)	Low (Controlled design, objective data)	Mihálikova et al. (2025)
Municipal Solid Waste Compost	-Increased Carbon & Nitrogen -Improved Soil Structure -Carbon Storage in Macroaggregates -Deep Layer Enrichment -Long-Term Fertility	14 yrs	Adequate (Four replicates per treatment)	Low (Complete randomized block design)	Gioacchini et al. (2024)
Coffee waste compost	-Improved soil fertility and plant growth - ↑ Nutrient use efficiency	N/A Review article	N/A	N/A	Trujillo-Gonzalez et al. (2024)
Green waste compost (Olive leaves + sheep manure (2:1))	- ↑ Soil organic carbon (SOC) -Increase of 0.5 in pHKCl, -1.9 times more extractable phosphorus, -Ten times more zinc	2 yrs	Adequate (Field plots)	Moderate (Pre-existing soil variability)	Alexandre et al. (2023)
Green-waste compost	-Major soil biological boost only after 2nd compost application. -low-SOM soils saw more microbial growth. -higher-SOM soils showed more enzyme activity. -Precision farming enables efficient compost use even on small farms.	2 yrs	Adequate (multiple farms) but region-specific	Low (standardized protocols)	Assirelli et al. (2023)
Coffee pulp biochar Coffee pulp compost * Combination	- ↑ pH, OC, TN, P, K, Ca^{2+}, Mg^{2+} -Improved CEC	2 yrs	Adequate (Field plots, 3 replications)	Low (Randomized complete block design)	Kebede et al. (2023)
Compost + Chemical Fertilizer (Combined application)	↓ Bulk density, -Enhanced soil porosity. -Improved water holding capacity	2 growing seasons	Adequate (Field plots with 3 replications)	Low (Randomized complete block design)	Noor et al. (2023)
Biochar + Lime + Compost (Combination)	- ↓ Bulk density (BD) - ↑ pH (reduced acidity) - ↑ Soil organic matter (SOM) - ↑ Ca^{2+} and Mg^{2+}	3 yrs	Adequate (Field experiment with controls)	Moderate (Single location study)	Dang et al. (2022)
Market waste compost and vermicompost	-Application of 10 t compost/ha: -Highest increase in soil total nitrogen: +44%	1 growing season	Limited (Pot experiment)	Moderate (Controlled conditions)	Syarifinnur et al. (2022)
Biochar and Compost (Urban organic waste)	- ↑ Soil organic matter (10.25%) - ↑ Soil organic carbon content (5.95%)	3 months	Limited (Small urban garden plots)	Moderate (Single location study)	Japakumar et al. (2021)
Compost + biochar mix	- ↑ Relative abundance of key microbial taxa. -Stimulation of plant growth-promoting bacteria. -Enrichment of microbes involved in carbon cycling.	4 yrs	Adequate(40 experimental plots.)	Low (Experimental setting)	Hale et al. (2021)
Plant-based compost + Urea (Integrated application)	-Integrating lower rates of urea with higher rates of PC is recommended to: -Increase soil biological activity. -Maintain higher soil pH. -Boost phosphorus content.	3 growing seasons	Adequate (Field experiment with controls)	Low (Randomized design, multiple indicators)	Habteweld et al. (2020)
Compost and Manure (Various application rates)	-Increasing the compost rate improved CEC and base saturation percentage	3 months	Adequate (Field trials with multiple rates)	Moderate (Single region study)	Masmoudi et al. (2020)
Sewage sludge compost	-Sludge application increased the organic status of the soil and nutrients.	N/A	Limited (Small-scale field trial)	Moderate (Single region study)	Oueriemmi et al. (2019)

Continued of Table 2.

Type	Key Effects on soil	Duration	Sample Size	Bias Risk	Reference
Beef cattle manure compost (BCMC) and mixed oilseed cake (MOC)	- ↑ (EC) - ↑ Soil nitrogen content - ↑ Soil phosphorus content - ↑ Exchangeable potassium content	2 growing seasons	Adequate (Field plots with 3 replications)	Low (Randomized complete block design)	Lee JongTae et al. (2018)
Spent mushroom compost SMC	- ↑ Aggregate stability - ↓ Modulus of rupture - ↑ Total N and SOC - SMC application improves soil physicochemical properties.	2 months	Adequate (3 replications per treatment with controls)	Low (Controlled lab conditions, randomized design	Gumuş and Şeker (2017)
Mineral fertilizer + compost (long-term application)	- ↑ Soil organic carbon (SOC). - ↓ Soil bulk density - ↑ Total porosity - ↑ The total amount of water-stable macro-aggregates ($>$ 0.25 mm). - ↑ Macropore volume by up to 91.7% - ↑ The proportion of small pores ($<$ 3.3 µm)	23 yrs	Robust (Long-term field experiment)	Very Low (Controlled long-term study)	Xin et al. (2016)
Compost + Grafting (Combined treatments)	- ↑ Bacterial abundance -Altered fungal abundance -Altered microbial diversity	2 growing seasons	Adequate (Controlled greenhouse trials)	Low (Replicated experimental design)	Gao et al. (2015)
Compost extract + N_2-fixing Bacteria	↑ Soil available nutrients (NPK) ↑ Soil organic matter (OM) ↑ Total bacterial counts ↓ Soil salinity ↓ pH	2 growing seasons	Adequate (Field experiment with controls)	Low (Randomized complete block design)	Mahmoud et al. (2015)
Generic compost	-Natural suppression of soil-borne pathogens -Enhancing beneficial soil microbes	N/A Review article	N/A	N/A	Mehta et al. (2014)
Agro-industrial waste compost	- ↑ Soil organic carbon, - ↑ Total nitrogen, - ↑ Available phosphorus levels. - ↓ Bulk density - Positively modified soil pore size distribution (increased macropores and mesopores).	2 yrs	Limited (Small plot trials)	Moderate (Conference proceedings data)	Miglierina et al. (2013)
Municipal solid waste compost (MSWC)	- ↓ Soil bulk density (Especially in initial cycles) - ↑ Aggregate stability -Higher permeability coefficient -Improved hydraulic conductivity -Mitigated freeze-thaw damage -Enhanced soil physical properties after multiple cycles -Optimal dosage at 10-20% -Potential for reclaiming saline-sodic soils -Enhanced leaching and drainage efficiency	5-6 months	Limited (Controlled lab/field study)	Moderate (Specific to freeze-thaw conditions)	Angin et al. (2013)
Olive pomace compost	-Maintained soil organic carbon content -Supplied macronutrients to the soil	2 yrs	Adequate (Organic farm field trials)	Low (Controlled organic system)	Diacono et al. (2012)
Tunisian agricultural waste compost	- ↑ Organic matter -Improved EC -Enhanced nutrient availability (N)	4-6 months (Estimated)	Limited (Small-scale trials)	Moderate (Specific waste types)	Rigane and Medhioub (2011)
Agricultural waste compost	- ↑ pH - ↑ Root colonization by arbuscular - ↑ Mycorrhizal fungi (AMF) - ↑ Fungal mycelium length - ↑ AMF spore number -Higher production of glomalin - ↑ Water-stable aggregates (WSA) - ↑ Water-holding capacity (WHC)	3 yrs	Adequate (Volcanic soil field trials)	Low (Controlled conditions)	Valarini et al. (2010)
Rice straw compost	-Improved soil physical properties -Maintained soil productivity -No significant increase in soil carbon	7 yrs	Adequate (Randomized block design with three replicates)	Low (Long-term, appropriate control treatments)	Watanabe et al. (2009)
Biowaste compost + N fertilization	-No significant change in total macropore volume. -No significant effect on biopores from compost application.	13 yrs	Limited (Single-site study, n=18 plots)	Moderate (Soil type specificity)	Glab et al. (2008)
High-Cu/Zn compost	-Strong soil-plant correlation for micronutrients -High EC, Cu, Zn, and Na may limit compost use	4 months	Limited (Controlled pot/field trials)	Moderate (Metal contamination risk)	Courtney and Mullen (2007)

Continued of Table 2.

Type	**Key Effects on soil**	**Duration**	**Sample Size**	**Bias Risk**	**Reference**
Long-term compost (Urban organic waste, green waste, manure and sewage sludge)	- ↑ soil organic C and total N across all compost treatments -Enhanced microbial biomass C in some compost treatments -Higher microbial diversity and activity (Shannon index H, carbon source utilization) -Unique sewage sludge compost effects: Elevated basal respiration and metabolic quotient (qCO$_2$) -Shift in bacterial community structure: -Distinct clustering for mineral fertilizer, compost, and compost + N treatments	12 yrs	Adequate (Multi-season monitoring)	Low (Controlled field trial)	Ros et al. (2006)
Organic amendments	-Reduced bulk density & penetration resistance -Increased aggregate stability, porosity & infiltration -Enhanced water-holding capacity -Supplied nutrients (with C:N $\leq$ 20:1) -Practical Recommendations: -33% volumetric rate for degraded soils -15-25% volumetric rate for turf establishment	N/A Review paper	N/A	N/A	Cogger (2005)
Manure and compost (Beef cattle)	-Residual Effects of Compost on Soil: - ↑ EC, pH & available P -Elevated nitrate (NO$_3$-N) for multiple years -P movement to 45-60 cm depth after 4 years -No change in total soil C -No effect on soil ammonium (NH$_4$-N) -No residual impact on ammonium levels	5 yrs (With residual monitoring)	Robust (Large field plots)	Very Low (Long-term replicated trial)	Eghball et al. (2004)
Organic amendments (The organic fraction of urban wastes both fresh and composted)	- ↑ microbial biomass & basal respiration -Boosted enzyme activities (C and N cycles) -Higher organic carbon levels (despite gradual decline) -Restoration of degraded soils: -Triggered spontaneous plant growth & cover -Improved microbial activity	2 yrs	Limited (Controlled microcosms)	Low (Precise biochemical assays)	Ros et al. (2003)
MSW compost (Municipal solid waste)	- ↓ Soil compaction - ↓ Columbia lance nematode densities - ↑ Soil organic matter and nitrogen (6 & 14 weeks after planting)	4 yrs	Adequate (Field-scale plots)	Moderate (Single region study)	Khalilian et al. (2002)
De-inking paper sludge compost	- ↑ pH & water content -Higher Mehlich-3 extractable P, K, Mg -Short-term increase in inorganic N (1 year) - ↑ phosphatase & urease activity -Most heavy metals unaffected (except Mn & Zn) -Improved properties of low-fertility soil	2 yrs	Limited (Controlled field trials)	Moderate (Industrial waste specific)	Baziramakenga et al. (2001)
Municipal waste + sewage sludge compost	- ↑ saturated/unsaturated hydraulic conductivity - ↑ water retention capacity - ↓ bulk density & soil penetration resistance - ↑ porosity & pore size distribution - ↑ aggregation & aggregate stability -Direct modification of soil chemical characteristics -Greater efficacy in loamy soil vs. clay soil	3-6 months (Estimated)	Adequate (2 soil types, n=24 plots total)	Moderate (Controlled but small-scale)	Aggelides and Londra (2000)

Continued of Table 2.

Type	Key Effects on soil	Duration	Sample Size	Bias Risk	Reference
Compost + fertilizer	-Prevented acidification from nitrogen fertilizer at both sampling depths -Decreased water penetration speed in soil -Elevated EC in high-compost treatments (44 Mg/ha) due to compost salt content	1 growing season	Adequate (Four replications are adequate for short-term field trials.)	Low (RCBD design)	Stamatiadis et al. (1999)
Long-term compost (unspecified organic)	-Gradual increase in C, N, P, and exchangeable bases -Improved pH (due to base cation accumulation) -Detectable impact even after 13 years without application -Higher P and Ca concentrations in rhizosphere soil -Limited effect on soil pH (especially in rhizosphere)	28 yrs	Limited (long-term plots)	Low (Consistent methodology)	Shen Alin et al. (1996)

Effects of compost addition on infiltration rate and hydraulic conductivity

Compost amendments have been widely documented to enhance water infiltration and hydraulic conductivity, key determinants of soil water dynamics that influence irrigation efficiency, runoff mitigation, and groundwater recharge (Agassi et al., 1998; Chen, 2015; Schwartz and Smith, 2016). These improvements are primarily attributed to increased porosity and reduced bulk density, though their efficacy is highly context- dependent, mediated by factors such as soil texture, compost composition, and climatic conditions.

Empirical studies demonstrate consistent increases in infiltration rates following compost application. Bouajila and Sanaa (2011) observed a 65 – 80% enhancement with household waste compost and manure (549 – 596 cm vs. 332 cm in control), while synergistic effects have been reported when compost is combined with vegetation. Logsdon et al. (2017) found significantly faster infiltration in systems amended with compost and prairie grasses, likely due to improved aggregate stability and macropore formation. Similarly, hydraulic conductivity is frequently enhanced in clay soils, where organic matter alleviates compaction and promotes aggregation (Aggelides and Londra, 2000). The underlying mechanisms involve organic carbon stabilizing aggregates and expanding pore networks (Adugna, 2016; Killi and Kavdır, 2013).

However, these benefits are not universal. Soil texture and mineralogy can dominate over compost effects, particularly in coarse textured soils where intrinsic permeability is already high (Cogger et al., 2008; Weindorf et al., 2006). Some studies report null effects, such as Curtis and Claassen (2009), who found no significant change in saturated hydraulic conductivity in soils low in coarse fragments, and Glab et al. (2008), who observed no improvement in bulk density, water retention, or conductivity with long-term compost and nitrogen fertilization, suggesting potential diminishing returns or nutrient-mediated interactions. Additionally, Yu et al. (2015) challenge assumptions of direct textura-infiltration relationships, emphasizing variability under heterogeneous field conditions.

In synthesis, compost exerts the most pronounced hydraulic benefits in fine textured or degraded soils, where organic matter compensates for structural deficiencies. In contrast, sandy or well-structured soils may exhibit marginal or short-lived improvements. Long-term outcomes depend on compost type, such as the efficacy of sewage sludge–maize straw blends, application rates, and management practices, including tillage and crop rotations. Future research should prioritize site-specific recommendations to optimize compost use for hydraulic improvements, ensuring tailored applications that account for local edaphic and climatic conditions.

Effects of compost on water retention and soil moisture

Compost application has been widely demonstrated to enhance soil water retention and moisture availability, though its effectiveness varies considerably depending on soil texture, compost characteristics, and environmental conditions. While the general consensus supports improved wáter holding capacity following compost application (Aggelides and Londra, 2000; Curtis and Claassen, 2009; Sax et al., 2017), the magnitude of improvement differs markedly across soil types and management systems.

In fine-textured soils (clay and loam), compost amendments significantly modify water retention curves, increasing moisture availability at both field capacity and wilting point (Aggelides and Londra, 2000; Celik et al., 2004). This improvement stems from enhanced soil aggregation, where organic matter creates a more stable pore structure that effectively retains water against gravitational drainage while maintaining plant available water. In contrast, coarse-textured sandy soils, which typically exhibit rapid drainage and poor water retention, show particularly strong responses to compost amendments. Turner (1994) documented substantial increases in wáter holding capacity in sandy soils, attributed to organic matter filling pore spaces and reducing macropore dominance. Zemanek (2011) further demonstrated that high application rates (50 – 100 t/ha) can dramatically improve moisture retention, enhancing drought resilience in these inherently dry soils.

The mechanisms underlying these improvements involve several interrelated processes. Compost modifies pore size distribution by increasing the proportion of mesopores ($0.2-30$ µm diameter) that retain plant-available water, while reducing non-capillary pores responsible for rapid drainage. The hydrophilic nature of organic matter, with its high surface area and water affinity, significantly enhances the soil's moisture retention capacity, particularly in coarse soils where mineral surfaces are less reactive. In fine textured soils, compost promotes aggregate stability that resists slaking during wetting-drying cycles, thereby maintaining pore connectivity and water retention capacity.

However, several limitations and contradictions exist in the observed effects. The benefits show clear dose dependency, with higher application rates (e.g., 100 t/ha) producing more pronounced improvements (Zemanek, 2011), while lower rates may have negligible effects, particularly in already organic rich soils. Temporal dynamics also play a crucial role, as Curtis and Claassen (2009) found that initial water retention improvements may diminish over time with compost decomposition, necessitating periodic reapplication. These factors underscore that optimal outcomes are often achieved not by compost alone, but through its integration with other management practices. For instance, maximum volumetric water content and turf cover were attained under the treatment combining tillage with the highest compost amendment rate of 604 m^3/ha (Schmid et al., 2017). In synthesis, while compost undeniably enhances soil moisture retention, its efficacy is highly context-specific. Sandy soils derive the greatest benefit due to their inherent drainage limitations, while clay soils experience improvements in plant available water but may face aeration trade-offs if over amended. Sustainable long term benefits require careful balancing of compost inputs with decomposition rates to maintain optimal soil physical conditions. Future research should focus on identifying optimal compost types (e.g., manure versus green waste) for different soil textures, understanding interactions with irrigation practices to maximize water-use efficiency, and establishing threshold levels beyond which additional compost applications yield diminishing returns.

Effects of compost addition on soil structure and porosity

Compost amendments have been widely demonstrated to enhance soil structure and porosity through organic matter-mediated aggregation processes, though the degree of improvement varies significantly depending on compost characteristics, application rates, and inherent soil properties (Turner, 1994; Celik et al., 2004; Aggelides and Londra, 2000). The primary mechanisms of improvement involve both aggregate formation/stability and porosity enhancement. Compost contributes binding agents such as polysaccharides and fungal hyphae that facilitate microaggregate formation, which subsequently combine into stable macroaggregates (Tisdall and Oades, 1982). This increased aggregate stability is particularly beneficial for reducing erosion susceptibility and surface crusting in sandy or degraded soils (Celik et al., 2004).

The porosity-enhancing effects of compost are manifested through the creation of a more heterogeneous pore system that improves the balance between air- and water-filled pores (Rabot et al., 2018). In fine-textured soils, compost plays a crucial role in mitigating compaction by stabilizing pore networks against structural collapse (Turner, 1994). Empirical evidence demonstrates these effects across different soil types: Aggelides and Londra (2000) observed $20-35\%$ increases in water-stable aggregates in clay soils following compost application, with corresponding improvements in porosity and hydraulic conductivity, while Turner (1994) documented up to 15% reductions in bulk density and proportional increases in macroporosity (> 30 µm pores) in sandy soils.

However, several important limitations and contradictions exist regarding compost's effects on soil structure. The benefits exhibit clear rate dependency, with excessive applications (> 150 t/ha) potentially causing pore occlusion in clay soils and impairing aeration (Diacono and Montemurro, 2011). Temporal dynamics also play a significant role, as aggregate stability improvements typically peak within $1-2$ years post-application before declining due to labile organic matter decomposition (Curtis and Claassen, 2009). Furthermore, soil texture mediates the response, with loamy soils often showing more immediate porosity improvements compared to sandy soils where measurable effects require organic matter accumulation over time (Logsdon et al., 2017).

In synthesis, while compost consistently improves soil structural properties, its effectiveness follows several key principles: texture determines the primary mechanism of improvement (aggregate stabilization in clays versus pore continuity enhancement in sands); moderate application rates ($20-50$ t/ha) optimize porosity without compromising gas exchange; and long-term maintenance requires periodic reapplication to counteract organic matter mineralization. Future research should focus on developing standardized metrics for pore-size distribution changes across different soil types and investigating interactions with tillage regimes to better understand the longevity of structural improvements. These advancements would facilitate more precise, context-specific recommendations for compost use in soil structure management.

5.2 Effects on soil chemical properties

Effects of compost addition on organic matter levels

The recycling of organic materials, particularly livestock manure, to enhance soil organic matter (SOM) has been a cornerstone of agricultural practice for millennia (Amlinger et al., 2007; Larney and Angers, 2012). This tradition remains relevant in modern agroecosystems, where SOM is universally recognized as a fundamental determinant of soil quality, influencing fertility, structure, water retention, and microbial activity (Gregorich et al., 1994). The critical role of SOM in maintaining soil health is well-documented, with Lal (2001) establishing a direct correlation between SOM depletion and declining crop yields, highlighting its importance in nutrient cycling, carbon sequestration, and overall soil resilience. Contemporary soil restoration frameworks, such as those proposed by Ivanchuk (2024), explicitly prioritize compost application as a key strategy to rebuild SOM and counteract degradation in intensively managed agricultural systems.

Compost serves as a targeted amendment for SOM enhancement through multiple mechanisms. It introduces stabilized organic carbon, reducing dependence on transient crop residues (Brown and Cotton, 2013), while long-term applications increase humic substances, which are essential for improving cation exchange capacity and aggregate stability (Weber et al., 2007). Field studies demonstrate that compost amendments at rates of $10-20$ Mg/ha can elevate SOM by $0.5-1.5\%$ within $3-5$ years (Diacono and Montemurro, 2011), with high-quality, lignin-rich composts (e.g., manure-based) exhibiting greater persistence in soil compared to green waste (Bernal et al., 2009).

Compost effectiveness for SOM restoration is context-dependent. Although non-linear responses with plateauing gains are commonly reported, some studies observe linear increases at high application rates. This contrast is primarily determined by the compost's chemical composition, specifically its ratio of labile to recalcitrant carbón (Fabrizio et al., 2009).

In summary, while compost is a proven tool for SOM restoration, its efficacy depends on composition, management practices, and system context. Lignin-rich materials (e.g., manure) outperform high-cellulose composts in long-term carbon storage (Cotrufo et al., 2015), while tillage can accelerate SOM mineralization, counteracting compost benefits (Haddaway et al., 2017). Perennial systems, in contrast to annual crops, more effectively retain compost-derived SOM (Shang et al., 2024). Future research should prioritize the development of standardized SOM sequestration coefficients for diverse compost types and explore strategies for subsoil enrichment to extend benefits beyond the plow layer.

Effects of compost addition on nutrient levels

Compost represents a comprehensive source of essential plant nutrients, including macronutrients (N, P, K, Ca, Mg, S) and micronutrients, making it a valuable alternative to synthetic fertilizers in sustainable agricultural systems (Haug, 1993; Madeleine et al., 2005; Roghanian et al., 2012). The nutrient-enhancing effects of compost have been well-documented through various studies examining its application in different agricultural contexts.

Regarding nitrogen dynamics, research demonstrates that compost provides a gradual release of plant-available N through mineralization processes. Bouajila and Sanaa (2011) reported that municipal waste compost applied at 20 t/ha increased mineralized N by 30 kg/ha, while Gamal (2009) established a clear dose-response relationship, with higher application rates (10 t/ha) yielding significantly greater N content compared to lower rates (5 t/ha). These findings underscore compost's capacity to serve as an effective N source while minimizing leaching risks associated with synthetic fertilizers.

The availability of phosphorus and potassium also improves substantially with compost application. Controlled pot experiments by Roghanian et al. (2012) revealed elevated levels of plant-available P and K in compost-amended soils, attributed to enhanced nutrient solubility during organic matter decomposition. Field studies by Brown and Cotton (2013) further confirmed that compost can match or even surpass conventional fertilizers in terms of nutrient availability, particularly when considering its additional benefits for soil structure and microbial activity.

The mechanisms underlying compost's nutrient contributions involve two primary processes: microbial mineralization of organic matter, which converts organic N into plant-available inorganic forms (NH_4^+ and NO_3^-) at rates dependent on the C:N ratio and compost maturity (Amlinger et al., 2007), and chelation of micronutrients by humic substances, which prevents their fixation in soil colloids and maintains their bioavailability (Seilsepour and Moharami, 2024). In calcareous soils, although compost application boosts overall nutrient levels (Manirakiza and Seker, 2020), its effectiveness is constrained by persistent phosphorus fixation issues, which can only be mitigated through compost acidification (Adugna, 2016). However, several limitations must be acknowledged. The nutrient content of compost varies considerably depending on feedstock composition (Haug, 1993), potentially leading to inconsistent results across different applications. The gradual nutrient release pattern, while beneficial for reducing losses, may not always synchronize with peak crop demand periods (Gamal, 2009). Additionally, long-term compost use carries the risk of phosphorus saturation, potentially leading to environmental concerns through runoff and eutrophication (Forber et al., 2018).

To optimize compost's nutrient benefits while mitigating potential drawbacks, several strategic considerations emerge: careful selection of compost feedstock based on specific nutrient requirements (manure-based for higher N and P versus green waste for K and micronutrients); proper application timing to better align nutrient release with crop uptake patterns (Amlinger et al., 2007); and regular soil testing to monitor nutrient levels and prevent imbalances, particularly regarding phosphorus accumulation. Future research should focus on developing standardized nutrient release coefficients for different compost types and investigating long-term strategies for reducing synthetic fertilizer dependence without compromising crop yields.

Effects of compost addition on cation exchange capacity (CEC)

Compost application enhances soil Cation Exchange Capacity (CEC) through two primary mechanisms. First, the humified organic fractions in compost introduce negatively charged functional groups (-COOH, -OH, phenolic), which create additional cation exchange sites (Ouedraogo et al., 2001). Second, compost-derived organic polymers bind to clay minerals, exposing new exchange sites and stabilizing existing ones (Agegnehu et al., 2014). A meta-analysis of 27 studies further confirmed a median CEC increase of 22%, with greater effects observed in coarse-textured soils (Agegnehu et al., 2014).

However, the extent of CEC enhancement depends on several factors. Sandy soils exhibit proportionally greater CEC gains (up to 40%) compared to clay-rich soils ($< 15\%$) due to their lower initial exchange capacity (Ouedraogo et al., 2001). The temporal dynamics of CEC enhancement reveal that peak effects occur $12-24$ months post-application as organic matter humifies, followed by a gradual decline (Agegnehu et al., 2014).

Compost's CEC-enhancing effects are particularly valuable in acidic soils, where they facilitate the displacement of Al^{3+} by basic cations (Ouedraogo et al., 2001).

In calcareous soils, however, organic matter-induced enhancement of cation exchange capacity (CEC) may be transient, as soil carbonates (particularly calcium carbonate) readily bind with cations, rendering them unavailable (Kelley et al., 2020). Despite these benefits, critical knowledge gaps remain, including the long-term persistence of CEC improvements beyond five years of continuous compost use and the role of compost-stimulated microbiota in maintaining exchange sites, which warrant further investigation.

Effects of compost addition on pH value and buffering capacity

Compost application generally exerts a liming effect on soils through multiple mechanisms, primarily due to the release of basic cations (Ca^{2+}, Mg^{2+}, K^{+}, Na^{+}) during mineralization processes (Agegnehu et al., 2014). While isolated cases of pH reduction have been documented (Zinati et al., 2001), the majority of studies confirm neutral to alkaline pH shifts, particularly in acidic soils (Stamatiadis et al., 1999; Ouedraogo et al., 2001; Roghanian et al., 2012). The pH-modifying effects of compost operate through two principal mechanisms: cation release during organic matter decomposition, which displaces H^{+} and Al^{3+} from exchange sites (Kluge, 2006), and the direct neutralization of acidity by carbonate minerals present in certain compost types, particularly manure-based varieties (Bernal et al., 2009).

Compost addition enhances the buffering capacity of soils by increasing soil organic matter. This organic matter provides pH-buffering functional groups (carboxyl and phenolic) and stimulates microbial activity that consumes protons during nitrification (Stamatiadis et al., 1999; Agegnehu et al., 2014). Quantitative studies demonstrate these effects clearly; for example, moderate applications (10 Mg/ha annually) can raise soil pH by 0.4 units (Kluge, 2006). Furthermore, the magnitude of pH modification is influenced by soil texture. Sandy soils, due to their lower native buffering capacity, typically show a faster response to compost application.

However, these effects are subject to important boundary conditions. Neutral or alkaline soils ($pH > 7.5$) may show negligible changes or even slight acidification when amended with composts high in NH_4^+ or S content (Zinati et al., 2001).

From a practical management perspective, compost applications of $15-20$ Mg/ha can effectively substitute for $0.5-1.0$ t/ha of agricultural lime in moderately acidic soils (Kluge, 2006). Additionally, compost-amended soils demonstrate superior resistance to pH fluctuations caused by acid rain or nitrogen fertilizers compared to unamended soils (Stamatiadis et al., 1999). Despite these demonstrated benefits, critical research gaps remain, particularly regarding long-term (> 10 years) pH trajectories under continuous compost use and the underexplored role of compost-stimulated microbiota in pH regulation processes.

5.3 Effects of compost on soil biological properties

Compost amendments are widely applied to enhance soil fertility by improving nutrient retention and reducing nitrogen losses through leaching and denitrification (Amlinger et al., 2007). A key benefit of compost application is its ability to stimulate soil biological activity (Brown and Cotton, 2013; Adugna, 2016). Generally, compost positively influences soil biological properties by increasing microbial activity, improving nutrient cycling, and fostering better soil structure. The most significant effects include an increase in microbial biomass and enzyme activity, a shift in the microbial community toward beneficial organisms, and the stabilization of soil organic matter. Hale et al. (2021) evaluated the effects of compost and biochar amendments on soil biological properties in turfgrass systems under deficit irrigation conditions. Findings demonstrate that both compost and biochar significantly enhance microbial activity, soil respiration, and microbial biomass, even under water-limited regimes. Therefore, compost application serves as a powerful catalyst for soil biological activity, fundamentally transforming microbial abundance, diversity, and function (Brown and Cotton, 2013). This biological activation manifests through distinct pathways, beginning with microbial population dynamics. Long-term field studies document $2-3$ fold increases in microbial biomass following compost application, while mature compost introduces diverse microbial inoculants that complement native soil communities (Brown and Cotton, 2013). Furthermore, BIOLOG assays demonstrate expanded carbon substrate utilization patterns, indicating greater metabolic diversity in compost-treated soils (Ros et al., 2006).

A well-established benefit of compost amendment is its capacity for disease suppression, mediated through three primary mechanisms (Bonanomi et al., 2020). First, competitive exclusion occurs as enhanced general microbial activity limits ecological niches for pathogens, while specific antagonists (e.g., *Trichoderma*, *Pseudomonas*) outcompete harmful microorganisms. Second, compost-derived elicitors prime plant defense pathways, leading to the upregulation of pathogenesis-related proteins. Third, direct antagonism arises through antibiotic production by compost-borne microbes and parasitism of pathogen structures, such as nematode egg predation. Empirical evidence supports these effects, with meta-analyses confirming significant suppression of fungal pathogens ($40-60\%$ reduction in Fusarium and Rhizoctonia incidence), oomycetes ($35-50\%$ decrease in Phytophthora root rot), and nematodes ($25-40\%$ reduction in root-knot nematode populations) (Mehta et al., 2014; Raviv, 2015).

However, the efficacy of compost-mediated disease suppression depends on several critical factors. Compost maturity is paramount, as immature materials may introduce phytotoxins or even promote pathogens; optimal C:N ratios ($15-20$) and proper curing temperatures (> 55 °C) are essential for maximizing benefits (Termorshuizen et al., 2006). Application timing also plays a crucial role, as disease suppression typically requires 2–4 weeks for microbial establishment, and annual applications are necessary to sustain protective effects. Additionally, pathogen-specific responses vary, with bacterial wilt (Ralstonia) exhibiting variable suppression rates ($40-80\%$), and some nematodes developing resistance to compost-mediated control.

Future research should focus on elucidating molecular mechanisms through omics approaches to identify key suppressive organisms, optimizing compost formulations for targeted pathogen systems, and validating findings in large-scale field trials across diverse agroecosystems. These advancements will enhance our ability to harness compost's full potential in improving soil health and sustainable crop production.

6. Environmental benefits of compost

Composting offers several environmental advantages, though its impacts require careful and context-specific evaluation. While it effectively diverts waste from landfills and reduces methane emissions (EPA, 2011), the carbon neutrality of composting demands nuanced assessment. The process generates $0.2-0.5$ kg CO_2 per kg of organic matter, comparable to natural decomposition rates (Martínez-Blanco et al., 2013), with only $8-12\%$ of initial carbon remaining stabilized beyond five years (Bayer et al., 2012).

The effectiveness of contaminant mitigation through composting varies. Composting efficiently degrades petroleum hydrocarbons ($> 80\%$ efficiency) but shows reduced efficacy for chlorinated compounds ($40-60\%$) and persistent pesticides such as DDT ($< 20\%$) (Zhou et al., 2022). Similarly, in metal remediation, amendment performance is element-specific: biochar preferentially immobilizes anionic Sb through adsorption, while compost enhances microbial activity and nutrient availability. Their combined use synergistically reduces metal mobility while restoring soil biological function (Garau et al., 2024).

Composting significantly enhances environmental safety by immobilizing heavy metals (HMs) through speciation changes, converting mobile and bioavailable forms (exchangeable and reducible) into stable, less hazardous forms (oxidizable and residual). This process markedly reduces HM mobility, leachability, and bioavailability, thereby mitigating environmental contamination and toxicity risks. The addition of specific adsorbents (e.g., bentonite, biochar) further promotes HM passivation by enhancing humification and microbial activity during composting. Although these additives primarily reduce bioavailable concentrations rather than total HM content, their integration with vermicomposting offers a comprehensive solution, simultaneously decreasing both bioavailability and total HM concentrations. This combined approach ensures the production of a safe final compost product, contributing to soil protection and pollution prevention (Ejileugha et al., 2024).

Industrial waste valorization presents both opportunities and challenges. Composts derived from olive mill waste accelerate soil organic matter (SOM) accumulation 1.5-fold compared to manure, but residual phenols ($200-400$ mg/kg) restrict their application in food crops, compounded by 40% higher processing costs (Bouhia et al., 2023). Future research should prioritize decadal-scale contaminant tracking, comprehensive lifecycle analyses, and pathogen inactivation thresholds to fully assess compost's environmental impacts.

This analysis reveals that while compost offers substantial environmental benefits, these advantages are highly system-dependent. Optimizing its role in sustainable waste management and soil improvement strategies requires site-specific risk assessments, advanced feedstock screening protocols, and robust long-term monitoring frameworks that account for local ecological conditions and management practices. This integrated approach would enable more accurate quantification of compost's net benefits while mitigating potential risks across different application scenarios. The development of standardized evaluation methodologies could further enhance our ability to predict compost performance under varying climatic conditions, soil types, and agricultural systems, ultimately supporting evidence-based policy decisions and operational guidelines for compost production and utilization.

7. Conclusion

Composting has emerged as a scientifically validated solution for sustainable organic waste management, demonstrating measurable benefits for both agricultural systems and environmental protection. The process effectively converts waste into a valuable soil amendment, enhancing key soil properties including structure, water retention, and nutrient availability while reducing reliance on landfill disposal. Research confirms compost's ability to improve soil physical characteristics, boost microbial activity, and suppress plant pathogens, though these effects vary significantly depending on compost composition, soil type, and climatic conditions.

Despite these advantages, several challenges require attention. The benefits of compost application often follow non-linear patterns, with diminishing returns at higher application rates and variable persistence over time. Nutrient release rates may not always align with crop demands, and concerns persist about potential contaminant accumulation, particularly heavy metals and emerging pollutants like PFAS compounds. It should be noted that composting is not an instantaneous stabilization process; depending on the technique employed, it may require several weeks to produce stable, mature compost. Consequently, ensuring the production of high-quality compost is critical to maximize its agronomic benefits and avoid potential adverse effects on soil health. The carbon sequestration potential of compost, while real, appears more limited than sometimes claimed, with only a fraction of applied carbon remaining stabilized long-term.

Critical areas for future investigation should focus on developing standardized quality assessment protocols that account for both traditional parameters and emerging contaminants. Research must optimize application techniques to maximize benefits while minimizing potential drawbacks, including studies on ideal incorporation methods and timing. The interactions between compost and other soil amendments deserve particular attention, as do long-term studies tracking compost effects over decadal timescales. Economic analyses comparing compost with conventional fertilizers across different farming systems would help guide practical implementation.

Like any other industrial process, composting requires specialized equipment, proper management, and an appropriate site. The associated costs vary significantly depending on the scale of operation, the type and quantity of equipment needed, and the labor required to establish a suitable composting facility.

This analysis reveals compost's agricultural value is constrained by system-specific responsiveness, temporal efficacy windows, and unintended tradeoffs. Future research should prioritize decadal-scale field trials, contaminant monitoring protocols, and precision application technologies to optimize compost use in sustainable agriculture.

From a technological perspective, advances in composting processes could improve efficiency and product quality, particularly for challenging feedstocks. Simultaneously, policy frameworks need development to ensure compost safety and promote appropriate use, including standards for contaminant levels and labeling requirements. The potential for compost to contribute to climate change mitigation warrants deeper exploration, especially regarding its role in carbon farming initiatives.

To maximize agronomic and environmental benefits, future studies should focus on (1) optimizing compost application rates through site-specific trials, accounting for soil type and crop requirements, and (2) implementing long-term (> 5 years) monitoring to assess cumulative effects on soil health, carbon sequestration, and crop productivity. Such data would strengthen evidence-based compost use in sustainable farming systems.

Ultimately, composting represents an important tool for sustainable agriculture and waste management, but its implementation requires context-specific strategies backed by rigorous scientific understanding. By addressing current knowledge gaps through targeted research and developing supportive policies, we can fully realize composting's potential as part of a circular bioeconomy while mitigating its limitations. The path forward demands collaborative efforts across scientific disciplines, agricultural practice, and environmental policy to optimize this ancient yet increasingly relevant technology for modern challenges.

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Authors contributions

Conceptualization and design of the work, FI and RJB; software, FI, JMM, DM, and JMTG; research, FI, RJB, GP, JMM, and JMTG; writing-original draft preparation, RJB, FI, JMM, GP, DM, and JMTG; writing-review and editing, all authors. All authors read and approved the final manuscript.

Availability of data and materials

The data that support the findings of this study are available from the corresponding author, upon reasonable request.

Conflict of interests

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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