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Combined use of vermicompost and biochar to enhance soil health and crop yield in sustainable agriculture

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1 Introduction

Soil plays a vital role on Earth as a living ecosystem that sustains plants, animals, and humans (Lehmann et al., 2020). Nonetheless, human-induced pressures on soil health have threatened and compromised long-term food security (FAO, 2023). Limited resources have also resulted in the mismanagement and improper disposal of organic waste in the environment, accelerating soil degradation due to the accumulation of waste in landfills (Zhang et al., 2022b). Maintaining nutrient-rich topsoil has become essential to counteract the numerous challenges derived from rapid population growth, economic development, urbanisation, and increased food demand (Amundson et al., 2015; Zeiss et al., 2022). The use of organic fertilisers with a carbon-to-nitrogen (C to N) ratio of 42:1 is a promising solution that would help to address this crisis by immobilising nutrients such as nitrogen, reducing leaching losses and, above all, preserving soil health (Cameron et al., 2013; Chivenge

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et al., 2011; Gentile et al., 2009). The role of earthworms in organic solid waste management has been well established since first highlighted by Darwin (1892). Vermicomposting technology has been expanded over the years aiming to produce a valuable bio-product called vermicompost (Domínguez, 2023; Ismail, 2004). Vermicompost, generated through the joint and synergistic action of earthworms and microorganisms, is widely recognised as a nutrient-rich, biologically active humus-like organic material with the potential to enhance soil health and crop yield by supplying essential nutrients, fostering beneficial microbial communities, and improving plant resilience against pests and diseases (Gómez-Brandón et al., 2020). The transformation of organic waste into vermicompost takes place under aerobic conditions as a result of the feeding, casting (deposition of faeces), and tunnelling activities of earthworms (Sanchez-Hernandez and Domínguez, 2017).

Biochar is a carbon-rich material produced through the pyrolysis of organic matter (OM). This material was first used as a soil amendment in the late twentieth century, when researchers began to investigate the properties of *Terra Preta*, a black soil with a high charcoal content and recognised its ability to enhance soil fertility and carbon sequestration. The term 'biochar' became widely recognised by the early 2000s, driven by the work of pioneers such as Johannes Lehmann, who emphasised the role of biochar in improving soil health, reducing greenhouse gas (GHG) emissions and addressing environmental challenges. Nowadays, biochar is considered a potentially valuable material for sustainable soil management and climate change mitigation (Li et al., 2020; Mosa et al., 2023; Siedt et al., 2021; Vijay et al., 2021). Indeed, the capacity of biochar to enhance soil organic carbon, improve fertiliser quality and promote plant growth has been demonstrated (Agegnehu et al., 2017). Based on these benefits, biochar addition also accelerates composting by increasing microbial diversity and shortening the composting cycle, thus yielding an enhanced final compost product (Chen et al., 2017).

Taking this a step further, researchers have begun exploring biochar–vermicompost combinations as a next-generation soil amendment for enhancing soil quality and for improving nutrient availability and ecological balance while aligning with circular economy principles and advancing net-zero waste processes (Antileo-Mellado et al., 2024; EL-Mogy et al., 2024; Li et al., 2024). In this context, the present chapter considers the synergistic effects of biochar and vermicompost in mitigating the adverse impacts of organic waste on soil health and in promoting soil restoration. This chapter also examines how earthworms respond to the presence of biochar and whether biochar affects their growth and activity. These critical questions address the potential challenges that earthworms may face in contact with biochar and the eventual benefits of incorporating biochar in the final vermicompost product (Fig. 1).

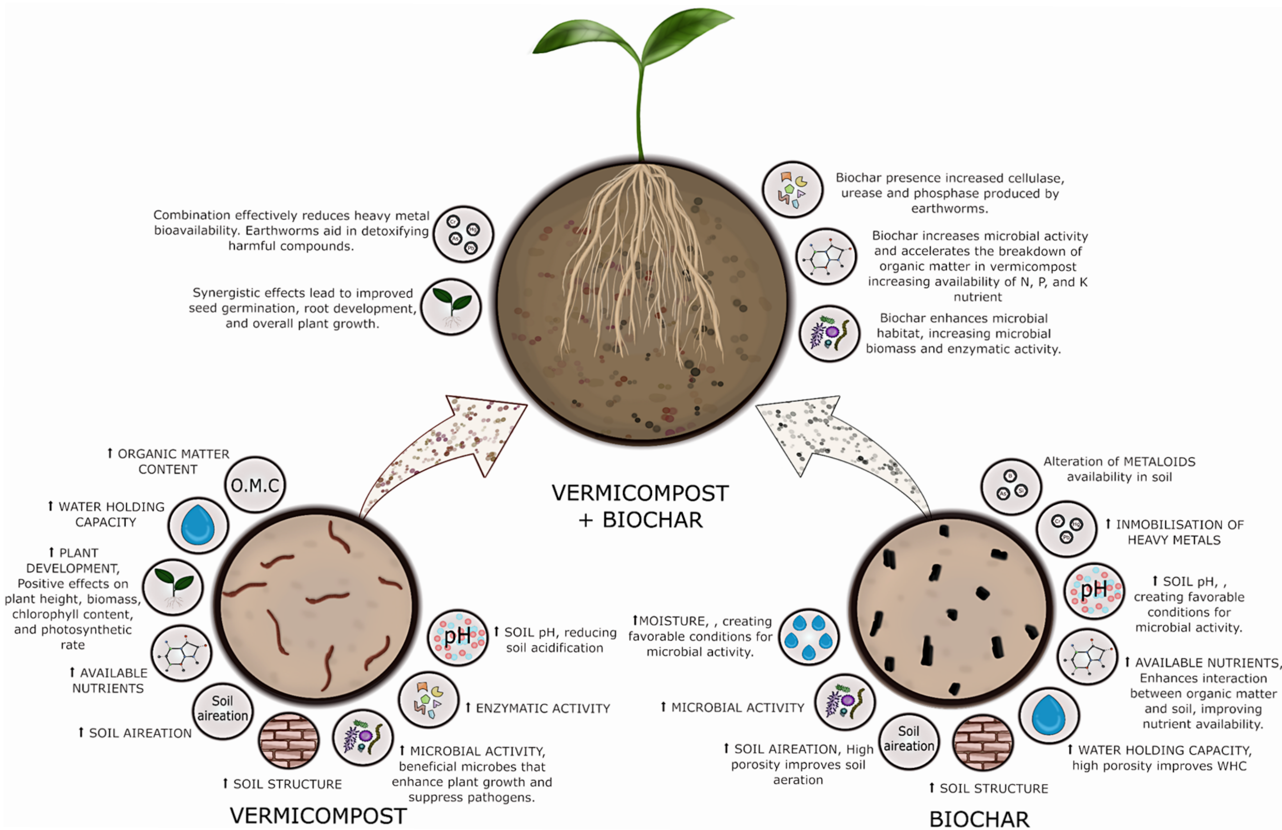

Figure 1 The figure illustrates the biochar–vermicompost interaction.

2 The role of biochar in composting

Biochar has been shown to improve compost quality and mitigate GHG emissions (Agyarko-Mintah et al., 2017). It has also been found that biochar produced at 550°C reduces CO_2 emissions by 50% relative to that generated at other pyrolysis temperatures (Lévesque et al., 2018). There are three plausible reasons for this: (1) Biochar acquires a more stable carbon structure at 550°C, which allows it to retain more carbon in a form resistant to microbial degradation, thus increasing carbon storage in the soil and reducing CO_2 release into the atmosphere. (2) The higher surface area and porosity of biochar produced at this temperature enhance the capacity of the material to absorb CO_2 and other gases. These properties also promote soil aeration and water retention, further decreasing GHG emissions from the soil. (3) Finally, pyrolysis at 550°C strikes a balance between maximising biochar yield and minimising production of GHGs (e.g. methane and CO_2), thus optimising environmental benefits.

Biochar interacts with microbes and, subsequently, with nutrient cycling in several ways. On the one hand, biochar slows down nitrification by adsorbing ammonium (NH_4^+) on its large, porous surface. This reduces the availability of NH_4^+ to nitrifying bacteria, which convert the cation to nitrate (NO_3^-), thus helping to reduce N_2O emissions. On the other hand, biochar increases soil pH and moisture, indirectly affecting microbial activity and also helping to slow down the nitrification process (Yang et al., 2017). Biochar also further accelerates carbon turnover through different mechanisms. First, it induces a 'priming effect' by providing a habitat for soil microorganisms that decompose carbon sources, thereby enhancing the interactions between soil microbes and organic matter (Rasul et al., 2022) and favouring decomposition and carbon cycling. Second, the highly porous surface of biochar interacts with soil organic matter (SOM), facilitating the adsorption and desorption of carbon materials (Kalu et al., 2024). This process makes carbon more bioavailable to microbes, which then transform the carbon into simpler compounds like CO_2 or more stable microbial-derived compounds like amino sugars and microbial necromass. Third, biochar improves soil aeration and moisture regulation, thus creating favourable conditions for aerobic microbial activity and carbon cycling (Gougoulias et al., 2014; Razzaghi et al., 2020). The high porosity of the biochar can also improve the physical properties of soil, including the water-holding capacity, due to the dissociation of H^+ ions and leaching of basic cations such as calcium (Ca), magnesium (Mg), potassium (K), and sodium (Na). Table 1 summarises the effect of H^+ ions on soil properties. The application of biochar also significantly increases soil pH, creating alkaline conditions that help to immobilise soil metals, further contributing to soil health and sustainability (Neina, 2019; Qiu et al., 2020).

Table 1 Effects of H^+ ions dissociation on soil properties

Process	Effect on soil chemistry	Implication for soil function
Dissociation of H^+ ions from biochar	Increases soil acidity (lowers pH)	Promotes cation exchange and mobilisation of nutrients
Displacement of basic cations (Ca^{2+}, Mg^{2+}, K^+, Na^+)	Enhances the leaching of these cations from exchange sites	Alters nutrient availability and buffering capacity
Increased cation exchange capacity (CEC)	Facilitates nutrient retention and exchange	Improves fertiliser efficiency and microbial access to ions
Mobilisation of Ca^{2+} and Mg^{2+}	May improve soil structure and flocculation	Enhances aeration and water infiltration
Leaching of K^+ and Na^+	Can reduce salinity and ionic imbalance in some soils	Supports root development and microbial activity

Source: Gougoulias et al., 2014; Razzaghi et al., 2020.

Another important factor to consider when using biochar as a soil amendment is its effect on seed germination, which varies depending on the feedstock and the application rate. While some studies have reported that biochar inhibits seed germination (Gasco et al., 2016), others have shown that applying biochar at rates of 10–50 t/ha improved seed germination and plant growth (Solaiman et al., 2012).

For instance, biochar can act as a biostimulant for growth of lentils but can also be phytotoxic to lettuce (Gasco et al., 2016), and it may also have no effect on plant growth, as reported by Alburquerque et al. (2014), after the application of more than 100 t/ha of biochar. Similarly, Bargmann et al. (2013) reported that biochar generally had no effect on the germination of spring barley (*Hordeum vulgare*). This lack of effect, however, does not preclude potential risks. Biochar can exhibit phytotoxicity, often attributed to the presence of phenolic compounds. Moreover, the phytotoxic effects on plants depend on the biochar and seeds considered. The variable effects of biochar on plant growth and germination highlight the complex interactions with different plants and biochar types, which extend to its influence on soil properties and metal dynamics. Biochar amendments greatly alter metal availability in soils (Antonangelo et al., 2021; Bilias et al., 2021; Xu et al., 2011). For instance, Wang et al. (2020) observed that arsenic concentration in rice straw biochar (RSBC)-amended soil increased to 29.96 mg/kg, while cadmium (Cd) levels decreased to 0.25 mg/kg in both RSBC and sewage sludge biochar (SSBC)-amended soils relative to the control treatment. These authors also reported that plant biomass increased by 37.91% in SSBC-amended soil and that RSBC boosted plant growth. Moreover, RSBC reduced arsenic concentration in plants and increased phosphorus (P) uptake, while SSBC reduced Cd accumulation in plants by 30.63% (Wang et al., 2020).

3 Earthworms and their role in vermicomposting

Over the last decades, vermicomposting has become a well-established bioconversion process that ensures the circular management of organic waste in a sustainable, eco-friendly, and low-impact manner (Domínguez, 2023). This bio-oxidative process is driven by the combined action of detritivorous earthworms, microorganisms, and other fauna within the decomposer community, thus accelerating the breakdown and stabilisation of organic matter and modifying its physical, chemical, and biological properties (Domínguez, 2004). In particular, the epigeic earthworm species *Eisenia fetida* (Savigny, 1826) and *Eisenia andrei* (Bouché, 1972) and the tropical species *Eudrilus eugeniae* (Kinberg, 1867) have been extensively used in vermicomposting systems due to their short life cycles, high reproductive rates, and high rate of consumption, digestion, and assimilation of organic matter. Earthworm feeding and digestion processes fragment and aerate the input material and alter microbial populations and communities, thereby affecting organic matter quality and nutrient availability, enhancing microbial activity, and accelerating the decomposition process (Bhat et al., 2018; Domínguez, 2004; Gómez-Brandón and Domínguez, 2014). The resulting vermicompost is a nutrient-rich, well-decomposed, and biologically active product (Aira and Domínguez, 2016), with beneficial effects on a wide variety of agronomic and horticultural crops (Blouin et al., 2019; Lazcano and Domínguez, 2011).

The chemical and (micro)biological properties of the final vermicompost and its potential value as an organic amendment are inextricably linked to the nature of the initial organic matter, as well as to the effects of earthworms on the decaying of these substrates and associated microbial communities through gut- and cast-associated processes, GAPs and CAPs, respectively (Gómez-Brandón et al., 2021; González et al., 2024). Indeed, the type and quality of the organic feedstock largely determine the transformations that occur during processing and, together with earthworm-driven mechanisms, shape the composition, dynamics, and performance of the system. These factors also influence the duration of the ageing period required before a stable end product is obtained. To this end, García-Sánchez et al. (2017) monitored the vermicomposting process of different feedstocks including horse manure, apple pomace, grape pomace, and digestate over time, that is after 60, 120, 180, and 240 days of processing with *E. andrei*. All materials exhibited neutral to alkaline pH throughout the process. Electrical conductivity (EC) remained largely unchanged (between 0.1 and 1.6 mS cm^{-1}), between days 60 and 240. Stabilisation of the materials was achieved after 240 days, as reflected by a decrease or stabilisation of the organic carbon content. Aligned with this, microbial activity also declined after 240 days, corresponding with a lower earthworm activity, which peaked at 120 days. Moreover, phytotoxicity tests indicated that apple pomace and digestate had reached a stable, nutrient-rich, and safe state, while horse manure and grape pomace did not reach the same level of maturation. Plaza et al. (2008) analysed the products obtained from a prolonged process of about eight months of vermicomposting with *E. andrei* using cattle manure and a mixture of olive pomace and cattle manure. The authors reported that the pH remained alkaline in cattle manure treatment and increased to 6.6 to 8.6 in the mixture. While the authors reported total organic carbon (TOC) was decreased in both organic sources, the mixture one kept more carbon. The C/N ratio decreased significantly in both cases, reflecting stabilisation and humification of the materials. Total nitrogen increased in the case of the mixture, while in the cattle manure, it decreased. Fernández-Gómez et al. (2010) conducted a pilot-scale experiment using a metal vermireactor with an initial layer containing sheep manure as habitat for the earthworms (*E. fetida*). The reactor was fed with tomato-fruit waste paste for 5 months (+2 months of maturation), and the chemical and enzymatic parameters were monitored over the course of the process. The results showed that the earthworm biomass increased after 90 days; followed by a decline due to an increase in pH level, EC, and ammonium concentration in the mixture. The temporal patterns of β-glucosidase, protease, and urease activities appeared to be related to earthworm growth and OM stabilisation. Taken together, the authors suggested that the continuous-feeding vermicomposting process could be a suitable management system for processing vegetable wastes. Hřebečková et al. (2019) compared vermicompost from household biowaste, malthouse sludge + agricultural waste, and grape marc. The process lasted more than 12 months, during which fresh layers of organic sources were added every 2 weeks. The pH stabilised in neutral ranges for all materials, and the EC decreased toward the end of the process. The authors reported that microbial biomass and activity were concentrated in the upper, fresher layers, where earthworm density was also the highest. Likewise, the maximum enzymatic activity occurred in these upper layers, whereas deeper, older layers showed reduced activity. To further investigate these spatial dynamics, Gómez-Brandón et al. (2021) evaluated the changes in vermicompost derived from grape marc using *E. andrei* for 42 weeks (294 days), sampling every 3 weeks in a continuously fed system, where fresh material was added weekly in layers. The main objective of this study was to compare the evolution of the initial feedstock with and without earthworms; only results from the treatments with earthworms are considered here. They reported that pH was weak-alkaline across the layers, while C/N ratio increased or remained stable, likely due to the high lignocellulosic content of the residues. By the end of the experiment, macro- and micronutrients content increased, while microbial biomass and activity decreased with depth, with fungi predominating in the upper, fresher layers (Table 2).

Table 2 Summary of initial and final values of physicochemical and biological parameters

Organic source	Maximum time of vermicomposting	pH initial	pH final	Electrical conductivity (mS cm^{-1}) initial	Electrical conductivity (mS cm^{-1}) final	Organic carbon/OM (TC/TOC/DOC) initial	Organic carbon/OM (TC/TOC/DOC) final	Nitrogen (TN, N-NO_3^-, NH_4^+-mgkg^{-1}-TKN) initial	*Nitrogen (TN (%), N-NO_3^-, NH_4^+ -mgkg^{-1}-TKN) final*	C/N initial	C/N final	Microbial activity initial	Microbial activity final	Study
Cattle manure (CM)	*8 months (≈244 days)*	8.6	8.5	760	143	TOC 212	TOC 88	TN (gkg^{-1}) 14.0	TN (gkg^{-1}) 11.0	15	8	NA	Humification: TEC, FAC, HAC, HR, HI increased; FTIR spectra: decrease in aliphatic and N-containing groups, enrichment of aromatic structures; E4/E6 ratio decreased approaching soil HA; fluorescence: decrease in RFI, increase in EEWP	Plaza et al., 2008
Cattle manure + olive pomace (CM + OP)	*8 months (≈244 days)*	6.6	8.6	321	249	TOC 483	TOC 292	TN (gkg^{-1}) 12.8	TN (gkg^{-1}) 20.0	38	15	NA	Humification: TEC, FAC, HAC, HR, HI increased; FTIR and fluorescence similar trends as above, indicating high degree of humification and maturity	Plaza et al., 2008
Sheep manure + tomato-fruit wastes	5 months + 60 days maturation (210 days)	8.3	10.4	168	4.4	TOC (gkg^{-1}) 139	TOC (gkg^{-1}) 148	*TKN (gkg^{-1}) 12.1 NH_4^+ 348*	*TKN (gkg^{-1}) 12.9 NH_4^+ 2561*	11.4	11.4	Dehydrogenase: peak at day 30, sharp increase 90–120; β-glucosidase: peak day 90; Protease: increase 0–60, decline day 90, rise 90–120; Urease: stable 0–60, increase 60–90	Dehydrogenase: stable after day 120; β-glucosidase decline with earthworm mortality; Protease: decline post day 120; Urease: decreased after maturation; bacterial/fungal DGGE: high diversity, community shifts	Fernández-Gómez et al., 2010

Horse manure (HM)	240 days	7.8	7.1	1.4	1.1	TOC 40 %	DOC (gkg^{-1}) 3.3	TN 2.7 %	*N-NO$_3$– 735NH$_4^+$ 215*	NA	NA	Dehydrogenase activity peak at 120 d; β-glucosidase decline at 120 d; Protease: increase 0–60 d, decline 90–120 d; Phosphatase: increase 240 d; o-diphenol oxidase peak 120 d	Dehydrogenase decline at 180–240 d; Protease increase at 240 d; β-glucosidase low; phosphatase stable; o-diphenol oxidase decline at 240 d	García-Sánchez et al., 2017
Apple pomace (AP)	240 days	7.9	8	1.3	0.4	TOC 40 %	DOC (gkg^{-1}) 2.6	TN 2.5 %	N-NO$_3^-$ 56.2NH$_4^+$ 163.7	NA	NA	Dehydrogenase peak 120 d; β-glucosidase stable; Protease 60–120 d increase; phosphatase high; o-diphenol oxidase peak 120 d	Dehydrogenase decline at 180–240 d; Protease decline at 240 d; β-glucosidase low; phosphatase remained stable; o-diphenol oxidase decline at 240 d	García-Sánchez et al., 2017
Grape pomace (GP)	241 days	7.7	9.2	1.2	1	TOC 42 %	DOC (gkg^{-1}) 3.6	TN 2.1 %	N-NO$_3^-$ 36.6NH$_4^+$ 162.3	NA	NA	Dehydrogenase peak 120 d; β-glucosidase 60–120 d increase; Protease 120 d peak; phosphatase stable; o-diphenol oxidase low	Dehydrogenase decline at 180–240 d; β-glucosidase decline at 180–240 d; protease decline at 240 d; phosphatase stable; o-diphenol oxidase increase at 240 d	García-Sánchez et al., 2017
Household biowaste	>12 months (365 days)	5.4	7.45	NA	0.23	NA	NA	NA	NA	26.7	NA	NA	Enzymatic activity varies: higher β-D-glucosidase, acid phosphatase, chitinase, cellobiohydrolase, aminopeptidases in intermediate layers; higher earthworm biomass in top layers	Hřebečková et al., 2019

(*Continued*)

Table 2 *Continued*

Organic source	Maximum time of vermicomposting	pH initial	pH final	Electrical conductivity (mS cm^{-1}) initial	Electrical conductivity (mS cm^{-1}) final	Organic carbon/OM (TC/TOC/DOC) initial	Organic carbon/OM (TC/TOC/DOC) final	Nitrogen (TN, N-NO_3^-, NH_4^+-mgkg^{-1}-TKN) initial	*Nitrogen (TN (%), N-NO_3^-, NH_4^+ -mgkg^{-1}-TKN) final*	C/N initial	C/N final	Microbial activity initial	Microbial activity final	Study
Malthouse sludge + agricultural waste (20:80 vol)	>12 months (365 days)	8.3	8.28	0.20	0.14	NA	NA	NA	NA	6	NA	NA	Enzymatic activity: moderate levels of β-D-glucosidase, lipase, and aminopeptidase; earthworms only present in top layers	Hřebečková et al., 2019
Grape marc	>12 months (365 days)	7.6	8.68	0.41	0.14	NA	NA	NA	NA	21.4	NA	NA	Earthworm biomass and enzymatic activity (β-D-glucosidase, acid phosphatase, chitinase, and lipase) were higher in top layers	Hřebečková et al., 2019
Digestate (DG): 50% slurry, 40% corn silage, 10% hay)	242 days	8.5	8.1	3.5	1.6	TOC 36 %	DOC (gkg^{-1}) 2.5	TN 2.2 %	N-NO_3^- 1170.5 NH_4^+ 159.6	NA	NA	Dehydrogenase peak at 120 d; β-glucosidase, protease, and o-diphenol oxidase were low; while phosphatase remained stable	Dehydrogenase decline at 180–240 d; decline in β-glucosidase and protease at 240 d; while, phosphatase remain stable; and o-diphenol increased	García-Sánchez et al., 2020
Grape marc var. Albariño	*42 weeks (≈294 days)*	8.23	8.5	0.37	0.35	TC (g) 112	TC (g) 154	TN (g) 4.93	TN (g) 5.50	23.3	28.5	Upper layers: high fungal activity, lower bacterial activity; high β-D-glucosidase in intermediate layers; high lipase; moderate acid phosphatase; moderate cellobiohydrolase and aminopeptidases.	Lower layers: reduction in fungal activity; β-D-glucosidase and other enzymes; bacteria remain present but overall activity was lower; stabilisation of organic matter.	Gómez-Brandón et al., 2021

Grape marc var. Mencía	*42 weeks (≈294 days)*	7.93	7.55	0.27	0.22	TC (g) 159	TC (g) 233	TN (g) 6.34	TN (g) 8.93	25.2	26.4	Upper layers: high earthworm biomass, increased fungal activity; high β-D-glucosidase in intermediate layers; moderate lipase and acid phosphatase; cellobiohydrolase and aminopeptidases present.	Lower layers: decrease in enzymatic activity; lower fungal activity; bacteria predominate; stabilisation of organic matter.	Gómez-Brandón et al., 2021
Common conclusions	Similar evaluation periods.	Most substrates had a slightly alkaline initial pH, except for household waste. During the vermicomposting process, the pH tends to stabilise or increase slightly in some cases (AP, sheep manure + tomato waste) or decrease moderately (HM, Mencía grape marc). However, all pH values remain in an alkaline to slightly alkaline range.		The EC varies depending on the original organic source. It generally decreases at the end of the study, indicating salt leaching and stabilisation of the vermicompost.		The organic carbon content is high at the start of the process. During vermicomposting, it decreases due to the mineralisation and degradation of organic matter, with a tendency towards stabilisation.		The nitrogen content varies depending on the organic source. During vermicomposting, nitrogen is preserved or increases slightly in some types of waste (e.g. grape marc, CM + OP), while in others it may decrease due to leaching or volatilisation.		The initial values are high, indicating a high proportion of available carbon. The C/N ratio decreases in most cases, indicating the maturity and stabilisation of the organic matter.		Dehydrogenase peaks at 120 days, then declines. ß-glucosidase, protease, phosphatase, and other enzymes show intermediate increases followed by a decline towards the end of the process. Spatial distribution may vary with the upper or fresher layers showing greater earthworm and enzyme activity.		

Physicochemical and biological parameters: pH, electrical conductivity, organic carbon, nitrogen forms, C/N ratio, and microbial/enzymatic activity reported in different vermicomposting studies.
The table presents mean values either before the start of the experiments or from the first available measurement, and the corresponding values at the end of the experimental period. When data are not available, cells are indicated as NA (Not Available).
Abbreviations: TOC: Total Organic Carbon; DOC: Dissolved Organic Carbon; TC: Total Carbon; OM: Organic Matter; TN: Total Nitrogen; TKN: Total Kjeldahl Nitrogen; N-NO_3^-: Nitrate Nitrogen; NH^{4+}: Ammonium; EC: Electrical Conductivity; C/N: Carbon-to-Nitrogen Ratio; TEC: Total Extractable Carbon; FAC: Fulvic Acid Carbon; HAC: Humic Acid Carbon; HR: Humification Ratio; HI: Humification Index; FTIR: Fourier Transform Infrared Spectroscopy; E4/E6: Absorbance ratio at 465 nm and 665 nm (humification indicator).

Nonetheless, apart from aforementioned properties, there is increasing evidence indicating that the potential usefulness of vermicompost lies in its biological components (Gopalakrishnan et al., 2011; Rehman et al., 2023; Vambe et al., 2023). These authors reported that vermicompost and its liquid derivatives (known as vermicompost teas) harbour a broad spectrum of bacterial genera, including *Bacillus*, *Enterobacter*, *Pseudomonas,* and *Streptomyces* spp., which are capable of inhibiting the growth of plant pathogenic fungi such as members of the genera *Phytophthora* and *Pythium* species. The presence of beneficial plant-growth promoting microorganisms (PGPMs) makes vermicompost of great agronomic value fuelling its use as a natural biofertiliser (Ma et al., 2022; Rehman et al., 2023). Recent studies have also shown that vermicompost derived from grape marc and leguminous shrubs have higher functional diversity and more genes putatively involved in metabolic processes that are potentially beneficial for plant growth and development than their respective parent materials (Domínguez et al., 2019; Gómez-Brandón et al., 2020). A similar trend has been observed regarding the microbial richness of bacterial communities, which was enhanced during the vermicomposting of grape marc (Domínguez et al., 2019; Kolbe et al., 2019). Earthworms also facilitate the replacement of these microbial communities in the vermicompost by introducing the microbiome from their digestive system into their casts, thus enhancing fungal populations, reducing bacterivorous nematodes and increasing mineralisation rates, CO_2 flux, and labile C and N pools in earthworm density-dependent processes (Aira et al., 2008). Earthworm activity can stimulate initial microbial growth and enzyme activity, with the response varying depending on the slurry rate and the age of the layer, indicating a relationship between microbial biomass, enzyme activity, and substrate availability (Aira et al., 2007).

During the early stages of vermicomposting, the levels of N_2O can increase as an intermediate product of fluctuating oxygen levels. Thus, N_2O emissions have been found to be higher in the vermicompost than in the control feedstock without earthworms (Lv et al., 2020). This study reported that both nitrification and denitrification contributed to N_2O production in the early stages, but nitrification became the dominant pathway as the process continued. Earthworms stimulated nitrifying bacteria, leading to higher *amoA* gene copies and increased N_2O emissions via nitrification. Additionally, denitrification occurred primarily in the earthworm gut, where conditions inhibited the *nosZ* gene, further contributing to N_2O production. Overall, nitrification was responsible for 55.8 to 88.7% of N_2O emissions, driven by the presence of earthworms. Altogether, it points to vermicomposting as a valuable and environmentally friendly approach for sustainable agriculture and environmental conservation. The most significant advantage of the process lies in its dual role in organic waste management and the generation of a product that contributes to soil fertility and health (Ambasta and Kumari, 2013; Vyas et al., 2022).

4 Effects of vermicompost on soil

In intensive cropping systems, the excessive use of nitrogenous fertilisers has been shown to accelerate soil acidification (Zhang et al., 2022a). Owing to its generally alkaline properties, vermicompost can potentially mitigate soil acidification and represents an environmentally sustainable alternative to mineral fertilisers. When added to acidic soils, vermicompost can act as a buffer, increasing the soil pH to more neutral values (Toor et al., 2024; Zhang et al., 2020). Adjusting the soil pH improves the solubility of some nutrients such as P, thus enhancing P availability to plants (Hinsinger, 2001; Lauber et al., 2009), as found after the addition of vermicompost (Zhang et al., 2020). Beneficial soil microorganisms, such as nitrogen-fixing bacteria and organic matter decomposers, also tend to thrive in slightly alkaline or almost neutral soils (Lauber et al., 2009). Soil pH also influences the dispersion of clays and aggregation of particles. As the pH increases, the negative charge on clay particles also increases, causing the particles to repel each other, which benefits the structural stability of soils with high clay dispersion. This process promotes the formation of large aggregates, especially in soils with high carbonate content (Bronick and Lal, 2005). Moreover, adding vermicompost, which is rich in OM, can favour soil microbial activity by enhancing microbial respiration (Bronick and Lal, 2005; García-Sánchez et al., 2017).

The changes that take place in soil following the application of vermicompost can enhance plant performance. For instance, Xu and Mou (2016) reported that variations in soil parameters, such as increased pH, EC and nutrient content and improved soil structure and water holding capacity, were accompanied by an increase in several plant traits, including plant height, number and area of leaves, chlorophyll content and photosynthetic rate, after the addition of vermicompost. Similarly, Arancon et al. (2006) observed that vermicompost has a positive effect on plant growth and strawberry yield. This was accompanied by a significant increase in soil microbial biomass, enzyme activity and available nutrients, as well as an improvement in soil structure, water-holding capacity and a reduction in soil bulk density. Based on a meta-analysis of 68 articles, Blouin et al. (2019) estimated that vermicompost increased plant yields by 26%, total biomass by 13%, shoot biomass by 78%, and root biomass by 57%. The maximum yields were obtained when vermicompost represented between 30% and 50% of the soil volume and when cattle manure was used as feedstock. Although the meta-analysis had some limitations – such as potential over-representation of studies with large effect sizes (e.g. substantial increases in biomass or yield) and variability in experimental setups – the authors concluded that vermicompost has significantly positive effects on plant growth. Furthermore, vermicompost application has also been reported to be an effective strategy for suppressing plant diseases (Vambe et al., 2023; Yatoo et al., 2021). Overall, these different findings indicate that vermicompost is a valuable amendment for improving soil and plant health and, in turn, increasing the abundance and diversity of microbial communities.

Despite the aforementioned advantages of vermicomposting and the potential benefits of vermicompost, there are some challenges that affect its efficiency. The slow breakdown of lignocellulosic materials (e.g. straw), which are complex and resistant to decomposition by earthworms and the associated microorganisms, and the presence of heavy metals can have harmful effects on earthworms. These negative aspects of vermicomposting could be addressed by combining vermicompost with other types of amendments (Tang et al., 2017; Zhang and Sun, 2014). To this date, the inclusion of biochar in vermicomposting has been reported to be a promising way of overcoming these limitations (EL-Mogy et al., 2024).

5 Combining biochar and vermicompost

The capacity of biochar to promote the degradation of pollutants and reduce GHG emissions has been demonstrated and attributed to properties such as its carbonaceous structure, high cation exchange capacity, and porous surface area, which help to enhance microbial activity and water retention (Li et al., 2024; Paul et al., 2020). These characteristics also favour soil aggregation and increase enzymatic activity, leading to faster decomposition and improved vermicompost quality (Hijikata et al., 2015).

Qiang et al. (2018) showed that adding biochar, particularly at a rate of 6%, during the vermicomposting process increased the activity of cellulase, urease, and phosphatase enzymes excreted by *E. fetida*. Roy et al. (2022) reported that the availability of essential nutrients such as N, P, and K increased by approximately 1.5–2.0 times in exfoliated biochar-based vermicompost beds. This improvement was attributed to the increased surface area, which provided an environment more conducive to microbial activity and earthworm colonisation. As a result, microbial biomass carbon and microbial respiration levels increased significantly, along with a 6 to 12-fold acceleration in dehydrogenase and fluorescein diacetate (FDA) hydrolysing enzyme activities in biochar-based vermibeds.

Earthworms are known to play a vital role in eliminating toxic compounds and heavy metals from their environment (Chen and Hu, 2019; Sinha et al., 2010). For instance, Roy et al. (2022) showed that *E. fetida* played an essential role in reducing arsenic (As^{3+}) levels in biochar vermibeds. The bioavailable arsenic fractions were reduced by 25–40%, while the recalcitrant arsenic fractions increased by 8–15%. This demonstrates the effectiveness of *E. fetida* in transforming arsenic into less bioavailable forms. The performance of *E. fetida* was particularly notable in the exfoliated biochar combined with cow dung (12.5% exfoliated biochar to 87.5% cow dung feedstock), making this combination highly effective for arsenic removal and nutrient recovery. Furthermore, some studies have demonstrated that biochar produced from rice husks significantly reduces the bioavailability and mobility of cadmium in contaminated soils (Cui et al., 2016; Oranratmanee and Tungittiplakorn, 2021). The porous structure and high cation exchange capacity of biochar enhance the adsorption and stabilisation of cadmium ions, thus preventing their uptake by plants. To enhance the bioremediation strategy, activation of biochar with extracellular enzymes is emerging as a potential alternative to chemical or physical activation, which is often expensive and generates chemical waste. In this process, microorganisms act as a source of enzymes that adhere to the biochar surface. Recent studies have highlighted the role of soil macrofauna, particularly earthworms, in enhancing enzyme adsorption onto biochar (Sanchez-Hernandez, 2018; Sanchez-Hernandez et al., 2019). Hence, the inclusion of biochar during the vermicomposting process, with the aim of removing pollutants, has also been investigated. Bošković et al. (2021) evaluated the addition of biochar during the vermicomposting process using *E. andrei* and studied the influence of the degradation rate of fungicides. These authors reported that mixing biochar with vermicompost changed the fate and bioaccumulation of the fungicides.

The addition of biochar to the vermicomposting process has been shown to improve humification processes, resulting in high-quality vermicompost with enriched fulvic acid content, which is beneficial for plant growth (Antileo-Mellado et al., 2024; Hou et al., 2023; Zhang et al., 2023). Moreover, the combination of vermicompost and biochar enhances CO_2 production and microbial respiration, leading to improved seed germination and plant growth (Dawar et al., 2022; EL-Mogy et al., 2024). In this regard, Zhang et al. (2023) reported that the combined application of vermicompost and biochar resulted in a higher yield of continuously cropped pepper grown in karst areas than yields obtained with each amendment alone. This indicates that the organic amendments had a synergistic effect on crop productivity that may be related to an improved nutrient status and microbial environment (Rivelli and Libutti, 2022; Wang et al., 2021).

6 Toxicity of biochar to earthworms

Despite the emerging benefits of biochar, the potentially adverse effects on earthworms have raised concerns (Odinga et al., 2021; Sanchez-Hernandez et al., 2019; Wu et al., 2023). Biochar contains ash and combustion by-products that can have harmful effects on earthworm growth, causing oxidative stress and inhibiting the vermicomposting process (Elliston and Oliver, 2020; Zhang et al., 2019). Studies have shown that biochar can contain toxic compounds, such as polycyclic aromatic hydrocarbons (PAHs), which may inhibit earthworm growth and cause oxidative stress (Pokharel et al., 2020; Zhang et al., 2017). The toxicity of biochar varies depending on feedstock type, pyrolysis temperature, and posterior treatment. For instance, cow dung biochar was found to be more toxic than corncob or sewage sludge biochar (Intani et al., 2018). However, thermal treatment of biochar can reduce its vermitoxicity by lowering the PAH content, as demonstrated by Buss et al. (2015).

Careful consideration must therefore be given to the strategy of including biochar in the vermicomposting process, to minimise the potential drawbacks. Recent studies have aimed to explore the vermitoxicity of biochar produced from various types of feedstock – animal (cow dung), plant (corncob), and sewage sludge, at different pyrolysis temperatures (350°C, 550°C, and 750°C) (Shi et al., 2021). The toxicity was evaluated using a combination of acute toxicity tests, neutral red retention time (NRRT) assay, and oxidative stress response assays. The test results revealed that cow dung biochar was more toxic to earthworms than biochar derived from corncob and sewage sludge. The toxicity level was measured by determining the LC50 and determining weight loss in the earthworms. Cow dung biochar caused significant disruption to lysosomal membrane stability, indicating cellular stress. Additionally, oxidative stress was indicated by disturbed antioxidant enzyme activity and elevated malondialdehyde levels, highlighting the vermitoxicity of cow dung biochar. Interestingly, the study demonstrated that thermal treatment can mitigate the toxic effects of biochar. By subjecting biochar to higher pyrolysis temperatures, the LC50 increased and earthworm weight loss decreased. This suggests that PAHs, which are by-products of biochar production, may be key contributors to the toxicity. The use of the NRRT assay provided further insights, offering a dose-response relationship that could be instrumental in assessing biochar toxicity. The findings highlight the importance of feedstock selection and thermal treatment in biochar production to minimise the harmful effects on earthworms, which are vital for soil health. These results emphasise the need for further research to understand the comprehensive ecological impacts of biochar and to develop guidelines for its safe application in agricultural practices (Shi et al., 2021).

Bošković et al. (2021) examined fungicide bioaccumulation in earthworms (*E. andrei*) in biochar-amended soils and found that bioaccumulation decreased over time but varied with soil properties. Equilibrium was reached faster (3–7 days) in more absorbent soils, while in less absorbent sandy soils it was not reached until around 21 days, indicating that biochar delays equilibrium in some types of soil. Wang et al. (2020) used high-throughput sequencing to examine the effects of biochar amendments on the gut bacteria of the earthworms (*E. fetida*). The analysis revealed high concentrations of metals in earthworm tissues, with earthworm gut bacterial composition dominated by Firmicutes (39.36%), Actinobacteria (23.69%), and Proteobacteria (13.02%); and different from that of the surrounding soil. Additionally, rice straw biochar (RSBC) had a more pronounced effect on the earthworm gut microbiome than sewage sludge biochar (SSBC). It is necessary to clarify the above process as *E. fetida* or *E. andrei* are not soil earthworms. However, to perform the toxicity test, the earthworms were bred separately in the lab with different substrates such as manure, garden waste, and peat, as in the experiment conducted by Bošković (2021). Before testing, adult earthworms with developed clitellum (~200 mg weight) were acclimatised in experimental soils moistened to 50% water-holding capacity with added manure (7 mg $g_{soil\text{-}dw}^{-1}$) for three days (Wang et al., 2020).

By contrast, some studies have reported no significant effect on earthworms when added to the biochar-amended soil. For example, Whalen and Benslim (2021) stated that wood-based biochar, applied as a soil amendment alone or in combination with dairy cattle slurry, had no effect on earthworm populations in agricultural fields on a dairy farm in southern Quebec (Canada). The study authors concluded that the changes in earthworm populations can be attributed to environmental stress, such as flooding and other unfavourable weather conditions. Similarly, Huang et al. (2020) reported no significant negative effects on earthworm survival rates in heavy metal-contaminated soil + biochar. However, these authors observed that the initial reduction in earthworm growth was consistent with that found in a previous study by Zhang et al., (2019), in which a decrease in earthworm biomass during the first 28 days of the vermicomposting process was reported. Interestingly, other studies showed that the presence of *E. fetida* led to an increase in antioxidant enzyme activity in the initial 28 days and subsequently declined (Liu et al., 2014; Panzarino et al., 2016). These findings are consistent with those of Sanchez-Hernandez et al., (2019), who reported that the enzyme activities of earthworms (*Lumbricus terrestris*) decreased significantly in the soil including 1% biochar for 30 days.

Several studies have explored methods of mitigating biochar toxicity, including water or solvent washing and thermal treatment. Kołtowski and Oleszczuk (2015) reported a significant reduction in the PAH content of biochar when subjected to drying at temperatures of 100°C to 300°C. Intani et al. (2018) also demonstrated that heat-treated biochar reduced phytotoxicity in ryegrass and improved plant biomass. Such findings highlight the importance of treating biochar to reduce its toxicity before application to agricultural soils.

7 Conclusion and future trends in research

Earthworms serve as effective bioindicators of soil pollution and play a significant role in soil remediation. The distinct differences between soil microbial communities and those in the earthworm gut highlight the gut's unique habitat and its influence on soil microbial dynamics. Vermicomposting remains a promising bioremediation strategy, and its integration with biochar offers a synergistic approach to improving soil quality and mitigating environmental impacts.

Remediation of metal-contaminated soils remains complex due to their heterogeneous physicochemical properties and the persistent risk of metal re-mobilisation. In this context, combining biochar with vermicompost presents a sustainable solution, enhancing contaminant stabilisation, boosting microbial diversity, and improving soil structure and nutrient retention. Their combined use not only improves soil health but also enhances climate resilience by increasing carbon sequestration and buffering crops against drought stress.

Ultimately, bioremediation should aim for holistic soil restoration, addressing biological, chemical, and physical dimensions of soil health. Vermicompost, enriched with beneficial microbes, plays a pivotal role in this transformation. Future research should focus on optimising biochar and vermicompost formulations to minimise toxicity and deepen our understanding of their combined effects on soil ecosystems. Future studies should also explore shifts in microbial functional groups and their roles in nutrient cycling, pathogen suppression, and long-term soil resilience. Advancing this knowledge will be key to developing resilient, regenerative agricultural systems.

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9 References

Agegnehu, G., et al. 2017. The role of biochar and biochar-compost in improving soil quality and crop performance: a review. *Applied Soil Ecology*, 119, 156–170.

Agyarko-Mintah, E., et al. 2017. Biochar lowers ammonia emission and improves nitrogen retention in poultry litter composting. *Waste Management*, 61, 129–137.

Aira, M., et al. 2007. Earthworms strongly modify microbial biomass and activity triggering enzymatic activities during vermicomposting independently of the application rates of pig slurry. *Science of the Total Environment*, 385(1–3), 252–261.

Aira, M., et al. 2008. Detritivorous earthworms directly modify the structure, thus altering the functioning of a microdecomposer food web. *Soil Biology and Biochemistry*, 40(10), 2511–2516.

Aira, M., et al. 2016. Characterization of the bacterial communities of casts from Eisenia andrei fed with different substrates. *Applied Soil Ecology*, *98*, pp.103-111.

Alburquerque, J.A., et al. 2014. Effects of biochars produced from different feedstocks on soil properties and sunflower growth. *Journal of Plant Nutrition and Soil Science*, 177(1), 16–25.

Ambasta, S.K. and Kumari, S. 2013. Earthworm: a natural ecofriendly organism for recycling of organic residues and improvement of soil health by Vermicompost. *International Journal of Applied Sciences and Biotechnology*, 1(4), 171–175.

Amundson, R., et al. 2015. Soil and human security in the 21st century. *Science*, 348(6235), 1261071.

Antileo-Mellado, S., et al. 2024. Effect of biochar on vermicompost production: chemical, biochemical, and biological properties. *Agronomy*, 14(3), 615.

Antonangelo, J.A., et al. 2021. The roles of co-composted biochar (COMBI) in improving soil quality, crop productivity, and toxic metal amelioration. *Journal of Environmental Management*, 277, 111443.

Arancon, N., et al. 2006. Influences of vermicomposts on field strawberries: part 2. Effects on soil microbiological and chemical properties. *Bioresource Technology*, 97(6), 831–840.

Bargmann, I., et al. 2013. Hydrochar and biochar effects on germination of spring barley. *Journal of Agronomy and Crop Science*, 199(5), 360–373.

Bhat, S.A., et al. 2018. Bioremediation and detoxification of industrial wastes by earthworms: vermicompost as powerful crop nutrient in sustainable agriculture. *Bioresource Technology*, 252, 172–179.

Bilias, F., et al. 2021. Towards a soil remediation strategy using biochar: effects on soil chemical properties and bioavailability of potentially toxic elements. *Toxics*, 9(8), 184.

Blouin, M., et al. 2019. Vermicompost significantly affects plant growth: a meta-analysis. *Agronomy for Sustainable Development*, 39, 1–15.

Bošković, N., et al. 2021. Conazole fungicides epoxiconazole and tebuconazole in biochar amended soils: degradation and bioaccumulation in earthworms. *Chemosphere*, 274, 129700.

Bronick, C.J. and Lal, R. 2005. Soil structure and management: a review. *Geoderma*, 124(1–2), 3–22.

Buss, W., et al. 2015. Inherent organic compounds in biochar–their content, composition and potential toxic effects. *Journal of Environmental Management*, 156, 150–157.

Cameron, K.C., et al. 2013. Nitrogen losses from the soil/plant system: a review. *Annals of Applied Biology*, 162(2), 145–173.

Chen, Y., et al. 2017. Influence of biochar on heavy metals and microbial community during composting of river sediment with agricultural wastes. *Bioresource Technology*, 243, 347–355.

Chen, Z. and Hu, S. 2019. Heavy metals distribution and their bioavailability in earthworm assistant sludge treatment wetland. *Journal of Hazardous Materials*, 366, 615–623.

Chivenge, P., et al. 2011. Comparison of organic versus mineral resource effects on short-term aggregate carbon and nitrogen dynamics in a sandy soil versus a fine textured soil. *Agriculture, Ecosystems & Environment*, 140(3–4), 361–371.

Cui, L., et al. 2016. Continuous immobilization of cadmium and lead in biochar amended contaminated paddy soil: a five-year field experiment. *Ecological Engineering*, 93, 1–8.

Darwin, C., 1892. The formation of vegetable mould, through the action of worms, with observations on their habits. J. Murray.

Dawar, K., et al. 2022. Maize productivity and soil nutrients variations by the application of vermicompost and biochar. *PLoS One*, 17(5), e0267483.

Domínguez, J. 2004. State-of-the-art and new perspectives on vermicomposting research. in: *Earthworm ecology*, CRC Press, pp. 401–424.

Domínguez, J. 2023. State-of-the-art and new perspectives on vermicomposting research: 18 years of Progress. in: *Vermicomposting for sustainable food systems in Africa*, Springer, pp. 27–44.

Domínguez, J., et al. 2019. Changes in the composition and function of bacterial communities during vermicomposting may explain beneficial properties of vermicompost. *Scientific Reports*, 9(1), 9657.

EL-Mogy, M.M., et al. 2024. Integration of biochar with vermicompost and compost improves agro-physiological properties and nutritional quality of greenhouse sweet pepper. *Agronomy*, 14(11), 2603.

Elliston, T. and Oliver, I.W. 2020. Ecotoxicological assessments of biochar additions to soil employing earthworm species Eisenia fetida and Lumbricus terrestris. *Environmental Science and Pollution Research*, 27(27), 33410–33418.

FAO. 2023. *The state of food security and nutrition in the world 2023*. FAO.

Fernández-Gómez, M.J., et al. 2010. Continuous-feeding vermicomposting as a recycling management method to revalue tomato-fruit wastes from greenhouse crops. *Waste Management*, 30(12), 2461–2468.

García-Sánchez, M., et al. 2017. Stabilization of different starting materials through vermicomposting in a continuous-feeding system: changes in chemical and biological parameters. *Waste Management*, 62, 33–42.

Gasco, G., et al. 2016. Relation between biochar properties and effects on seed germination and plant development. *Biological Agriculture & Horticulture*, 32(4), 237–247.

Gentile, R., et al. 2009. Managing N availability and losses by combining fertilizer-N with different quality residues in Kenya. *Agriculture, Ecosystems & Environment*, 131(3–4), 308–314.

Gómez-Brandón, M. and Domínguez, J. 2014. Recycling of solid organic wastes through vermicomposting: microbial community changes throughout the process and use of vermicompost as a soil amendment. *Critical Reviews in Environmental Science and Technology*, 44(12), 1289–1312.

Gómez-Brandón, M., et al. 2020. Vermicomposts are biologically different: microbial and functional diversity of green vermicomposts. *Earthworm Assisted Remediation of Effluents and Wastes*, 125–140.

Gómez-Brandón, M., et al. 2021. Changes in the nutrient dynamics and microbiological properties of grape marc in a continuous-feeding vermicomposting system. *Waste Management*, 135, 1–10.

González, A.B.M., et al. 2024. Earthworms and microplastics: transport from sewage sludge to soil, antibiotic-resistant genes, and soil remediation. in: *Earthworm technology in organic waste management*, Elsevier, pp. 207–229.

Gopalakrishnan, S., et al. 2011. Evaluation of actinomycete isolates obtained from herbal vermicompost for the biological control of Fusarium wilt of chickpea. *Crop Protection*, 30(8), 1070–1078.

Gougoulias, C., et al. 2014. The role of soil microbes in the global carbon cycle: tracking the below-ground microbial processing of plant-derived carbon for manipulating carbon dynamics in agricultural systems. *Journal of the Science of Food and Agriculture*, 94(12), 2362–2371.

Hijikata, N., et al. 2015. Suitability of biochar as a matrix for improving the performance of composting toilets. *Waste Management & Research*, 33(4), 313–321.

Hinsinger, P. 2001. Bioavailability of soil inorganic P in the rhizosphere as affected by root-induced chemical changes: a review. *Plant and Soil*, 237(2), 173–195.

Hou, S., et al. 2023. Role of vermicompost and biochar in soil quality improvement by promoting Bupleurum falcatum L. nutrient absorption. *Soil Use and Management*, 39(4), 1600–1617.

Hřebečková, T., et al. 2019. Changes of enzymatic activity during a large-scale vermicomposting process with continuous feeding. *Journal of Cleaner Production*, 239, 118127.

Huang, C., et al. 2020. Role of biochar and Eisenia fetida on metal bioavailability and biochar effects on earthworm fitness. *Environmental Pollution*, 263, 114586.

Intani, K., et al. 2018. Phytotoxicity of corncob biochar before and after heat treatment and washing. *Sustainability*, 11(1), 30.

Ismail, Z.I. 2004. New machine set to boost palm kernel cake industry. *Business Times*.

Kalu, S., et al. 2024. Biochar reduced the mineralization of native and added soil organic carbon: evidence of negative priming and enhanced microbial carbon use efficiency. *Biochar*, 6(1), 7.

Kolbe, A.R., et al. 2019. Bacterial succession and functional diversity during vermicomposting of the white grape marc Vitis vinifera v. Albariño. *Scientific Reports*, 9(1), 7472.

Kołtowski, M. and Oleszczuk, P. 2015. Toxicity of biochars after polycyclic aromatic hydrocarbons removal by thermal treatment. *Ecological Engineering*, 75, 79–85.

Lauber, C.L., et al. 2009. Pyrosequencing-based assessment of soil pH as a predictor of soil bacterial community structure at the continental scale. *Applied and Environmental Microbiology*, 75(15), 5111–5120.

Lazcano, C. and Domínguez, J. 2011. The use of vermicompost in sustainable agriculture: impact on plant growth and soil fertility. *Soil Nutrients*, 10(1–23), 187.

Lehmann, J., et al. 2020. The concept and future prospects of soil health. *Nature Reviews Earth & Environment*, 1(10), 544–553.

Lévesque, V., et al. 2018. Mitigation of CO_2, CH_4 and N_2O from a fertigated horticultural growing medium amended with biochars and a compost. *Applied Soil Ecology*, 126, 129–139.

Li, J., et al. 2024. Optimizing biochar addition strategies in combined processes: Comprehensive assessment of earthworm growth, lignocellulose degradation and vermicompost quality. *Bioresource Technology*, 406, 131031.

Li, Y., et al. 2020. Soil, biochar, and nitrogen loss to runoff from loess soil amended with biochar under simulated rainfall. *Journal of Hydrology*, 591, 125318.

Liu, T., et al. 2014. The cytotoxic and genotoxic effects of metalaxy-M on earthworms (Eisenia fetida). *Environmental Toxicology and Chemistry*, 33(10), 2344–2350.

Lv, B., et al. 2020. Elucidating the role of earthworms in N_2O emission and production pathway during vermicomposting of sewage sludge and rice straw. *Journal of Hazardous Materials*, 400, 123215.

Ma, H., et al. 2022. Vermicompost improves physicochemical properties of growing medium and promotes plant growth: a meta-analysis. *Journal of Soil Science and Plant Nutrition*, 22(3), 3745–3755.

Mosa, A., et al. 2023. Biochar as a soil amendment for restraining greenhouse gases emission and improving soil carbon sink: Current situation and ways forward. *Sustainability*, 15(2), 1206.

Neina, D. 2019. The role of soil pH in plant nutrition and soil remediation. *Applied and Environmental Soil Science*, 2019(1), 5794869.

Odinga, E.S., et al. 2021. Occurrence, formation and environmental fate of polycyclic aromatic hydrocarbons in biochars. *Fundamental Research*, 1(3), 296–305.

Oranratmanee, M. and Tungittiplakorn, W. 2021. Application of biochar for cadmium stabilization in contaminated paddy soil. *E3S Web of Conferences*. *EDP Sciences*. pp. 02021.

Panzarino, O., et al. 2016. Rank-based biomarker index to assess cadmium ecotoxicity on the earthworm Eisenia andrei. *Chemosphere*, 145, 480–486.

Paul, S., et al. 2020. Biogenic stabilization and heavy metal immobilization during vermicomposting of vegetable waste with biochar amendment. *Journal of Hazardous Materials*, 390, 121366.

Plaza, C., et al. 2008. Organic matter humification by vermicomposting of cattle manure alone and mixed with two-phase olive pomace. *Bioresource Technology*, 99(11), 5085–5089.

Pokharel, P., et al. 2020. Biochar increases soil microbial biomass with changes in extra- and intracellular enzyme activities: a global meta-analysis. *Biochar*, 2, 65–79.

Qiang, G.X., et al. 2018. Bamboo biochar amendment improves the growth and reproduction of Eisenia fetida and the quality of green waste vermicompost. https://doi.org/10.1016/j.ecoenv.2018.03.023.

Qiu, Z., et al. 2020. Remediation of cadmium-contaminated soil with biochar simultaneously improves biochar's recalcitrance. *Environmental Pollution*, 256, 113436.

Rasul, M., et al. 2022. Biochar-induced priming effects in soil via modifying the status of soil organic matter and microflora: a review. *Science of the Total Environment*, 805, 150304.

Razzaghi, F., et al. 2020. Does biochar improve soil water retention? A systematic review and meta-analysis. *Geoderma*, 361, 114055.

Rehman, S.u., et al. 2023. Vermibiochar: a novel approach for reducing the environmental impact of heavy metals contamination in agricultural land. *Sustainability*, 15(12), 9380.

Rivelli, A.R. and Libutti, A. 2022. Effect of biochar and inorganic or organic fertilizer co-application on soil properties, plant growth and nutrient content in Swiss chard. *Agronomy*, 12(9), 2089.

Roy, S., et al. 2022. Assessing the arsenic-saturated biochar recycling potential of vermitechnology: insights on nutrient recovery, metal benignity, and microbial activity. *Chemosphere*, 286, 131660.

Sanchez-Hernandez, J.C. 2018. Biochar activation with exoenzymes induced by earthworms: a novel functional strategy for soil quality promotion. *Journal of hazardous materials*, 350, 136–143.

Sanchez-Hernandez, J.C. and Domínguez, J. 2017. Vermicompost derived from spent coffee grounds: assessing the potential for enzymatic bioremediation. in: *Handbook of coffee processing by-products*, Elsevier, pp. 369–398.
Sanchez-Hernandez, J.C., et al. 2019. Biochar and earthworms working in tandem: Research opportunities for soil bioremediation. *Science of the Total Environment*, 688, 574–583.
Shi, Z., et al. 2021. Effects of biochar and thermally treated biochar on Eisenia fetida survival, growth, lysosomal membrane stability and oxidative stress. *Science of The Total Environment*, 770, 144778.
Siedt, M., et al. 2021. Comparing straw, compost, and biochar regarding their suitability as agricultural soil amendments to affect soil structure, nutrient leaching, microbial communities, and the fate of pesticides. *Science of the Total Environment*, 751, 141607.
Sinha, R.K., et al. 2010. Earthworms–the environmental engineers: review of vermiculture technologies for environmental management and resource development. *International Journal of Global Environmental Issues*, 10(3–4), 265–292.
Solaiman, Z.M., et al. 2012. Biochars influence seed germination and early growth of seedlings. *Plant and Soil*, 353, 273–287.
Tang, R., et al. 2017. Metabolic responses of Eisenia fetida to individual Pb and Cd contamination in two types of soils. *Scientific Reports*, 7(1), 13110.
Toor, M.D., et al. 2024. Vermicompost rate effects on soil fertility and morpho-physio-biochemical traits of lettuce. *Horticulturae*, 10(4), 418.
Vambe, M., et al. 2023. Potential role of vermicompost and its extracts in alleviating climatic impacts on crop production. *Journal of Agriculture and Food Research*, 12, 100585.
Vijay, V., et al. 2021. Review of large-scale biochar field-trials for soil amendment and the observed influences on crop yield variations. *Frontiers in Energy Research*, 9, 710766.
Vyas, P., et al. 2022. Vermicomposting with microbial amendment: implications for bioremediation of industrial and agricultural waste. *BioTechnologia*, 103(2), 203.
Wang, F., et al. 2021. Biochar and vermicompost improve the soil properties and the yield and quality of cucumber (Cucumis sativus L.) grown in plastic shed soil continuously cropped for different years. *Agriculture, Ecosystems & Environment*, 315, 107425.
Wang, H.-T., et al. 2020. The effect of biochar on soil-plant-earthworm-bacteria system in metal (loid) contaminated soil. *Environmental Pollution*, 263, 114610.
Whalen, J.K. and Benslim, H. 2021. Earthworm populations are stable in temperate agricultural soils receiving wood-based biochar. *Pedosphere*, 31(3), 398–404.
Wu, X., et al. 2023. Earthworms enhance the bioremediation of tris (2-butoxyethyl) phosphate-contaminated soil by releasing degrading microbes. *Journal of Hazardous Materials*, 452, 131303.
Xu, C. and Mou, B. 2016. Vermicompost affects soil properties and spinach growth, physiology, and nutritional value. *HortScience*, 51(7), 847–855.
Xu, R.-K., et al. 2011. Adsorption of methyl violet from aqueous solutions by the biochars derived from crop residues. *Bioresource Technology*, 102(22), 10293–10298.
Yang, D., et al. 2017. Potential benefits of biochar in agricultural soils: a review. *Pedosphere*, 27(4), 645–661.

Yatoo, A.M., et al. 2021. Sustainable management of diseases and pests in crops by vermicompost and vermicompost tea. A review. *Agronomy for Sustainable Development*, 41(1), 7.

Zeiss, R., et al. 2022. Challenges of and opportunities for protecting European soil biodiversity. *Conservation Biology*, 36(5), e13930.

Zhang, F., et al. 2020. Influences of a vermicompost application on the phosphorus transformation and microbial activity in a paddy soil. *Soil & Water Research*, 15(4), 19–9210.

Zhang, L. and Sun, X. 2014. Effects of rhamnolipid and initial compost particle size on the two-stage composting of green waste. *Bioresource Technology*, 163, 112–122.

Zhang, M., et al. 2017. Effects of straw and biochar amendments on aggregate stability, soil organic carbon, and enzyme activities in the Loess Plateau, China. *Environmental Science and Pollution Research*, 24, 10108–10120.

Zhang, M., et al. 2023. Effects of biochar and vermicompost on growth and economic benefits of continuous cropping pepper at karst yellow soil region in Southwest China. *Frontiers in Plant Science*, 14, 1238663.

Zhang, Q. et al. 2019. Effects of biochar on the earthworm (Eisenia foetida) in soil contaminated with and/or without pesticide mesotrione. *Science of The Total Environment*, 671, 52–58.

Zhang, Y. et al. 2022a. Soil Acidification caused by excessive application of nitrogen fertilizer aggravates soil-borne diseases: Evidence from literature review and field trials. *Agriculture, Ecosystems & Environment*, 340, 108176.

Zhang, Z. et al. 2022b. Environmental impacts of hazardous waste, and management strategies to reconcile circular economy and eco-sustainability. *Science of The Total Environment*, 807, 150856.