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Vermicomposting for climate change mitigation and sustainable soil health: Organic waste management, nitrogen use efficiency, and ecosystem services

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ABSTRACT

Environmental and agricultural systems are under constant threat from the ever-increasing amounts of eco-agricultural waste, which is the primary focus of this review. By utilizing scientific and environmentally friendly techniques to reuse and recycle organic waste, proper management can help reduce waste. This analysis assessed the potential of earthworm species in agriculture and the role of vermicompost in the long-term recycling of crop nutrients, specifically nitrogen (N) recovery, which is at 76%. Sustainable organic farming relies on a scientific understanding of organic material management and nitrogen use efficiency through the application of vermicompost. The emphasis is on reusing and recovering nutrients from vermicompost at carbon-to-nitrogen ratios of 10 - 23, which reduces emissions of reactive nitrogen gases, achieves soil fertility, and allows the application of fertilizers made from sustainable sources. Vermicompost improves the soil's properties and mitigates the adverse effects of global warming. Based on literature reviews and numerous trials, a proposal has been put forth to emphasize the importance of vermicomposting technology in agroecosystems. Reducing pollution, improving waste management, and lowering health hazards are all significant issues that could play an important role. In conclusion, vermicompost is a win-win technology for sustaining today's agricultural system. It enhances soil properties, increases land productivity, and reduces greenhouse gas emissions by decreasing chemical fertilizers.

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1. INTRODUCTION

Vermicomposting (VC) has become phenomenally celebrated among soil biologists as the process that can create an ecological resilience in soil and at the same time mitigate the effects of climate change. To improve agricultural land productivity and feed the world's expanding population, nitrogen (N) is essential for all living organisms (Bhatt et al., 2025; Wang, 2022). Nitrogen losses occur through several channels when inorganic fertilizers are used excessively to meet food supply demands (S. Cai et al., 2025). Among these are the significant environmental issues of ammonia vaporization, leakage, and emissions of greenhouse gases (Wang et al., 2023; Zhang et al., 2016). In recent decades, chemical fertilizers have become an increasing problem for food production. Emerging nations will account

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for 85% of the world's projected 260 Tg N nitrogen use by 2050 (Mogollón et al., 2018). By 2022, the FAO predicts the global need for nitrogen fertilizers will reach approximately 112 M tons. Manure and sewage sludge, organic waste products, have become increasingly problematic due to the rapid growth of the cattle breeding industry (Raza et al., 2022; Shamsuddoha & Nasir, 2024). Statistics show that cattle excreted 7 B tons of manure, resulting in the loss of many naturally occurring carbon, phosphorus, potassium, nitrogen (NPK), and other fertilizers (van den Broek et al., 2024). This amount is 3.4 times the amount of manure produced by industries nationwide. Fertilizer losses in China typically range from 8% to 20%, while phosphate losses are at 5% (Santolin et al., 2024). Based on this data, animal manure's nitrogen and phosphorus losses are approximately one-and-a-half times greater than those in chemical fertilizers (Guo et al., 2020). The inherent fertility of soils can be improved by reusing agricultural waste products containing macro and micronutrients instead of synthetic fertilizers, and if necessary, only on the basis of soil testing of scientifically collected samples (Raza et al., 2022). Research into the direct or indirect use of crop residues, surplus manure from various animals (including pigs and cows), and other similar materials such as nano-biochar is currently highly active (N. V. Kumar et al., 2025; Ndoung et al., 2021). Organic materials have an impact on renovating cultivable areas in different climates (Colombi et al., 2025).

The FAO classifies regosols (purplish soil) as soils with low organic carbon and moderate nutrient content. They cover about 7% of the arable land in hilly areas that provide nearly 10% of the country's food supply, making them critical for subtropical agriculture (P. Zhang et al., 2021). Organic fertilisers are still very important in these systems, but for farming to be sustainable, it is just as important to recycle crop residues from previous research and field trials (Khan et al., 2024). Microbes and earthworms working together can make organic matter and stabilise it without using heat (Kauser & Khwairakpam, 2022). In addition, biochar, a carbon-rich amendment that improves soil fertility and helps slow down global warming, can be made from various feedstocks (Fu et al., 2023; Hajam et al., 2023; Iwuozor et al., 2023; F. Wang et al., 2021).

Organic inputs like vermicompost and biochar improve the soil's quality and help plants grow (Fitriani et al., 2020; Oyege & Balaji Bhaskar, 2023). Vermiculture, in particular, is well-known for using organic waste to raise earthworms on a large scale. This practice has spread to many countries, including Australia, the United States, Brazil, China, and others (Edwards & Arancon, 2022a; Oyege & Balaji Bhaskar, 2023). Although the majority of studies on soil quality have focused on physicochemical properties and their correlation with plant growth (Vasu et al., 2024), biological factors, particularly in organic farming and vermicomposting in mountainous environments, are still inadequately investigated (Raza et al., 2022).

Earthworms are ecological engineers that convert organic residues such as animal and crop residues into compost (Kumar et al., 2023; Lavelle & Spain, 2024; Singh & Sinha, 2022), lowering the C:N ratio (Enebe & Erasmus, 2023b), loaded with nutrients (Enebe & Erasmus, 2023b; Mago et al., 2021; Shafique et al., 2023), which further improves the grain yields (Guo et al., 2015; Ratsiatosika et al., 2024). Vermicompost improves soil health, yields, biodiversity, enzyme activity, and microbial growth (Dume, Hanč, et al., 2023; Manzoor et al., 2024; Oyege & Balaji Bhaskar, 2023; Yang et al., 2023). Earthworms' activity enhances plant growth and salinity tolerance (Hodson et al., 2023; Hossain et al., 2025; Xu et al., 2016). Vermicompost is used for household waste such as vegetables, etc., to sustainable compost (Alshehrei & Ameen, 2021; Pirsaheb et al., 2013) and also repels pests and functions as a bioreactor through gut microbes (Ahmed & Al-Mutairi, 2022; Aira et al., 2007; Mohite et al., 2024).

Microorganisms in soil ecosystems are considered important parts of ecological processes because they affect nutrient cycling, primary productivity, soil structure, and the health of the whole ecosystem (Chen et al., 2024; García-Sánchez & Száková, 2016). Soil microbes, especially when working with earthworms, help with vermicomposting by breaking down agricultural waste mixed with manure. This step improves the biological properties of the soil while reducing greenhouse gas emissions and climate effects (Ratsiatosika et al., 2024). Vermicomposting is a biotechnological improvement over traditional composting because it uses earthworms (*Eisenia fetida*) to break down organic waste. The worms eat the leftovers and then poop out casts (worm manure), which stay stable between 10°C and 32°C (Rehman et al., 2023; Usta & Guven, 2024). Nevertheless, the interactions among nutrient-dense substrates, surplus crop residues, ammonia volatilisation, and greenhouse gas emissions in upland systems necessitate further examination (Raza et al., 2024). Research in environmental waste management has examined various methodologies, including waste management models, CO_2 recovery from composting, biochar-based fertilisers, enthalpy-driven food waste decomposition, and microbial digestion of animal excreta (Wang & Tester, 2023). With this introductory understanding, the long-term utilization of diverse organic wastes and residues can be better promoted in a sustainable and climate-smart way. Accordingly, this review article, supported by meta-analysis tables, has been systematically organized around specific objectives: (i) to examine the role of earthworms in ecosystems and soil ecology; (ii) to assess the influence of VC on the physical, chemical, and biological properties of soil; (iii) to evaluate the potential of VC in mitigating the impacts of global warming; (iv) to identify the key factors influencing earthworm activity; (v) to highlight the importance of VC in improving soil fertility and crop productivity; (vi) to analyze VC's role in nutrient recovery and recycling; (vii) to explore VC as an organic fertilizer; and (viii) to critically assess both the pros and cons of VC. Overall, this review is enriched with meta-analysis, highlighting the significant contribution of VC in enhancing soil health and crop yields while simultaneously alleviating the adverse consequences of global warming in the region.

2. Value of earthworms in the ecosystem and soil ecology

Earthworms have a variety of vital tasks in ecological systems that support climate-smart and sustainable agriculture practices.

2.1. Role of earthworms in the ecosystem

Earthworms played an important role in ecosystem services *viz.,* soil aeration, nutrient cycling, soil structure improvement, increased soil fertility, pest control, decomposition, soil erosion prevention, water regulation, carbon sequestration, biodiversity support, soil pH regulation, seed dispersal, recreational value, educational value, and reduced greenhouse gas emissions (Table 1) as already shown by different researchers across the globe. Earthworms are also known as the "intestines of the earth" by Aristotle (384 - 322 BCE). Earthworm castings have high nutrient availability for plant growth (Van Groenigen et al., 2019). Earthworms are thought to reduce N_2O emissions during vermicomposting (C. Zhang et al., 2023). The quality of the substrate is altered and influenced by nutrients such as carbon (C) and nitrogen (N) (Zhang et al., 2018). It has been shown that epigeous worms are adept at turning solid organic materials into manure. These invertebrates effectively prepare compost. Previous research studies have documented vermicomposting techniques and various substrates (Enebe & Erasmus, 2023b). There is a decrease in heavy metal sludge because earthworms require heavy metals to reproduce (Yadav et al., 2023). Vermicompost can be consistently produced by earthworms fed at a 2.5 - 3.5 kg^{-1} density without affecting the soil or agricultural ecology.

Vermicomposting of biodegraded materials can be used to evaluate soil properties and patchouli development (Singh et al., 2013). In terms of physico-chemical parameters, the bio-inoculated vermicompost performed better in the experiment than the control treatment, compost bio-inoculants, traditional vermicompost, application of chemical fertilizers, and vermicompost inoculants, among five treatments. Earthworms play an important role in soil fertility of organic substrate (Table 1) (Ahmed & Al-Mutairi, 2022). Vermi worms are associated with the phylum Annelida; in controlled nitrogen (N) emissions in earthworm-tilled soils to examine soil moisture (Hajam et al., 2023). Although vermicomposting has many advantages, there is also a significant drawback. Earthworm activity can dissolve humus present in soil, which has both advantageous and disadvantageous effects (M. Kumar et al., 2025). The release of nutrients is accelerated by earthworms and bacteria (Medina-Sauza et al., 2019). Earthworms enhance their inherent fertility and nutritional content by improving the soil's physical, chemical, and biological properties (Ahmed & Al-Mutairi, 2022).

Chemicals released by earthworms lead to the synthesis of siderophores and the solubilization of phosphates (Chiba et al., 2024; Pathma & Sakthivel, 2013). Besides controlling plant metabolism and ionic absorption, phytohormones and hormone-like substances activate enzymes (Ahmed & Al-Mutairi, 2022). Modulating soil characteristics is difficult and has numerous methods. Humus and clays, which adsorb organic molecules and impede plant growth. These processes enhance plant growth. Clayey soils with substantial structures react differently to earthworm casts (Clause et al., 2016). Basically, earthworm casts are their waste from breaking down organic matter. Granular, tower-shaped, single-mass, and spherical earthworm casts are formed. Last cast structures are smaller and lighter than the first three, which are heavier and more compact. Vermicomposting has two steps: cast-linked and gut-linked. Earthworms help plants flourish. Earthworms' symbiotic actions enhance low soil textures, accelerating plant growth (Ahmed & Al-Mutairi, 2022). Earthworms transform waste organic materials into compost and vermicompost, lowering chemical fertilisers and greenhouse gas (GHG) emissions (Singh & Sinha, 2022).

2.2. Role of Earthworms in the Soil Ecology

In hilly regions, the variety of soil fauna is greater, with species such as acari, millipedes, termites, earthworms, *etc*. Earthworms and termites help break down chaetae and are the most abundant animals in the terrestrial ecosystem, with over 3,000 species present in most soils (Bora et al., 2021). These invertebrates aerate and enrich the soil by tilling or ploughing it. Earthworms help combat pollution by detoxifying heavy metals, agrochemicals, and some toxic substances in their stomach" (Šrut et al., 2019). The ecological roles that different earthworm species play in soil, such as their contributions to the decomposition of organic matter, the cycling of nutrients, and the creation of soil, vary (Table 1). The epigeic earthworms such as *E. fetida*, *Eisenia eugeniae*, and *Perionyx excavatus* are more effective in this process than anecic or endogeic earthworms.

2.3. Role of earthworms in the enzyme activity

Vermicomposting is a mesophilic process that requires temperatures between 10°C and 32°C. With the assistance of enzymes and microorganisms, the process of transforming trash into vermicompost in the stomachs of the worms is far faster than the process of traditional composting. Microbial biomass and enzymes are crucial elements of the vermicomposting process. There are other enzymes that are sensitive to earthworm activity, even though invertase and urease are frequently reported indicators. Invertase catalyses the hydrolysis of sucrose into glucose and fructose, while urease is a useful predictor of vermicompost maturity and nitrogen stabilization (Sudkolai & Nourbakhsh, 2017). Additionally, earthworms have an impact on a wider variety of soil enzymatic processes, such as those related to the phosphorus and sulphur cycles (such as phosphatases and arylsulfatase). In earthworm-mediated systems, these enzymes often become more active, indicating improved organic matter mineralization and nutrient cycling during vermicomposting.

An investigation that compared the urease activity that occurs during the process of vermicomposting to that which occurs in farmyard waste revealed that the vermicomposting process results in much higher levels of urease activity (Raza et al., 2024). The treatment of organic waste involves the application of vermicompost and rock dust, as well as the incorporation of sewage water as an inoculant.

Table 1. Ecosystem services provided by earthworms.

Sr. No	Ecosystem Service	Category	Description	References
1	Soil Aeration	Regulating service	Earthworms burrow tunnels to exchange gases like oxygen and carbon dioxide, improving soil aeration and the plants' rhizosphere.	Arrázola-Vásquez et al. (2022)
2	Nutrient Cycling	Supporting service	Earthworms digest plant and animal waste to generate nutrient-rich casts that plants may use. This process decomposes organic matter and cycles nitrogen, phosphorus, and potassium.	Edwards and Arancon (2022d)
3	Soil Structure Improvement	Supporting service	Earthworm activity helps break down soil aggregates and mix organic matter with mineral particles, improving soil structure.	Q. Zhang et al. (2021)
4	Increased Soil Fertility	Supporting service	Earthworm casts increase soil fertility and microbiological activity by adding nutrients. This boosts ecosystem plant growth and productivity.	Ahmed and Al-Mutairi (2022)
5	Pest Control	Regulating service	Earthworms consume various soil-dwelling pests such as nematodes, larvae, and small insects, helping to regulate their populations. This natural form of pest control can reduce the need for chemical pesticides in agricultural systems.	Gudeta et al. (2021)
6	Decomposition	Regulating service	Earthworms break down carbon-based chemicals, plant leftovers, and dead organic material for microbes to digest. This accelerates nutrient recycling and builds soil organic matter.	Dinesh et al. (2022)
7	Soil Erosion Prevention	Regulating service	Earthworm burrows and casts reinforce soil aggregates, decreasing water and wind erosion. Earthworms prevent and conserve soil erosion by increasing soil structure and vegetation development.	Sharma et al. (2017)
8	Water Regulation	Regulating service	Earthworm burrows improve soil water infiltration, storage, and drainage. This controls soil moisture, reducing ecosystem damage from droughts and floods.	Hallam and Hodson (2022)
9	Carbon Sequestration	Regulating service	Earthworms decompose plant leftovers and generate stable organic matter, which helps soil absorb organic carbon. Long-term soil carbon sequestration reduces atmospheric carbon dioxide, mitigating climate change.	Thomas et al. (2020)
10	Biodiversity Support	Supporting service	Earthworms feed birds, rodents, and insects, supporting higher trophic levels in terrestrial environments. Their presence affects soil microbial diversity and composition.	Prendergast-Miller et al. (2021)
11	Soil pH Regulation	Regulating service	Earthworm feeding and casting change ion availability, affecting soil pH. It depends on soil conditions and earthworm species, but they usually maintain a plant-friendly pH.	Desie et al. (2020)
12	Seed Dispersal	Supporting service	Earthworms transfer seeds through their digestive tracts and deposit them with their casts to disperse them. This aids plant regeneration and colonization in varied settings.	Clause et al. (2016)
13	Recreational Value	Cultural service	Earthworms serve as bait for fishing, making them valuable to recreational anglers and providing opportunities for leisure activities.	Klein et al. (2020)
14	Educational Value	Cultural service	Studying earthworm ecology and behavior provides insights into ecosystem dynamics, soil health, and the importance of biodiversity conservation.	Paul et al. (2022)
15	Vermicompost	Provisioning service	Earthworms convert organic waste into nutrient-rich vermicompost, which can be used as an organic fertilizer to enrich soil fertility and improve crop yield.	Singh et al. (2020)
16	Reduced GHG emissions	Regulating service	Earthworms speed soil organic matter (SOM) mineralization, which may increase CO_2 emissions. Earthworms improve soil oxygen penetration and methanotroph activity, reducing methane (CH_4) emissions.	John et al. (2020)

An experiment on vermicomposting that involves the combination of organic waste with a mixture of sawdust and inorganic waste, which may include tannery sludge, is most effective when carried out outside Poornima et al. (2024). Because sewage water contains vermicompost, which is a resource that is abundant in nutrients, it can be used for inoculation. Compost made from worms, which is formed from agricultural waste, is a great source of organic compost and supplies vital nutrients (Sheer et al., 2024).

3. Effect of vermicompost on soil properties

3.1. Vermicompost effects on the physical properties of soils

Vermicompost, often called "black gold" in agriculture, is produced by earthworms' decomposition of organic materials (Gabur et al., 2024; Lei et al., 2024). This compost is not only beneficial for plant development but also has a profound impact on the physical properties of soils (Table 2) (Fig. 1) (Ma et al., 2022). In this review, we will explore the effects of vermicompost on soil physical properties and how it contributes to soil health and productivity. Firstly, vermicompost enhances soil structure by improving aggregation and porosity. The organic matter in vermicompost acts as a binding agent, promoting the formation of stable soil aggregates. These aggregates create pore spaces in the soil, allowing for better air and water infiltration and drainage. As a result, soils amended with vermicompost exhibit improved water retention capacity, reducing the risk of waterlogging during heavy rainfall and enhancing drought tolerance during dry periods.

Table 2. Meta-analysis table for vermicompost and its effect on soil physical properties.

S. No.	Location	Crop	Soil Type	Description	References
1.	Agricultural location, Hamedan province, Iran	-	Soil texture-impact	Vermicompost improved the different soils' physical properties and improved the soil health.	Safadoust et al. (2025)
2.	Hindu College Farm, Guntur, Tamil Nadu, India	Black gram (*Vigna mungo*)	Clay loam, sandy loam soil.	Applying vermicompost (2.5 to 15 t ha^{-1}) improved the soil's pore space in all soil types, especially clay loam.	Vennela et al. (2024)
3.	India	-	Sandy loam soil	Vermicompost-treated soil had lower bulk density due to increased microbial population and activity, which produced aggregates and increased soil porosity.	Saha et al. (2022)
4.	Italy	-	Clay loam soil	Plant available water of coarse-textured soil was enhanced from an average initial value of 0.056 to an optimal value of 0.15 cm^3 cm^{-3} when vermicompost was added at about one-third by volume (34 %).	Castellini et al. (2024)
5.	South Africa	-	Climate change mitigation	Vermicompost improves soil physical properties, yields during the era of climate change.	Vambe et al. (2023)
6.	China	Tomato (Lycopersicon esculentum L.)	-	Vermicompost improves the soil physical properties, which are further seen in crop quality and enhanced sugar/acid ratio.	Wang et al. (2017)
7.	India	-	Silty loam	Vermicompost increases the porosity and infiltration rate of the soil, which helps with salt leaching.	Srivastava et al. (2016)
8.	Turkey	-	Sandy loam	Applying 4% vermicompost raised the stability of the soil's wet aggregate from 26·9% to 52·2%.	Aksakal et al. (2016)
9.	Egypt	Wheat (Triticum aestivum)	Saline sodic soil	Vermicompost and water treatment residuals improved soil physical qualities together, making them ideal for salinity-impacted soils.	Ibrahim et al. (2015)
10.	Czech Republic	-	-	Because humic acid affects soil structure, vermicompost improves the soil's physical qualities, including bulk density, porosity, aggregate formation, and electrical conductivity.	Hanc and Vasak (2015)
11.	Malayer University greenhouse for three months, Iran	Medicago polymorpha	Sand, clay, and loam in a 2:1:1 ratio	Vermicomposting affected soil pH, bulk density, and electrical conductivity. Higher vermicompost rates improved soil pH and EC and reduced bulk density.	Akhzari et al. (2015)
12.	India	-	Sandy loam	Vermicompost-amended soils had a significantly ($P \leq 0.05$) lower soil bulk density than control plots.	Singh et al. (2017)
13.	Turkey	-	Sandy clay loam	After treating soils with 5% vermicompost, notable improvements were seen in soil physical properties.	Demir (2019)
14.	Iran	-	Clay	Over time, vermicompost enhances the soil's chemical and physical characteristics, primarily in the uppermost soil layers.	Pasha et al. (2020)
15.	Wasit, Iraq	Potato	Clay Loam	Increasing vermicompost application improved soil pH and EC and reduced bulk density.	Al-Maamori et al. (2023)

Moreover, vermicompost enhances soil aeration, which is essential for root respiration and nutrient uptake by plants (Table 2) (Xu & Mou, 2016). The digging activity of earthworms aerates the soil, creating channels and tunnels that facilitate the free movement of air and water. This increased soil aeration promotes the growth of beneficial soil microorganisms, such as bacteria and fungi, which play crucial roles in nutrient cycling and organic matter decomposition. Consequently, soils amended with vermicompost exhibit higher microbial activity and biodiversity, improving soil fertility and resilience. Another important physical property influenced by vermicompost is soil compaction. Compacted soils have poor porosity and drainage, resulting in restricted root growth and reduced plant productivity. Vermicompost helps alleviate soil compaction by improving soil structure and increasing aggregate stability.

The organic matter in vermicompost acts as a sponge, absorbing excess moisture and preventing soil particles from compacting tightly together. Additionally, the secretions of earthworms contain enzymes that break down compacted soil particles, further improving soil friability and tilth. Furthermore, vermicompost contributes to soil erosion control by enhancing soil stability and surface cover. The formation of soil aggregates and the presence of organic matter in vermicompost help bind soil particles together, reducing the susceptibility of soils to erosion by wind and water.

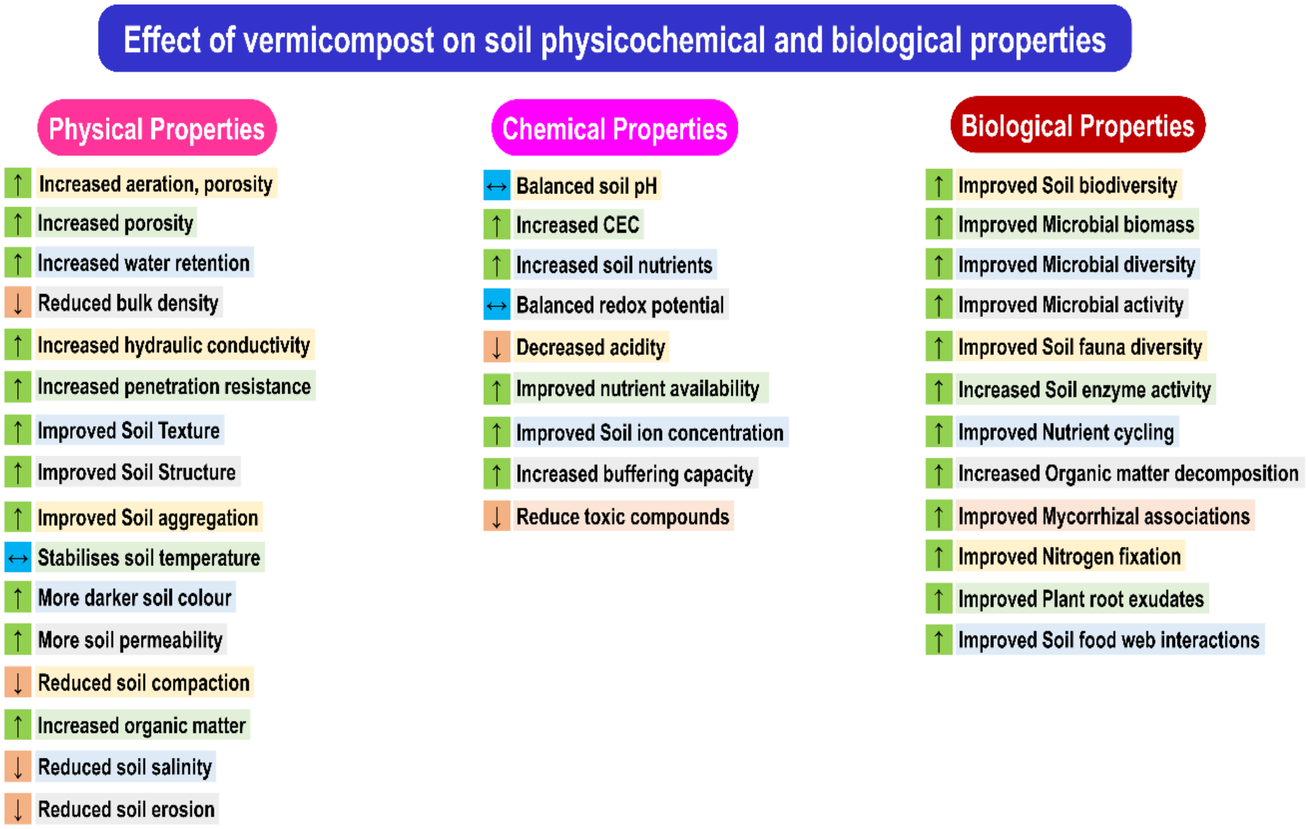

Figure 1. Vermicompost vis-à-vis soil physicochemical and biological properties.

Additionally, vegetation growth in soils amended with vermicompost provides extra surface cover, further reducing erosion risk. As a result, vermicompost plays a vital role in soil conservation efforts, particularly in areas prone to erosion and degradation. Furthermore, vermicompost has been shown to suppress soil-borne pathogens and pests, contributing to plant health and disease resistance. The beneficial microorganisms in vermicompost produce antagonistic compounds that inhibit the growth and proliferation of harmful pathogens, such as fungi, nematodes, and bacteria. Moreover, the humic substances in vermicompost stimulate plant defence mechanisms, enhancing resistance to diseases and pests. Consequently, soils amended with vermicompost exhibit a reduced incidence of plant diseases and improve overall plant vigor and productivity. Vermicompost positively affects soil physical properties, including improved structure, aeration, water retention, compaction resistance, erosion control, and disease suppression. By enhancing soil health and fertility, vermicompost promotes sustainable agriculture practices and contributes to the conservation of natural resources (Hossain et al., 2025; Mohite et al., 2024; Oyege & Balaji Bhaskar, 2023). Incorporating vermicompost into soil management strategies can help optimize soil physical properties, leading to healthier, more productive soils and resilient ecosystems.

3.2. Vermicompost effects on chemical properties of soils

Compost, the organic fertilizer produced through the decomposition of organic materials by earthworms, exerts profound effects on soil chemical properties (Table 3) (Bhunia et al., 2021). This nutrient-rich compost improves soil fertility and enhances nutrient availability, pH balance, and cation exchange capacity (CEC), promoting plant growth and productivity. This review will explore how vermicompost influences soil chemical properties and contributes to soil health. Firstly, vermicompost enriches soil fertility by supplying essential plant nutrients in a readily available form. The vermicompost's organic matter serves as a nutrient reservoir, including macro- and micronutrients. These nutrients are released slowly over time as the organic matter decomposes, providing a continuous and balanced supply to plants. Furthermore, the digestive processes of earthworms enhance nutrient mineralization and transformation, making nutrients more accessible to plants. Consequently, soils amended with vermicompost exhibit higher levels of nutrient availability, promoting healthier plant development (Table 3) (Oyege & Balaji Bhaskar, 2023). Moreover, vermicompost influences soil pH, helping maintain optimal plant growth conditions (Manzoor et al., 2024; Oyege & Balaji Bhaskar, 2023). The decomposition of organic matter in vermicompost releases organic acids and bases, which can buffer soil pH and prevent excessive fluctuations (Table 3) (Pizzanelli et al., 2023).

Additionally, calcium carbonate ($CaCO_3$) in some vermicompost can neutralize soil acidity and raise pH levels in acidic soils. Conversely, the acidic nature of vermicompost can lower pH in alkaline soils, helping to create a more favourable pH range for plant nutrient uptake. By regulating soil pH, vermicompost ensures that essential nutrients remain in their most plant-available forms, contributing to improved nutrient uptake and plant utilization.

Table 3. Meta-analysis table for vermicompost and its effect on soil chemical properties.

Sr. No.	Location	Crop	Soil Type	Description	References
1.	China	-	-	The addition of vermicompost enhanced the soil's available P content by promoting microbial activity in lateritic soils.	Tian et al. (2024)
2.	USA	-	-	Vermicompost improves soil chemical properties, increases nutrient availability, and boosts crop productivity.	Oyege and Balaji Bhaskar (2023)
3.	India	-	-	Applying vermicompost at a 7.5 t/ha rate increased the soil's available nitrogen and organic carbon content.	Pooja et al. (2022)
4.	South Africa	-	-	Vermicomposting significantly downregulated toxic metals to levels below the optimum permissible limit of potentially toxic elements in the soil.	Mupondi et al. (2018)
5.	Turkey	Lettuce (*Lactuca sativa* L.)	Saline soil	Saline soil reduced macro and micronutrients of plants significantly, compared to control. Sodium reduced due to VC, other mineral elements enhanced significantly and more effectively with VC application.	Demir and Kıran (2020)
6.	Ethiopia	-	Acidic soil	The combined use of lime and coffee husk vermicompost also improved soil organic matter, total N, exchangeable bases, and cation exchange capacity, demonstrating their potential to enhance soil properties.	Regasa et al. (2025)
7.	Thailand	-	Loamy sand	When vermicompost is used, the exchangeable Na^+ and Ca^+ ions increase, reducing the soil's electrical conductivity.	Dume, Hanč, et al. (2023)
8.	Turkey	-	Sandy loam	For 0.5%, 1.0%, 2.0%, and 4.0% vermicompost application dosages, the corresponding increase rates in organic matter content were 14%, 23.8%, 42%, and 90% compared to the control.	Aksakal et al. (2016)
9.	India	-	Clay loam	Organic carbon levels peaked at 8.5 g kg^{-1} with vermicompost 5 t ha^{-1} and were lowest under control. Available N (367.5 kg ha^{-1}), P_2O_5 (25.6 kg ha^{-1}), K_2O (459.9 kg ha^{-1}), S (11.3 mg kg^{-1}), Zn (2.09 mg kg^{-1}), Fe (6.09 mg kg^{-1}), Mn (6.78 mg kg^{-1}), and Cu (2.78 mg kg^{-1}) were also observed.	F. Wang et al. (2021)
10.	Baltic coast	Larix decidua seedlings	Loam texture	Vermicompost increased C/N ratio, nitrate (78-134 mg kg^{-1}), ammonium (14-139 mg kg^{-1}), phosphorus (92-521 mg kg^{-1}), and potash (142-1912 mg kg^{-1}).	Przemieniecki et al. (2021)
11.	West Bengal	*Eichhornia crassipes* (Mart.) Solms	Acid laterite soils	Enhanced VC treatment significantly increases soil P (60%) and exchangeable K (10%) concentrations ($p \leq 0.05$), which highlights that conventional VC builds significantly more soil organic carbon than rock-based VC.	Das et al. (2022)
12.	Wasit, Iraq	Potato (*Solanum tuberosum* L.)	Clay Loam	Compared to other treatments, imported earthworm vermicompost had higher pH, O.M., nitrogen, phosphorus, and potassium levels of 7.05, 1.92%, 3.09%, 3.44%, and 4.08%.	Al-Maamori et al. (2023)
13.	India	-	Sandy loam	Replacing 100% of the prescribed N dose with vermicompost and poultry manure results in a greater soil organic carbon stock in the surface soil layer, accumulating 4.78 Mg ha^{-1}.	Garg et al. (2023)

Furthermore, vermicompost enhances soil CEC, the soil's ability to retain and exchange cations. The organic matter in vermicompost contains negatively charged functional groups, such as carboxyl and hydroxyl groups, which attract and hold positively charged ions (cations) like calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^+), and ammonium (NH^{4+}). This increased CEC improves soil fertility and nutrient retention capacity, reducing the risk of nutrient leaching and runoff. Additionally, vermicompost enhances soil structure, promoting the formation of stable aggregates that further enhance CEC and nutrient retention. In addition to nutrient supply and pH regulation, vermicompost also contributes to soil chemical properties by enhancing soil microbial activity and diversity (Table 3) (Manzoor et al., 2024). The organic matter in vermicompost provides a food source for soil microorganisms, stimulating their growth and metabolic activity (Vuković et al., 2021). This increased microbial activity results in enhanced nutrient cycling, decomposition of organic matter, and humus formation, further improving soil fertility and structure. Additionally, the beneficial microorganisms in vermicompost produce enzymes and organic acids that facilitate nutrient mineralization and solubilization, making nutrients more available to plants. In conclusion, vermicompost significantly affects soil chemical properties, including nutrient supply, pH regulation, CEC enhancement, and microbial activity stimulation. Vermicompost is crucial in sustainable agricultural practices as it enriches soil fertility, improves nutrient availability, and promotes soil health. Incorporating vermicompost into soil management strategies can help optimize soil chemical properties, leading to healthier, more productive soils and sustainable food production systems (Hossain et al., 2025; Oyege & Balaji Bhaskar, 2023).

3.3. Vermicompost effects on the biological properties of soils

Compost produced from earthworms, often hailed as nature's wonder fertilizer, profoundly affects soil biological properties. As the product of organic materials decomposed by earthworms, vermicompost is teeming with beneficial microorganisms, enzymes, and humic substances that foster a vibrant soil ecosystem (Table 4) (Poornima et al., 2024). In this compilation, we will explore the multifaceted impact of earthworm compost on soil biological properties and how it contributes to soil health and productivity. Firstly, vermicompost enhances soil microbial diversity and activity. The rich organic matter in vermicompost is a food source for soil microorganisms such as bacteria, fungi, actinomycetes, and protozoa. These microorganisms are critical in nutrient cycling, decomposition of organic matter, and disease suppression. The introduction of vermicompost into the soil boosts microbial populations, stimulating their growth and metabolic activity. As a result, soils amended with vermicompost exhibit higher microbial biomass and activity, leading to improved nutrient availability, organic matter decomposition, and soil fertility. Moreover, vermicompost promotes the growth of beneficial soil microorganisms that contribute to plant health and disease resistance. The humic substances in vermicompost contain bioactive compounds that stimulate the development of beneficial microbes while constraining the proliferation of harmful pathogens. Additionally, the enzymes produced by earthworms and soil microorganisms in vermicompost help break down organic matter and release nutrients in plant-available forms. This symbiotic relationship between vermicompost and soil microorganisms creates a dynamic ecosystem that supports healthy plant growth and suppresses soil-borne diseases.

Furthermore, vermicompost enhances soil biological diversity, essential for ecosystem resilience and productivity. The introduction of vermicompost into the soil provides habitat and food sources for various soil organisms, including earthworms, insects, nematodes, and microarthropods. This increased biological diversity promotes soil particle arrangement, nutrient dynamics, and carbon-based matter breakdown. Additionally, diverse soil communities contribute to ecosystem stability by providing ecosystem services such as nutrient cycling, soil aeration, and pest regulation (Table 3). As a result, soils amended with vermicompost exhibit greater resilience to environmental stresses and disturbances, leading to improved soil health and productivity (Table 4) (Malal et al., 2024; Romero et al., 2024). In addition to promoting soil microbial diversity and activity, vermicompost enhances soil organic matter content and humus formation.

Table 4. Meta-analysis table for vermicompost and its effect on soil biological properties.

S. No	Location	Crop	Soil Type	Description	References
1	India	Carrot (*Daucus carota* L.)	-	The addition of VC and arbuscular mycorrhizal fungi (AMF) into the soil, either individually or combined, significantly mitigates the adverse effects of nematode infestation on carrot plants.	Ahamad et al. (2023)
2	China	Pepper (*Capsicum annuum* L.)	-	The application of VC reduced the nitrate content and enhanced biological activities.	M. Zhang et al. (2023b)
3	Pakistan	-	-	Applied VC to soil reduces the pH, improves porosity, water retention capacity, and finally enhances microbial activity in the soil profile.	Manzoor et al. (2024)
4	Turkey	Aloe vera (*Aloe barbadensis* Mill.)	Calcareous soil	Application of VC; enhanced soil bacterial number (140%), dehydrogenase (170%), urease (125%), alkaline phosphatase (122%), and β-glycosidase activities (123%).	Tavali and Ok (2022)
5	Thailand	-	Loamy sand	Microbial biomass carbon in salty soil reached a maximum when VC was applied.	Oo et al. (2015)
6	USA	-	-	VC has a notable increase in the overall microbial population and activity.	Oyege and Balaji Bhaskar (2023))
7	Spain	-	-	VC enhances the taxonomic diversity, accompanied by increases in functional diversity of the bacterial community in soils.	Domínguez et al. (2019))
8	West Bengal	Water hyacinth and animal waste/cow dung	Acid laterite soils	VC increases soil microbiological, enzymatic, and nutritional qualities.	Das et al. (2022)
9	South Africa	Vermicompost leachates (VCL)	--	Humic acids, nutrients, earthworm excretions, rich microbial populations, growth hormones, and enzymes in VC.	Vambe et al. (2023)
10	Pontevedra, Spain	White grape marc (*Eisenia Andrei*)	--	Detailed bacterial succession during white grape marc vermicomposting indicated increasing diversity and community composition.	Kolbe et al. (2019)
11	Hawaii at Hilo	Bell peppers, strawberries, and grapes	--	VC increases soil microorganisms, which reduce plant diseases, improve soil health, and boost plant growth.	Chen et al. (2022)

The organic matter in vermicompost serves as a foundation for vigor and nutrients for soil microorganisms, stimulating their growth and metabolic functions. As microorganisms decompose organic matter, they release carbon dioxide (CO_2) and other byproducts, contributing to soil humus formation. Humus improves soil structure, water retention, and nutrient availability. Consequently, soils amended with vermicompost exhibit higher levels of organic matter and humus, resulting in improved soil fertility and productivity. Therefore, vermicompost significantly impacts soil biological properties, including microbial diversity, activity, and organic matter content. Vermicompost enhances soil health, fertility, and productivity by fostering a vibrant soil ecosystem rich in beneficial microorganisms, enzymes, and humic substances. Incorporating vermicompost into soil management practices can help optimize soil biological properties, leading to healthier, more productive soils and sustainable agricultural systems (Table 4) (Manzoor et al., 2024).

4. Vermicompost effects in mitigating the global warming consequences

Vermicompost, an organic fertilizer formed through the decomposition of organic materials by earthworms, plays a significant role in mitigating the adverse effects of global warming (Lu et al., 2025; Singh et al., 2019; Zhu et al., 2023) (Table 5). As a sustainable soil amendment, vermicompost contributes to carbon sequestration, soil carbon storage, and improved soil health, helping reduce greenhouse gas emissions and enhance climate resilience. This section will explore how vermicompost mitigates the adverse effects of global warming and contributes to climate change adaptation and mitigation efforts. Firstly, vermicompost enhances soil carbon sequestration by promoting the accumulation of organic matter and humus in the soil. The organic matter in vermicompost contains carbon derived from atmospheric CO_2 through photosynthesis. When applied to the soil, vermicompost adds organic carbon to the soil carbon pool, increasing soil organic carbon (SOC) stocks.

Additionally, the stable humic substances in vermicompost contribute to long-term soil carbon storage by forming complexes with soil minerals, preventing the decomposition of organic matter and sequestering carbon in the soil for extended periods. Consequently, soils amended with vermicompost exhibit higher levels of soil carbon sequestration, helping to mitigate the accumulation of atmospheric CO_2 and alleviate global warming (Table 5) (Farooqi et al., 2024; Vambe et al., 2023). Moreover, vermicompost improves soil structure and fertility, enhancing soil water retention and drought resilience. Hence, vermicompost on one side enhances the soil health, while on the other hand, it mitigates global warming (Fig. 2).

The organic matter in vermicompost acts as a sponge, absorbing and retaining moisture in the soil, reducing the risk of drought stress and water scarcity. Additionally, the stable aggregates formed by vermicompost improve soil structure, promoting better root penetration, aeration, and nutrient uptake by plants.

Consequently, soils amended with vermicompost exhibit improved drought tolerance and resilience to extreme weather events associated with climate change, such as droughts and floods. Furthermore, vermicompost reduces dependence on synthetic fertilizers and chemical pesticides, significant sources of greenhouse gas emissions. By providing essential nutrients and promoting soil health, vermicompost reduces the need for chemical inputs, lowering the carbon footprint associated with fertilizer production, transportation, and application. As a result, the widespread adoption of vermicompost in agriculture can help reduce greenhouse gas emissions from fertilizer and pesticide use, contributing to climate change mitigation efforts (Table 5) (Panda et al., 2022; Raza et al., 2024).

Table 5. Vermicomposting impacts on mitigating the adverse effects of global warming**.**

Sr. No.	Substrate Used	Key Findings / GHG Impact	Specific Environmental Benefits	Reference
1	Horticultural crops	Improves soil carbon sequestration	Enhances soil fertility; reduces erosion and GHG emissions	Abad and Shafiqi (2024)
2	Duck manure	Reduces GHG emissions and heavy metal contamination	Improves nutrient availability and microbial quality	Yasmin et al. (2022)
3	Animal manure	CH_4, N_2O & NH_3 emission factors: 10.8, 62.3 and 12.8 g Mg^{-1} biowaste; high worm density increases N_2O	LCA shows reduced global warming and eutrophication; improper disposal may increase eutrophication	Komakech et al. (2016)
4	Pre-decomposed garden waste	CH_4 and N_2O emissions reduced by 32% and 40% (or 16% and 23% under low moisture)	Lower GHG emissions compared to conventional composting	Nigussie et al. (2017)
5	Sawdust, red mud, fly ash	Aeration + C-rich materials reduce GHG emissions during VC	Inorganic amendments to improve aeration and GHG reduction efficiency	Mupambwa and Mnkeni (2018)
6	Pelletized wheat straw	Reduces methane emissions from sewage sludge	Earthworms enhance aeration, lowering CH_4 generation	Dume et al. (2021)
7	Sawdust and fly ash	The addition of inorganic materials lowers GHG emissions	Improve process aeration and stabilization	Panda et al. (2022)
8	Vermicompost	Supports organic waste degradation with reduced GHG emissions	Contributes to long-term soil health improvement	Robatjazi (2023)
9	Vermicompost leachate	VCL improves crop resilience under climate stress	Enhances yield; mitigates abiotic stress; concerns: salts, metals, biotoxins	Vambe et al. (2023)

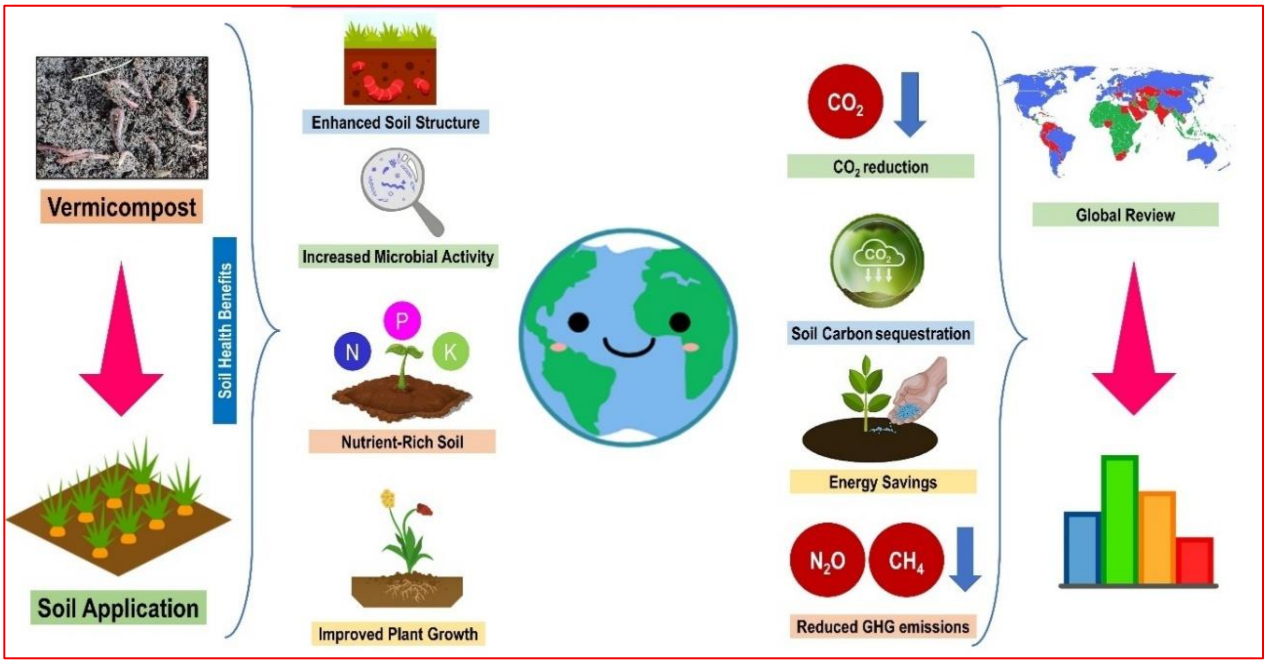

Figure 2. Vermicompost enhances soil health and mitigates global warming.

Despite its contributions to carbon sequestration and soil health, vermicompost indirectly supports climate change adaptation by enhancing crop productivity and resilience. The improved soil fertility and water retention capacity provided by vermicompost enable plants to withstand better environmental stresses associated with climate change, such as heat waves, droughts, and heavy rainfall.

In drought-stricken Iran, vermicompost tea improved sugar beet and Thymus vulgaris tolerance to water stress. In the Czech Republic, straw-amended vermicomposting reduced methane emissions from sewage sludge. In Germany, vermi-worms enhanced carbon mineralization from organic matter. In Bangladesh, vermicompost improved rice yield, nutrient efficiency, and soil carbon sequestration (Table 6). Additionally, vermicomposting significantly lowered greenhouse gas emissions compared to traditional composting, with moisture levels influencing the extent of reduction. These findings highlight vermicomposting's role in sustainable agriculture and climate-smart waste management practices (Table 6). Integrating vermicompost into soil management practices can help build climate-resilient agricultural systems and contribute to global efforts to combat climate change.

5. Factors affecting the earthworm activity

The vermicomposting process is influenced by a wide range of physical and chemical variables that, in turn, affect soil health and productivity and, finally, agricultural profitability. The following are key factors that could affect the earthworms and their performance during preparation.

Table 6. Effects of Vermicompost on mitigating environmental stress.

Sr. No	Study place and Brief description	Mitigating impacts	References
1	To measure sugar beets' biochemical and abdicate responses to topically applied and stretched vermicompost tea during Iranian droughts.	VCL treatment helps ease the impacts of dry spells in sugar beet (*Beta vulgaris* L.)	Ghaffari et al. (2022)
2	To examine the impact of dry season, stretch and VC on morphological and biochemical characteristics of *Thymus vulgaris* in Iran	VC reduced dry season stress in *Thymus vulgaris* beneath mild and extreme water stress (55–70% field capacity).	Alla Sharafi et al. (2019)
3	The goal is to study CO_2 and CH_4 emissions during sewage slime composting and vermicomposting in the Czech Republic, focusing on straw pellet ratios.	The amount of methane released from the sewage slime can be reduced by adding pelletized wheat straw to the vermicomposting process.	Dume et al. (2021)
4	To assess the effect of vermin worms on C and N mineralization.	Activating organic mattar mineralization and tagging with C13 boosted straw carbon mineralization.	Panda et al. (2022)
5	Examine impacts of INM using VC on rice yield, nutrient use efficiency, soil richness, and carbon (C) sequestration in cultivated land in Bangladesh.	Vermicompost was added at a rate of 5 t ha^{-1}, resulting in a slight expansion of the soil's natural C stock and carbon sequestration.	Urmi et al. (2022)
6	To examine if vermicomposting (VC) lowers nitrogen losses and nursery gas emissions better than thermophilic composting and how worm thickness, moisture content, carbon quality, and C/N ratio affect greenhouse gas emissions.	With more moisture, vermicomposting lowered nitrous oxide emissions by 40%; with less, 23%. Vermicomposting reduced methane outflows by 16% and 32% at higher and lower moisture levels.	Nigussie et al. (2016)

5.1. Influence of pH of the soil on the earthworm activity

The best pH for stabilizing solid waste and speeding up processing is 7.0, while many earthworm species may survive at varying pH values. The ideal pH range is between 5.5 and 8.5, as neutral pH is where earthworm activity peaks. Although a range of substrates can be utilized to create vermicompost, the type of base used determines the final product's pH. Because the substrates of various compost components vary, earthworm species also control pH in a way that is comparable to these substrates. The vermicomposting of banana stems in a pH range of 8.0 to 8.8 (Khatua et al., 2018). Vermicompost made in paper cups had a pH rise from 6.18 to 8.0 (Arumugam et al., 2018). The theory holds that the acidic environment is the cause of pH rise. Vermicomposting treatments may cause a pH drop of 5% to 9% (Katiyar et al., 2023). This decrease could be because of the organic acids generated by microbial decomposition, as well as the mineralization and bioconversion of organic waste into CO_2 (Adetunji et al., 2023). The breakdown of organic materials and the release of carbon dioxide gas during the creation of organic acids are two of the mechanisms by which vermicomposting lowers pH (Yasmin et al., 2022). The pH drop can be brought on by the increased moisture created during vermicomposting, which aids in maintaining the pH equilibrium of the substrate. Composting enhances the quality of organic materials by alkalizing the substrate. Without carbohydrates or simple organic acids, the microorganisms can raise the pH and release ammonia by using the carbon from amino acids and the protein in the raw materials, along with the waste produced when the microorganisms die.

5.2. Influence of electrical conductivity of the soil on the earthworm activity

Since soluble salts can cause EC to rise or fall from the first day of vermicomposting, it is an important metric (Z. Wang et al., 2021). Using vermi-technology, the slight decrease of EC in all feedstocks significantly slows down after two months, showing that the decomposition process is maturing and stabilizing (Dume, Hanc, et al., 2023). During the first 30 days of vermicomposting, researchers noted several microbiological activities, considerable methane emissions, and a noticeable increase in EC. As a consequence of composting, methane releases carbon and nitrogen over time. Similarly, soluble salts in compost piles affect concentration variations from the beginning to the end. The earthworms also absorb soluble salts, which microorganisms use to create microbial biomass. This increased microbial activity can result in a fall in EC. From day 0 to day 150, there was an increase in EC in all four piles, which is similar to what happens during bio-oxidative composting (Santana et al., 2020). The vermicomposting heaps showed a discernible decline at the end of the process. The formation of insoluble salts and ammonia volatilization may be the cause of this decline. Additionally, leaching from the moisture that drip irrigation maintains may result in EC loss (Guo & Li, 2024). Compared to conventional composting, vermicomposting significantly decreased salinity (87% - 90%). Thus, all four heaps' final EC values fell below the 4 dS m^{-1} threshold, which is thought to be enough for composting and vermicomposting to promote plant development. Many studies have looked at the physical and chemical properties, like pH and EC, that come up during cow vermicomposting after adding nutrients (Ferraz Ramos et al., 2022; Ghandehari Yazdi et al., 2024).

5.3. Influence of soil moisture on the earthworm activity

The amount of moisture in each composted medium can balance the roles of microorganisms and earthworms. Although 80% moisture is necessary for the best earthworm growth, the *E. fetida* species needs moisture levels between 50% and 90% for earthworm activity. Excessive moisture can cause earthworms' clitellum to develop later than usual. High moisture content has biological effects on microbes, especially bacteria and fungi. As long as there is enough oxygen in the water, worms can stay submerged for several days (Edwards & Arancon, 2022c). The height and growth rate of tomato plants using manure-derived nutrients rose by 15% to 50% on soilless media when the moisture content was sufficient (Gao et al., 2023). Consequently, bacterial cellulose synthesis requires moisture. For soil additives, this cellulose can subsequently be used as small storage chambers for water and nutrient transporters. Bacteriological cellulose can be produced by bacteria.

5.4. Influence of the temperature of the soil on the earthworm activity

Temperature has a major effect on earthworm activity and is an essential vermicomposting characteristic (Zhou et al., 2021). Earthworms crawl into the lowest layers of the compost during hibernation and eat less in colder climes. The medium's temperature should stay between 10 and 35 C° for best results (Edwards & Arancon, 2022c). Therefore, warmer temperatures encourage earthworm activity throughout the composting process. Seasonal temperature fluctuations, ranging from 25 to 27 C°, impact the chemical and biological oxygen demand levels of compost (Arora & Kazmi, 2015; Cui et al., 2022). Vermi-filter can endure harsh environments, but earthworms cannot flourish in frigid climates (Alli, 2023; Hajam et al., 2023). Plant genetics, fruit ripening, olive tree farming practices, and pedoclimatic conditions can all have an impact on the phenolic content of olive mill wastewater (OMWS) and different extraction techniques. Overall, it was discovered that phenolic compounds dramatically dropped at the beginning of decomposition when temperatures rose to thermophilic levels. Following this stage, the rate of breakdown decreased until there was roughly 401 mg kg^{-1} of material in either vermicomposting or composting, respectively.

5.5. Influence of light exposure on the earthworm activity

Because they are photophobic, vermicomposting worms are either nocturnal or light-sensitive (J. Cai et al., 2025). They hate intense light because their skin can detect it (Kavassilas et al., 2024; Mittmannsgruber et al., 2024). Earthworms may die as a result of skin damage from direct sunlight or extreme heat. The worms spend most of their time in the dark, and light quickly damages them, which forces them to burrow farther as the compost decomposes. Furthermore, their lack of resistance to direct light impacts their biological processes. This allows them to consume organic material and generate worm castings. Standard white light decreased production by around 29.9%, whereas worms exposed to sunlight produced 65.9% more castings. Red light had a greater effect on cast production than green or blue light. The most tolerant organisms to red and dark light were earthworms. This study found that while worms feel at ease in the dark, they are not as stimulated by it. Given that all light colours produce similar amounts of warmth, this study demonstrates that light is unquestionably the cause of the health advantages. Because red light is more efficient at producing ATP in the mitochondria, it increases earthworm activity (Lee et al., 2024).

5.6. Influence of the aeration status of the soil on the earthworm activity

Because they are able to breathe via their skin, worms are a unique species. This skin contributes to the body's ability to absorb oxygen by facilitating the circulation of blood and cells throughout the body. The cells of earthworms require oxygen to digest food, which results in the production of carbon dioxide (Edwards & Arancon, 2022b). The porosity of the matrix may prevent ventilation into the mixture, leading to anaerobic conditions. Additionally, the moisture that is derived from the components that are resistant to change causes the temperature to rise. Because of this, it is difficult to detect bioactivation at an early stage in the process of breakdown. When analysing the emissions of greenhouse gases that occur during the process of organic decomposition, rotation and aeration are two of the most important elements to consider. Low aeration is more effective in reducing the generation of greenhouse gases (Ma et al., 2020). The recurrent aeration is more efficient than continuous aeration in terms of reducing CO_2 emissions (Mannina et al., 2024; Peng et al., 2023). This is because recurrent aeration speeds up oxygen exchange in compost, which in turn reduces methane emissions and shortens maturity periods.

5.7. Influence of the carbon-to-nitrogen ratio of the soil on the earthworm activity

Several substrata, including tomato, paper mill sludge (24.9 - 13.1), vegetable waste (51 - 22), banana stem (75.8 - 9), and paper waste (134 - 31.3), were among the substances in terms of their carbon-to-nitrogen ratios (Samal et al., 2019). Vermicomposting is a process in which earthworms and microflora mineralise organic waste, therefore lowering the carbon-to-nitrogen ratio to a level that is suitable for agricultural use (Enebe & Erasmus, 2023b). The grade of vermicompost is based on its maturity and the amount of palm oil mill effluents that were produced. Through the process of fragmentation and conditioning of the substrate, earthworms are the major agents responsible for the breakdown of organic waste. To ensure the earthworms' continued existence and activity during the vermicomposting process, it is necessary to have the appropriate combination of organic wastes (Ratsiatosika et al., 2024). The expansion of their surrounding territory and the transformation of waste materials are both accomplished via the practice of burrowing activities. The degradation of organic waste materials is accelerated by these microbial activities, which results in a lower carbon-to-nitrogen ratio and a reduced availability of high porosity, which is rich in nutrients (Chimanbhai Saypariya et al., 2024). Impact on the efficiency of vermicomposting includes pH levels and the initial carbon-to-nitrogen ratio, and they were explored with a variety of earthworm species (Ndegwa & Thompson, 2000). Vermicomposting was performed with *E. fetida* after the materials had been decomposed for a period of twenty days, which is known as the composting stage (Kauser & Khwairakpam, 2022). Vermicomposting was shown to considerably improve nutrient status ($P \leq 0.05$), with a C:N ratio of 40 (Ravindran & Mnkeni, 2016). Total nitrogen (TN), total phosphorus (TP), and total potassium (TK) levels increased over the course of the vermicomposting process. This was the case throughout the entire procedure. The optimal ratio of carbon to nitrogen for earthworms is between 40 and 50. Even though vermicomposting is affected by a number of different substrates, the utilisation of agricultural wastes for vermicomposting resulted in an increase in the amount of nitrogen that was present in the compost (Wongkiew et al., 2023). Earthworms improve soil fertility by breaking down components that contribute nutrients and expanding the surface area available for microbiological activity (Ahmed & Al-Mutairi, 2022). Earthworms are responsible for this modification. Vermicomposting effectively recovers nitrogen (TN) from a variety of substrates that have the necessary ratio of carbon to nitrogen (C:N) (Nigussie et al., 2016). The researchers were able to achieve enhanced quality using 10 different treatments. The therapy that consisted of cow dung, *P. chrysosporium*, and *T. harzianum* at a ratio of one to one proved to be the most successful. Vermicast is produced when organic waste is digested due to the fact that it has the same weight as the insects and contains nitrate, phosphorus, magnesium, and calcium. Through the observation of the interactions that occurred between native earthworms and shrubs that had been injected with rhizobium, the effects of soil nitrogen mobility were studied. Earthworm-induced soil aeration was responsible for the change in the amount of moisture that was present in the rhizosphere (Ghandehari Yazdi et al., 2024). This is because the nitrogen cycle has the ability to influence this moisture by supporting the growth of microbial communities that are found in organic matter. The incorporation of vermicompost not only brought about significant alterations to the chemical and biological properties of the soil, but it also led to an increase in the microbial population. Increasing the application of vermicompost and compost led to an increase in the levels of phosphate, nitrate, calcium, and soil organic carbon (SOC).

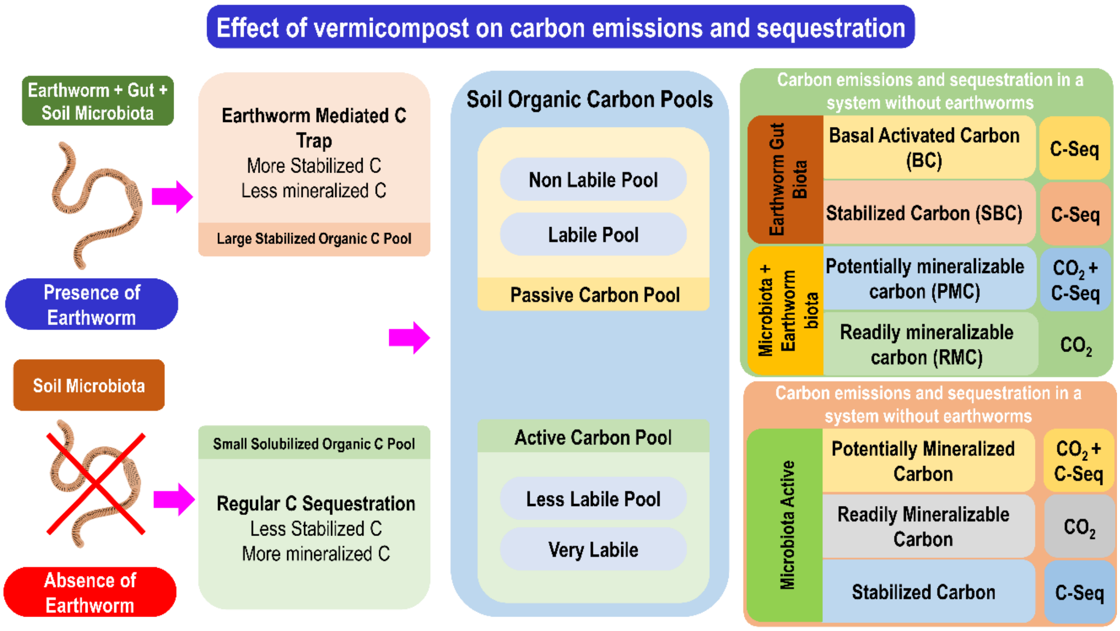

Figure 3. Vermicompost action on carbon emissions and impounding (modified from Zhang et al. (2013) & Panda et al. (2022)).

5.8. Emission of greenhouse and ammoniacal gas emissions from compost

While thermophilic composting loses between 10% and 20% of its nitrogen (N) during the process, vermicomposting loses a substantially smaller amount of nitrogen (N) than thermophilic composting does. Both the release of ammonia (NH_3) into the air and the production of greenhouse gases (GHG) were studied to see how nutrients can be recovered during the vermicomposting process (Yasmin et al., 2022). The dynamics of aggregates and the organic matter in the soil are largely reliant on the history of land use as well as the qualities of the soil when it was first created. There are significant repercussions associated with the selection of earthworm species. In the course of the composting process, earthworms exert a significant influence on the level of dissolved organic carbon (DOC) ($P \leq 0.05$). In Figure 3, the specific effects of vermicomposting on carbon emissions and sequestration are discussed in greater depth. The components of compost are connected to feeding ratios and greenhouse gas emissions. The production of compost and vermicompost, greenhouse gas emissions are a significant and non-negligible issue (Nordahl et al., 2023). In vermicomposting, earthworms can compensate for greenhouse gas emissions and nitrogen losses. The number of carbon dioxide (CO_2) and nitrous oxide (N_2O) emissions from the soil was raised by earthworms by 33% and 42%, respectively. However, there is not enough information in the literature about greenhouse gas emissions during vermicomposting. Lim et al. (2016) and Lubbers et al. (2013) conducted a study that investigated the impacts of greenhouse gas emissions during earthworm activity in soil. Both studies published their findings in 2016. The detailed effects of vermicomposting on greenhouse gas emissions are mentioned in Figure 4. A comparison was made between vermicomposting and composting before the process was even started (Raza et al., 2024). A mixture of weed straw and vermicompost was used to make the fertilizer that was applied. While the addition of reed straw resulted in a reduction of NH_3 emissions, vermicomposting resulted in a significant reduction of CO_2 and methane (CH_4) emissions. When combined, vermicompost and reed straw resulted in a reduction of emissions of greenhouse gases. During the chemical analysis of solid organic waste mixed with cow dung, researchers found nitrogen compounds in the leftover vermicompost filter cake. The vermicomposting of cow dung was observed for a predetermined amount of time, during which the pH, temperature, and humidity levels were measured (Ghandehari Yazdi et al., 2024). There was a recording of the levels of nitrogen (N), carbon (C), and protein.

The use of earthworms to recycle nutrients resulted in the establishment of eight vermin bins, each of which contained one kilogram of waste mixes. The nutrient content was greatly increased as a result of this, which also facilitated the growth of plants and improved the overall health of the soil (Ganapathy et al., 2025). With the help of *E. fetida*, this was obtained. The levels of nitrogen, phosphorus, and potassium (NPK) dramatically rose, but the pH and the ratio of carbon to nitrogen in the water fell. The utilization of volatile matter in a biochar media allows for the breakdown of wastes derived from crops and animals (Amalina et al., 2022; Awogbemi & Kallon, 2023). The biochar and vermicomposting are effective methods to boost crop yields (Wu et al., 2019; M. Zhang et al., 2023a). However, nitrous oxide emissions from soil increase when earthworms are active (Maslov et al., 2022). Recycling solid waste through composting and vermicomposting is a popular method of boosting soil fertility. Vermicomposting has two applications: managing solid waste and enhancing soil fertility. The existing literature suggests that vermicomposting is a cost-effective alternative to artificial fertilizers due to its ability to increase N content and prolong its retention in soil. In addition to reducing soil pathogens and heavy metals, it boosts soil fertility, enzyme activity, nutrients (especially nitrogen), and microbial biodiversity. The research conclusively demonstrates that vermicomposting has a positive impact by reducing pH, carbon levels, and the C:N ratio.

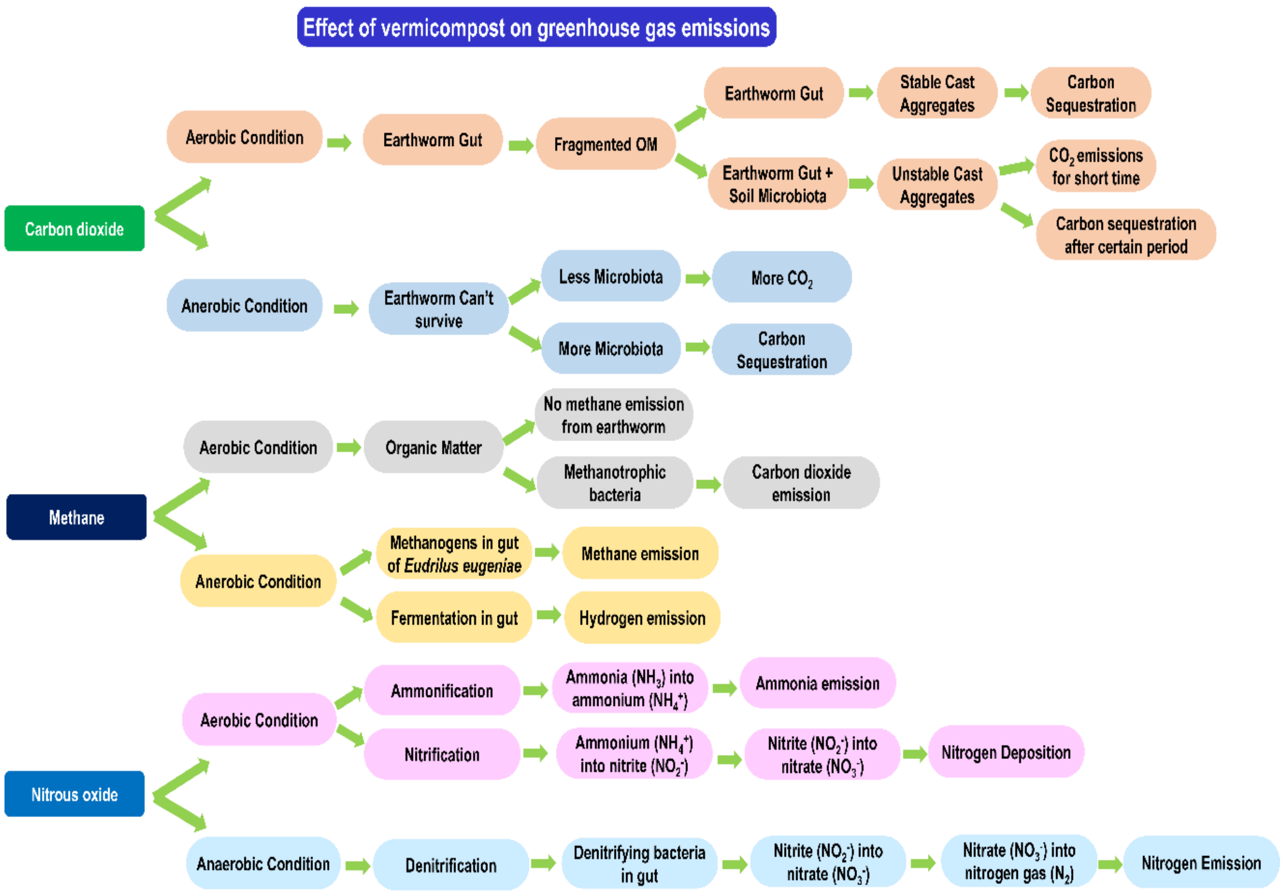

Figure 4. Effect of vermicompost on greenhouse gas emissions.

6. Vermicomposting for nutrient recovery and recycling

Vermicomposting decreased the C:N ratio and increased 1.2 to 2.9 times the NPK content (0.56 to 18.58 g kg^{-1}) (Biruntha et al., 2020). Vermicompost accelerated the decomposition of both above- and below-ground plant wastes, leading to a higher rate of nitrogen release through organic material (Enebe & Erasmus, 2023b). Crops can benefit from the nitrogen that vermicompost releases, with 70% released in the first 30 days (Enebe & Erasmus, 2023b). Utilizing vermicompost as an organic amendment showed noticeably elevated N and C levels compared to NPK (Amaya-Gómez et al., 2025). This is accomplished by intensifying the decrease in nitrogen availability and the synergistic impact of soil heterogeneity and earthworms on plant species dominance and biomass (Adomako et al., 2021).

One possible explanation for the observed rise in total N levels following vermicomposting is the associated decrease in organic C by dry mass, affecting CO_2 emissions (Poblete et al., 2022). Water loss from the mineralization of organic materials and evaporation, as well as metabolic wastes and enzymes, resulted from the actions of earthworms and microorganisms. In vermin reactors, vermicomposting reduced the pH of X-rays (Enebe & Erasmus, 2023a). The acidity of the pH could be caused by the mineralization of N and P. The inclusion of vermicompost was found to enhance microbial development. For ten weeks, *E. Eugeniae* will study the redistribution of supplement chemicals (Mg, K, Na, P, Ca, and N) during vermicomposting and soil fertilization in a metropolis with significant garbage. The following supplements were shown to increase in all forms: magnesium (12.2% to 63.8%), nitrogen (4.2% to 12.9%), potassium (24.9% to 45.8%), phosphorus (67.2% to 87.5%), calcium (19.9% to 33.9%), and sodium (30.2% to 40.5%). Compared to composting soil substrates in containers, vermicomposting in vermins resulted in a more significant increase in absolute N and Ca and a larger increase in Na, P, Mg, and K. The use of *E. fetida* in vermicomposting for localized trash control yielded positive results in composting (Usta & Guven, 2024).

A notable rise in SOC and C stock was noted by reducing the soil's bulk density through vermicomposting. Using a value of 67.04 t ha^{-1}, the maximum plant yield over three years was achieved using 100% vermicompost. The control group saw a yield increase of 94.8%, while the NPK group rose 73.8% (Raza et al., 2024). Recycled several types of organic garbage. For 45 days, *E. fetida* was used in the vermicomposting process. For every pit, the starting TN value was 0.91. Compared to artificial fertilizers, vermicomposting improved soil N retention capacity and increased N content (Amaya-Gómez et al., 2025). Using three distinct species of earthworms, researchers examined the efficacy of vermicompost on three types of sewage sludge. With biotic and abiotic factors considered, vermicomposting was monitored using parameters including mental body stress and body loads. Under these experimental conditions, *Dendrobaena veneta* exhibited reduced resistance. Cr < Pb < Ni < Zn < Cu < Co < Cd reflects the sequence in which earthworms accumulated heavy metals. *Eisenia* sp. worms showed the highest capacity for heavy metal accumulation. After 45 days, the vermicompost obtained met all the criteria for compost quality (Rini et al., 2020). Earthworms had a more favorable effect on plant development (134%) compared to inorganic fertilizers (110%) or no fertilizer (120%). If farmers are unable or unwilling to use nitrogen fertilizer, or if they do not have the funds to do so, the authors suggest that earthworms can assist in closing the production gap. Based on the review's findings, vermicomposting is an advantageous and cost-effective field choice due to its ability to handle diverse organic waste and other benefits.

According to multiple studies, earthworms influence microbial community conditions and substrate digestion rates, subsequently affecting DOC quality and compost quantity, and regarding stability, vermicomposting outperformed thermophilic composting in terms of CO_2 emission (Domínguez et al., 2021). In a separate study, chemical analyses and field observations found that the species *Dichogaster bolaui* and *Placusa simlaensis* effectively decreased the carbon-to-nitrogen ratio and increased the nitrogen content of vermibed materials (mineralization and breakdown). The C: N ratio is an intricate factor regulating the earthworm population. It is more difficult to extract enough nitrogen for tyre production as the carbon-to-nitrogen ratio of the feedstock rises. The observed reduced C: N ratios may have been caused by gas loss, particularly carbon dioxide (CO_2), during microbial respiration during vermicomposting (Nigussie et al., 2017). DOC can be used to assess compost stability. To evaluate the impact of earthworms, we assessed DOC and GHGs. When researchers compared vermicompost with thermophilic compost, they discovered that earthworms considerably reduced the stabilized vermicompost's DOC content. Greenhouse gas emissions from food were decreased by earthworms (Forey et al., 2023). The organic additions improved plant performance and soil quality. The use of vermicompost produced favorable outcomes. PGPR considerably increased tomato output when the vermicompost dose was high. In order to create biochar with a pH of 11.18, a nitrogen concentration of 0.23%, and a bulk density of 0.15 g cm^{-3}, filtered 40 g of BC across 0.26 to 2.7 mm. Using slow pyrolysis on fruit tree orchard cutting remnants, created biochar with a pH of 10.2, an N content of 0.48%, and a C content of 86% (Kazimierski et al., 2021). In a study by Doan et al. (2015), bamboo was carbonized in airless brick furnaces for 8.5 to 10.5 hours at 601°C. The resultant biochar had a low nitrogen concentration (N=0.87%), a high carbon content, and a pH of 7.0.

7. Use of vermicompost as an organic fertilizer

Manure and other organic waste materials can be vermi-composted. Using tomato and yard trash as substrata and *E. eugeniae* earthworms as the primary organisms, vermicompost is produced. When *E. eugeniae* was applied to Zinnia and Chinese cabbage, the feedstocks produced more main nutrients (NPK) than organic fertilizer. As an alternative to organic tomato fertilizer, vermicompost has more supporting evidence (Wang et al., 2017). Interactions between soil type and application rates of vermicompost on vegetable crops resulted in plants with higher chlorophyll content, increased plant biomass, and taller plants (Zucco et al., 2015). Sandy soils amended with VC gave tomato plants the best growth metrics, whereas loam soils gave the fewest (Zucco et al., 2015). Quite a few nations, including Australia, use vermicomposting as a sustainable agricultural practice. Sewage sludge and other types of organic matter are produced by treating wastewater, and vermicompost can handle various waste items. Polycyclic aromatic hydrocarbons, heavy materials, and microbes are just a few examples of the potentially harmful contaminants that might be found in these categories.

Meanwhile, valuable nutrients like P and N can be extracted. Vermicomposting is an effective way to increase the soil's carbon and nitrogen content while also recovering these nutrients (Jiang et al., 2023). The vermicomposting process can transform sewage sludge into stable vermicompost by lowering its TN, pH, TP, organic content, heavy metals, and harmful microorganisms. Sludge stabilization was achieved through microbial and vermicompost interactions. In this experiment, earthworms helped microbes convert and absorb organic materials. High N and lowered pH resulted from a sustainable solid waste management approach involving pre-decomposition for 15 days and vermicomposting for 21 days (Ducasse et al., 2022). The resulting material had trace levels of NPK. The VC process drastically changed the waste material's physical and chemical properties. It was proposed as a substitute for organic fertilizer. VC started at a pH of 7.9 and steadily dropped to 7.1 over 60 days (Vyas et al., 2022). Vermicompost outperformed conventional composts in terms of plant output, growth, and germination because its nutrients were quickly released (Enebe & Erasmus, 2023b). The amount of growth hormones produced by the plants was also shown to increase (Ravindran et al., 2016). Rosemary was grown in a semi-arid tropical region with a mix of vermicompost and inorganic fertilizer to observe how the plants responded regarding growth rate, oil quantity, fertility, and nutrient uptake. The group using a mixture of chemical fertilizer and vermicompost (4.0 t ha^{-1}) had the best results. Nitrogen was more readily available after vermicomposting.

8. Pros and cons of vermicompost

Soil nutrient loss can be mitigated in several ways with the help of vermicomposting, an organic fertilizer (Manzoor et al., 2024). As a management practice in agricultural systems, nitrogen retention in this area has been extensively studied. A novel organic strategy for lowering environmental loadings is vermicompost, which is made from various substrates and is then applied to fields. As with all organic materials, the nutrient-rich vermicompost improves soil health and fertility by acting as a conditioner. Mixing earthworms with other agricultural wastes is advisable because direct invasion is still ineffective, and some of the worms escape from the ecological waste medium (ditch plants, especially *Hydrocotyle vulgaris*) during vermicomposting. The local bacteria attached to the starting materials showed significant differences in gene abundance when vermicomposting maize stover and cow manure.

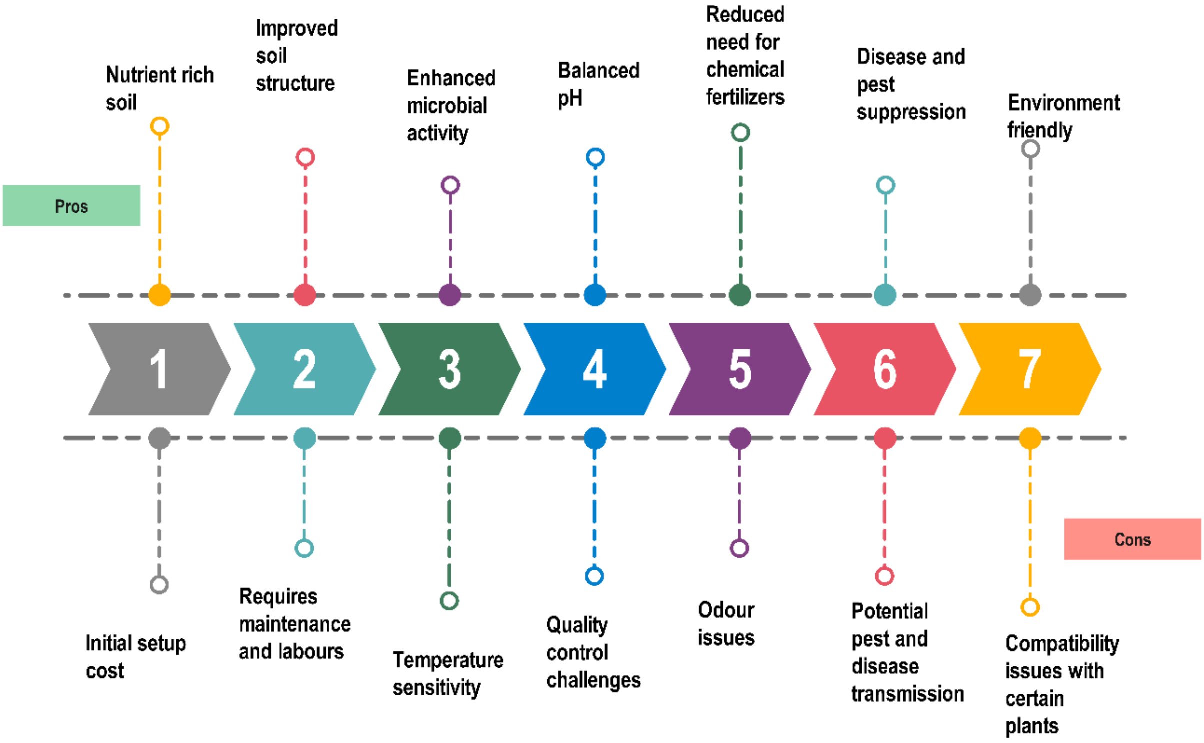

Figure 5. Pros and cons of vermicompost technology.

The GH6 gene was found persistently high in Cellulomonas and Cellulosimicrobium, the two most common taxa in earthworm treatments. The fact that earthworms break down cellulose faster than other species helps explain the enhanced breakdown rate. Vermicompost is employed as an advanced technology to lower ARGs in organic waste and to ensure that scarab larvae (*P. brevitarsis*) do not propagate manure-borne antibiotic resistance genes (ARGs) across the soil-plant system (Zhao et al., 2022). Instead of throwing resources away, developing countries should establish systems for recycling and reusing them. Developed nations have implemented vermicomposting on a considerable scale. Nevertheless, it remains difficult for developing nations to manage their garbage in a way that benefits both human and environmental health. Some common pros and cons are mentioned in Figure 5.

9. CONCLUSION

Vermicomposting (VC) and its significance in sustainable agriculture are addressed in this current study. It emphasizes earthworms as ecological engineers by improving soil ecology through better aeration, aggregation, and microbial activity. The physical, chemical, and biological qualities of soil are improved by VC, which also increases the amount of organic matter, nutrient availability, and beneficial microbial diversity. It also helps to reduce greenhouse gas emissions and trap carbon, promoting climate-smart farming practices. Temperature, substrate quality, and moisture are important variables that affect earthworm activity. With improved nutrient recovery and recycling, less dependence on chemical fertilizers, and reduced cultivation expenses, VC increases soil fertility and crop output. It preserves ecological balance and provides sustainable substitutes for conventional inputs. Furthermore, a comprehensive evaluation of both the benefits—such as waste management, soil enrichment, and climate resilience—and the limitations—such as labor requirements and operational challenges—offers a well-informed perspective on its adoption. Overall, vermicomposting is a practical, environmentally sustainable, and scientifically supported approach to improving soil health, enhancing crop productivity, mitigating the impacts of climate change, and supporting farmers' livelihoods. Integrating vermicomposting into agricultural systems can contribute to long-term sustainability through improved nutrient cycling, reduced environmental stress, and efficient utilization of organic waste.

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Declaration of Competing Interest

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

Data availability statement

All data generated or analyzed during this study are included in this published article.

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