



Dual roles of earthworms in climate change: Emission contributors or climate mitigators?

Syarifinnur^{1,*}

¹ Department of Agrotechnology, Faculty of Agriculture, Universitas Nahdlatul Wathan Mataram, Mataram, West Nusa Tenggara 83125, Indonesia.

*Correspondence: syarifinnur@gmail.com

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ABSTRACT

Background: Soil biodiversity is a key element of terrestrial ecosystems that underpins their resilience to environmental stress, especially amid accelerating climate change. Among soil organisms, earthworms are vital ecosystem engineers that regulate soil structure, nutrient cycling, and organic matter decomposition. However, intensive land use and climatic pressures have led to declining soil biodiversity, threatening ecosystem stability and sustainable land management. **Methods:** This review synthesizes recent empirical and experimental studies on the dual roles of earthworms in carbon and nitrogen cycling, soil organic carbon (SOC) accumulation, and greenhouse gas (GHG) fluxes under different management systems. **Findings:** The analysis emphasizes conservation tillage, organic amendments, and precision nutrient management as key strategies influencing earthworm-mediated processes. Evidence shows that earthworm activity can increase nitrous oxide (N₂O) emissions by up to 42% in nitrogen-enriched soils. Conversely, interactions with organic amendments such as compost and biochar can enhance SOC by up to 32.69%. Conservation tillage, particularly strip tillage, improves carbon sequestration (1.21 Mg C ha⁻¹ year⁻¹) and increases earthworm abundance by up to 133%. These results demonstrate that management practices strongly mediate the balance between earthworm-driven GHG emissions and carbon storage. **Conclusion:** Earthworms are central to sustainable agriculture through their roles in improving soil quality and mitigating climate impacts. Implementing earthworm-friendly practices, such as reduced tillage, organic matter addition, and balanced nutrient application, can optimize their ecological benefits while minimizing GHG emissions. **Novelty/Originality of this article:** This review provides an integrative perspective on the paradoxical function of earthworms as both GHG emitters and climate mitigators. It offers a conceptual framework to guide future research on enhancing carbon sequestration and sustainability through earthworm-based soil management.

KEYWORDS: carbon sequestration; earthworms; ecosystem engineers; greenhouse gas emissions; sustainable agriculture.

1. Introduction

Earthworms play a fundamental role in terrestrial ecosystems, serving as key agents of soil health and nutrient cycling. As “ecosystem engineers,” their burrowing and feeding activities influence soil structure, fertility, and microbial communities (Jorge-Escudero et al., 2024; Li et al., 2023; Sutri et al., 2024). These functions enhance aeration, water infiltration, and organic matter decomposition, fostering favorable conditions for plant growth. However, the ecological functions of earthworms extend further, as they are intricately involved in carbon and nitrogen cycles, both of which are crucial for climate regulation (Liu et al., 2024; Toor et al., 2024).

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Rising greenhouse gas (GHG) concentrations (particularly CO₂, CH₄, and N₂O) have intensified interest in the role of natural systems in emissions and mitigation (Hugelius et al., 2024; Karim et al., 2024; Rabbi & Kovács, 2024). Soils are a major carbon sink, and earthworms influence both carbon sequestration and GHG emissions. While they promote humus formation and stabilize aggregates, their interactions with organic matter and microbes may increase CO₂ and N₂O release (Forey et al., 2023; Gao et al., 2022; Liu et al., 2024).

Despite these emissions, earthworms contribute positively to soil ecosystems, playing a key role in sustainable agriculture and climate resilience (Johnston et al., 2018; Toor et al., 2024). However, debate persists regarding their net impact on global warming, underscoring the need to examine the mechanisms behind their dual role.

The relationship between soil and climate highlights the importance of studying earthworms (Ahmad & Wang, 2024; Hamidov et al., 2018). As stewards of the largest terrestrial carbon sink, soils depend on biotic agents, such as earthworms, to regulate carbon storage, nutrient cycling, and organic matter decomposition (Azevedo et al., 2024; Narváez et al., 2022; Patoine et al., 2020). Understanding how earthworms both emit and mitigate GHGs is vital for guiding sustainable land management.

Given their introduction in agriculture to boost productivity (Gora et al., 2024; Lal, 2021; Vambe et al., 2023), it is essential to balance their ecological benefits with potential climate impacts. This review explores the dual role of earthworms in global warming, highlighting their contributions to GHG emissions and their potential as climate change mitigators.

Earthworms influence carbon and nitrogen cycling through multiple biological and biochemical pathways (Lv et al., 2019; Shang et al., 2026). Their ingestion and fragmentation of organic residues accelerate microbial decomposition, activating the priming effect that stimulates soil respiration and carbon mineralization. Simultaneously, casts and mucus exudates promote the formation of soil macroaggregates, physically protecting soil organic carbon from microbial degradation and contributing to long-term carbon stabilization (Emmerling et al., 2011; Meng et al., 2023). For nitrogen, earthworm burrowing enhances aeration, promoting nitrification in aerobic burrow walls, while micro-anaerobic zones in casts favor denitrification, resulting in nitrous oxide (N₂O) emissions. Additionally, earthworm gut microbiota facilitate mineralization of organic N into plant-available nitrate and ammonium, while supporting denitrifying communities (Chen & Whalen, 2016; Lv et al., 2019; Parkin & Berry, 1999). These interacting mechanisms illustrate the dual capacity of earthworms to stimulate carbon sequestration and nutrient availability, yet potentially increase greenhouse gas fluxes under intensive fertilization or moist soil conditions. (Boito et al., 2025; Du et al., 2025; Lv et al., 2018)

Recent advances in soil biogeochemistry provide deeper insights into how earthworms modulate biogeochemical cycles under diverse ecological settings. Their ability to fragment complex polymers such as lignin and cellulose through combined enzymatic and microbial interactions highlights a sophisticated decomposition system influenced by temperature, moisture, and substrate quality (Liao et al., 2024; Yang et al., 2023; Zhao et al., 2025). Earthworm mucus, rich in labile carbon compounds, stimulates microbial growth and enzyme activities, accelerating nutrient turnover. In addition, the gut environment, characterized by fluctuating oxygen levels and pH gradients, acts as a transient bioreactor where facultative anaerobes drive both nitrification and denitrification (Sun et al., 2020; Yang et al., 2023; Zhao et al., 2025). These mechanistic pathways demonstrate that earthworm-mediated nutrient cycling is not only physical but also biochemical, contributing to both soil fertility enhancement and greenhouse gas fluxes (Dang et al., 2025; Liu et al., 2019). Research integrating isotope tracing and microbial functional gene analysis increasingly supports the dualistic ecological pathways through which earthworms regulate soil carbon and nitrogen (Boito et al., 2025; Li et al., 2024). This scientific advancement suggests a paradigm shift from simplistic views of earthworms as universally beneficial to a more nuanced understanding that recognizes context-dependency across

climatic zones, soil textures, and management systems (Fonte et al., 2023; Gudeta et al., 2023).

2. Methods

This review synthesizes and critically evaluates current scientific literature on the dual role of earthworms in greenhouse gas (GHG) emissions and climate change mitigation. A structured literature search was conducted using electronic databases including Scopus, Web of Science, PubMed, and Google Scholar for articles published between 2000 and 2025. The search terms included combinations of keywords such as "earthworm AND carbon sequestration", "earthworm AND greenhouse gas", "earthworm AND CO₂/CH₄/N₂O emissions", "vermitechnology AND soil health", and "earthworm AND climate change mitigation". The inclusion criteria for this study consisted of peer-reviewed journal articles or review papers that examined the influence of earthworms on greenhouse gas (GHG) emissions. Eligible studies included field experiments, mesocosm trials, meta-analyses, and laboratory simulations related to the role of earthworms in GHG dynamics. In addition, the selected articles addressed topics such as soil carbon dynamics, nitrogen cycling, microbial interactions, and plant productivity within the context of earthworm activity. Articles were excluded if they lacked sufficient methodological detail, did not involve earthworms as a primary focus, or concentrated solely on ecosystem functions unrelated to GHG processes.

Articles were selected after screening titles, abstracts, and full texts. Priority was given to high-impact studies reporting quantitative GHG flux data, soil biogeochemical changes, or meta-analytic insights. Key findings were categorized thematically into several major areas, including earthworm-driven greenhouse gas (GHG) emissions such as CO₂, N₂O, and CH₄, carbon sequestration and soil aggregation processes, as well as the effects of soil properties and organic matter on ecosystem dynamics. In addition, the review examined the impacts of agricultural practices and vermitechnology, together with the role of earthworms in enhancing plant productivity and resilience. Data were qualitatively synthesized to highlight mechanisms and contextual dependencies influencing whether earthworms function more as GHG contributors or climate mitigators.

3. Results and Discussion

3.1 Earthworms as emission contributors

While earthworms play a vital role in ecosystem services, their activities can also contribute to greenhouse gas (GHG) emissions under certain conditions. By influencing soil respiration, nitrogen cycling, and methanogenesis, earthworms have been identified as potential sources of increased carbon dioxide (CO₂), nitrous oxide (N₂O), and methane (CH₄) emissions. These processes highlight the duality of earthworms' ecological roles, requiring a balanced assessment of their impact on greenhouse gas budgets.

3.1.1 Carbon dioxide CO₂ production

Soil respiration, primarily the CO₂ emitted by roots, microbes, and soil fauna, is a major flux in the global carbon cycle and a key indicator of soil health (Phillips & Nickerson, 2015; Sofu et al., 2023). Earthworms, as "ecosystem engineers," influence this process both directly through their respiration and indirectly by stimulating microbial decomposition via their burrowing and feeding activities (Ahmed & Al-Mutairi, 2022; Lubbers et al., 2013). Global soil respiration is estimated at $\sim 98 \pm 12$ Pg C annually, exceeding fossil fuel emissions and accounting for over 60% of ecosystem respiration (Bond-Lamberty & Thomson, 2010; Reichstein & Beer, 2008).

Earthworms contribute an estimated 1–2% of total soil CO₂ emissions, depending on density and activity (Lubbers et al., 2013). Their digestion of organic matter induces the "priming effect," accelerating microbial activity and releasing additional CO₂ and N₂O, a

potent GHG (Linden & Clapp, 2018). These effects are enhanced in warm, moist soils, especially in tropical or intensively farmed environments (Khan et al., 2022; Wang et al., 2024a). The temperature sensitivity ($Q_{10} = 2-3$) of soil respiration further amplifies concerns, as global warming could enhance both earthworm activity and GHG emissions (Lloyd & Taylor, 1994; Li, 2008).

Model projections suggest soil respiration could increase by 30% under future warming, accelerating climate change through positive feedbacks (Davidson & Janssens, 2006; Ren et al., 2024). Understanding the nuanced role of earthworms in these dynamics is vital for refining carbon models and designing sustainable soil management strategies that balance productivity with climate mitigation.

3.1.2 Nitrous oxide (N_2O) emissions

Nitrous oxide (N_2O) is a potent greenhouse gas with a global warming potential ~300 times greater than CO_2 over a century (IPCC, 2021). Earthworms significantly influence N_2O emissions by altering soil structure, aeration, and microbial communities through burrowing, feeding, and casting activities (Abail & Whalen, 2019; Maslov et al., 2022). These activities stimulate microbial processes, such as nitrification and denitrification, which are the primary drivers of N_2O release.

Aerobic conditions in worm burrows enhance nitrification, while anoxic microsites in casts favour denitrification, making earthworm-modified zones hotspots for N_2O production (Lubbers et al., 2013; Manono, 2016). Some studies report up to 42% higher N_2O emissions in soils with active earthworm populations (Depkat-Jakob et al., 2013; Wu et al., 2015). Earthworm species influence these dynamics differently: epigeic worms accelerate surface decomposition, while anecic and endogeic species promote deeper mixing and oxygen fluctuation, intensifying emissions (Hoeffner et al., 2018; Pham et al., 2024).

Lumbricus terrestris, for example, increases N_2O emissions in temperate soils, even under reduced fertilizer inputs, primarily due to stimulated denitrifiers and efficient residue-soil mixing (Maslov et al., 2022). Earthworm guts also host denitrifiers, further contributing to emissions (Patoine et al., 2020; Waqar et al., 2019).

To mitigate these risks, land management must strike a balance between the ecological benefits of earthworms and their contributions to GHG emissions. Practices such as reduced tillage, organic amendments, and precision fertilization can reduce emissions by 15–20% (Lubbers et al., 2013; Van Groenigen et al., 2014). Stabilizing organic matter in casts may also reduce the availability of substrates for denitrification. While earthworms enhance soil fertility and nutrient cycling, they can also increase N_2O emissions, particularly under conditions of warming and intensive agriculture. Integrating their role into climate-smart practices is essential for sustainable agroecosystem management.

3.1.3 Methane (CH_4) emissions

Methane (CH_4), a potent greenhouse gas with a global warming potential 25–80 times greater than CO_2 over 20 years, originates mainly from agriculture, fossil fuels, and waste systems (South, 2024). Earthworms, though not direct CH_4 producers, can influence CH_4 fluxes by modifying soil conditions that affect methanogenesis and methanotrophy (Dean et al., 2018; Maccanti et al., 2017).

The environments of the earthworm gut and cast may harbor methanogenic archaea and methanotrophic bacteria. Their bioturbation alters soil aeration, moisture, and nutrient dynamics, potentially shifting microbial balances. Kang et al. (2024) demonstrated that *Eisenia fetida* and *Moniligaster japonicus* significantly reduced soil CH_4 uptake at 14.2°C and 17.2°C. At 14.2°C, control soils absorbed 0.459 mg CH_4 -C kg⁻¹, while earthworm treatments absorbed only 0.340 and 0.163 mg CH_4 -C kg⁻¹, respectively. This was attributed to enhanced methanogen diversity and reduced methanotroph abundance resulting from the influence of earthworms.

Li et al. (2023) further found that earthworms increased total dissolved nitrogen and microbial biomass carbon by 30.1% and 9.4%, respectively, indirectly affecting CH₄ dynamics. Earthworm activity can foster CH₄-emitting microenvironments, especially under moist conditions and nitrogen enrichment. While millipedes emit CH₄ directly through gut fermentation, earthworms regulate net CH₄ fluxes by influencing microbial interactions. The impact of earthworms on CH₄ emissions is thus highly context-dependent, influenced by soil temperature, moisture, and nutrient status.

3.2 Earthworms as climate mitigators

Earthworms play a crucial role in critical ecosystem processes through their burrowing, feeding, and casting activities. Their ability to store carbon in stable soil aggregates, improve water infiltration, and enhance plant growth underscores their role as key players in maintaining soil health and productivity

3.2.1 Carbon sequestration

Rising atmospheric CO₂ concentrations necessitate effective carbon mitigation strategies, particularly through the enhancement of natural carbon sinks. Soils, as the largest terrestrial carbon reservoir (~2,500 Gt C), store more carbon than the atmosphere and vegetation combined (Lal, 2004). Soil organic matter (SOM), resulting from plant litter decomposition, is central to this function, with a global sequestration potential of ~0.12 Pg C yr⁻¹ (Poepflau & Don, 2015). Earthworms, as ecosystem engineers, play a crucial role in carbon cycling through their impact on soil structure, microbial communities, and the turnover of organic matter (Lal, 2021; Wu et al., 2017).

Earthworm activity enhances carbon stabilization by promoting macroaggregate formation and protecting SOM from mineralization. Comparative studies reveal that earthworms increase stabilized carbon pools while decreasing potentially mineralizable fractions (Fonte et al., 2010). Their feeding and casting actions stimulate priming effects and carbon turnover, while also contributing to deeper root penetration and increased carbon incorporation into soil aggregates (Yang et al., 2022; Zhu et al., 2021). Vermicompost application (another earthworm-mediated process) has been shown to boost SOC by up to 52% in salt-affected soils, improving soil fertility and carbon sequestration (Farooqi et al., 2024).

Furthermore, earthworms create biogenic macroaggregates that physically protect organic matter, particularly in no-till systems, where rhizodeposit carbon is efficiently stored (Leon et al., 2014). Their activities form what has been termed an "earthworm-mediated carbon trap," where stabilization outweighs mineralization, thereby enhancing long-term soil carbon retention (Lago et al., 2020; Zhang et al., 2013). Sustainable practices, such as reduced tillage, organic amendments, and vermicomposting, further amplify this effect by enhancing soil biodiversity and carbon storage (Barthod et al., 2021).

3.2.2 Improved soil structure and water infiltration

Earthworms significantly enhance soil structure through burrowing and casting activities, improving porosity, water infiltration, and retention. Studies have shown that earthworm burrowing can increase macroporosity by up to 30%, facilitating water movement and root penetration in compacted soils. Their casts, which contain 50-70% organic matter, are more stable than the surrounding soil and contribute to the formation of aggregates with a mean diameter of 2-4 mm. These aggregates enhance soil porosity and water-holding capacity (Tiwari et al., 2022)

The improved soil structure has critical implications for water infiltration, drought resistance, and erosion control (Galindo et al., 2022; Muoni et al., 2020). For instance, macropores created by earthworms increase rainwater infiltration rates by 25-40%, resulting in a 20-35% reduction in surface runoff. This enhanced infiltration replenishes soil

water reserves, ensuring 10-20% more water is available to plants during dry periods, which improves drought resistance. Furthermore, the stable aggregates formed through earthworm activity reduce soil erosion by up to 50%, particularly in areas prone to heavy rainfall (Bertrand et al., 2015).

Numerous studies confirm the positive influence of earthworms on soil physical properties. For example, the physical recovery of the topsoil was assessed over four years using a visual structure evaluation method alongside standard physical soil quality measurements, including soil bulk density, macroporosity, water infiltration rates, and earthworm populations. Macroporosity increased during the initial four years after establishing permanent pasture, while soil bulk density significantly decreased from the first to the fourth year. Earthworm populations grew substantially, increasing from 120 to 440 and 620 individuals per square meter. Additionally, water infiltration rates doubled after the second year (McLenaghan et al., 2017). These findings emphasize the potential of earthworms in climate change adaptation strategies. Promoting earthworm populations in agricultural and natural ecosystems can enhance soil resilience to drought and erosion, contributing to more sustainable land management practices.

3.2.3 Enhanced plant growth and productivity

Earthworms are vital components of agroecosystems, significantly enhancing plant growth and productivity. A meta-analysis by Van Groenigen et al. (2014) found that earthworms can increase crop yields by 25% or more and aboveground biomass by 23%, particularly in low-nitrogen soils with crop residues. They facilitate nutrient cycling by decomposing organic matter and mobilizing nitrogen, thus supporting optimal plant development.

Beyond nutrient supply, earthworms mitigate drought effects by maintaining soil moisture and slowing the rate of drying, thereby aiding plant survival under water stress (Das & Isaac, 2024; Zheng et al., 2022). Recent research has highlighted that these benefits are also linked to shifts in the microbiome. Earthworm activity fosters beneficial microbial communities that support plant growth by promoting the production of phytohormones and enhancing nutrient mineralization (Hodson et al., 2023).

Additionally, earthworms enhance soil structure through their burrowing activities, which improve porosity, water infiltration, and root access. Their nutrient-rich casts serve as natural fertilizers, thereby reducing the need for synthetic inputs (Zheng et al., 2022; Manzoor et al., 2024). These ecosystem services have inspired the advancement of vermitechnology, a sustainable method of composting and soil enhancement that improves soil health and crop yields using earthworms (Pan & Huang, 2024; Terefe et al., 2024; Sharma et al., 2024; Tran et al., 2024).

3.3 Factors influencing greenhouse gas emissions from earthworms

Earthworms significantly influence the emissions of greenhouse gases (GHGs) such as carbon dioxide (CO₂), nitrous oxide (N₂O), and methane (CH₄) through their activities in soil ecosystems.

3.3.1 Earthworm functional groups and population

Earthworms are classified into three functional groups (epigeic, endogeic, and anecic) each contributing differently to greenhouse gas (GHG) dynamics based on their feeding strategies and burrowing behaviour. Their activities influence soil carbon and nitrogen cycling, thereby modulating CO₂, N₂O, and CH₄ emissions. Engell et al. (2021) found that anecic earthworms (*Lumbricus terrestris*) increased CO₂ emissions by 22% compared to controls, while soil inversion (buried residues) raised N₂O emissions by 188%. Anecic worms also assimilated more crop-derived carbon than endogeic ones, indicating distinct roles in carbon turnover.

The interaction between soil fauna and management practices further affects GHG fluxes. Ganault et al. (2024) reported that endogeic earthworms or their combination with anecic types reduced N₂O emissions by up to 44.8%, especially under drying–wetting cycles. Earthworm-induced increases in soil macroporosity reduced anaerobic microsites, thereby lowering GHG emissions. The presence of plants also reduced N₂O emissions while slightly increasing CO₂.

Species-specific responses were evident in Zhu et al. (2023), where *Metaphire tschiliensis* (endogeic) induced greater CO₂ and N₂O emissions than the epigeic *Eisenia nordenskioldi*, especially under conventional tillage (CT). No-till (NT) systems promoted more stable soil carbon, whereas CT accelerated decomposition and GHG release. Interestingly, combined species treatments reduced emissions, possibly due to food competition, and earthworm survival was higher in less disturbed NT soils.

John et al. (2020) further showed that earthworm density significantly shaped GHG outcomes in upland rice systems. At high densities (450 earthworms m²), CH₄ emissions dropped by 71%, especially under rice straw amendment. While earthworms had minimal impact on N₂O, they reduced overall global warming potential (GWP) by up to 55%, demonstrating their mitigation potential in agroecosystems.

Overall, the identity of the earthworm group, population density, and interactions with tillage and organic inputs collectively determine GHG dynamics. Their ecological functions can either exacerbate or mitigate emissions, highlighting the need to manage earthworm populations strategically within sustainable land-use systems.

3.3.2 Quality and quantity of organic matter

The type and quality of organic matter consumed by earthworms strongly influence GHG emissions. Nitrogen-rich materials, such as fresh manure, enhance microbial activity, promoting nitrification and denitrification, which in turn increases N₂O emissions. Earthworm guts and casts create favourable microsites for denitrifiers, amplifying these effects (Lubbers et al., 2013). In contrast, easily decomposable carbon sources (rich in cellulose and hemicellulose) stimulate microbial respiration, leading to bursts of CO₂ emissions, especially during early decomposition stages.

Wang et al. (2021) found that compost and biochar amendments increased soil organic carbon (SOC) by 23.26% and 32.69%, respectively. Earthworms enhanced soil carbon (SOC) under compost by increasing humic acid (HA) content and stability, thereby reducing CO₂ emissions. However, in biochar-amended soils, earthworms reduced HA aromaticity and promoted carbon mineralization, increasing CO₂ release. This highlights the dual role of earthworms: stabilizing carbon through compost, but undermining the sequestration effect of biochar.

Earthworm functional groups also influence emission patterns. Epigeic species intensify CO₂ emissions by processing surface litter, while endogeic species more strongly affect N₂O due to their subsurface activity (Jin et al., 2023; Wu et al., 2024). Gao et al. (2022) reported that while biochar reduced CO₂ emissions by enhancing carbon fixation, combining it with earthworms increased N₂O due to elevated substrate availability and microbial gene activity (e.g., *nirA*). Similarly, Duan et al. (2025) showed that Bt rice straw properties (not Bt protein) determined GHG outcomes. The presence of earthworms increased N₂O emissions by as much as 1.28 times, primarily due to nitrate (NO₃⁻) accumulation and shifts in microbial communities. These findings underscore the importance of carefully selecting organic inputs and considering their interactions with soil fauna. Optimizing C/N ratios and aligning organic matter quality with soil management goals can mitigate GHG emissions while enhancing soil health.

3.3.3 Soil moisture and aeration

Soil moisture is a pivotal factor that governs the fluxes of greenhouse gases (GHGs) mediated by earthworm activity. The availability of moisture in the soil determines the

aerobic or anaerobic nature of microbial habitats, which directly impacts the production of carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O). In well-aerated soils, aerobic conditions prevail, promoting microbial respiration and the decomposition of organic matter, which leads to increased CO₂ emissions (Chen et al., 2014; Horváthová et al., 2021).

The study by Gorbunova et al. (2020) investigated the influence of soil moisture levels on the capacity of *Eisenia fetida* (earthworms) to reintegrate carbon from decomposed rice straw into the soil and its impact on greenhouse gas (GHG) emissions. The experiment, conducted in mesocosms using rice paddy soils from three regions in Russia, tested varying soil moisture levels (12%, 25%, 50%, and 75% of the soil's water-holding capacity). The results showed that earthworms significantly increased CO₂ emissions in Krasnodar and Kalmykia soils, with the highest CO₂ emissions occurring at 25% moisture, followed by 12%, 50%, and 75% moisture levels. Methane (CH₄) emissions were negligible at 12% and 25% moisture levels but significantly increased at 50% and 75%, with earthworms further amplifying these emissions, especially at the highest moisture level. Additionally, soil carbon content was positively affected by earthworms at the 25% moisture level, with no significant change at higher moisture levels. The study concluded that *Eisenia fetida* can contribute to carbon sequestration during rice straw degradation, but its effect on GHG emissions depends on moisture conditions. At optimal moisture levels (around 25%), earthworms can promote carbon reincorporation into the soil, but at higher moisture levels, increased GHG emissions, mainly CH₄, may offset the benefits of carbon sequestration. This emphasizes the importance of soil moisture management in controlling soil carbon and GHG fluxes during rice straw decomposition.

3.3.4 Earthworm-microbe interactions

Earthworms enhance microbial activity in soils through their gut processes and the production of nutrient-rich casts. Their digestive system creates a favourable environment for microbial proliferation, transforming complex organic matter into bioavailable forms. The excreted casts act as microbial hotspots, intensifying processes such as nitrification and denitrification, which can lead to elevated N₂O emissions. However, some species mitigate these effects. For example, *Maoridrilus transalpinus* reduced N₂O emissions by 20% in nitrogen-enriched soils due to improved soil aeration and suppressed denitrification, while also increasing dehydrogenase activity by 65% (Kim et al., 2017).

Earthworm-microbe interactions enhance carbon and nitrogen turnover, supporting nutrient cycling. Studies have shown that microbial communities undergo shifts in response to environmental conditions. In a biocover system, Lee et al. (2018) observed an increase in methanotroph abundance from winter to summer (5.4% to ~14.8%), resulting in an improvement in methane oxidation efficiency from 43% to 96%. This highlights seasonal effects on microbial functions relevant to GHG mitigation.

Similarly, Yasuda et al. (2017) found that microbial communities in compost biofilters shared genetic similarities with those in earthworm guts. Denitrification gene abundance (e.g., *nosZ*) was linked to microbial communities adapted to low-oxygen and high-organic matter environments. Compost extracts further boosted denitrification activity, underscoring the role of earthworm-associated microbes in engineered and natural systems. These findings demonstrate the dual ecological role of earthworms: promoting soil fertility while potentially increasing GHG emissions. Balancing the benefits of their use with environmental costs is essential for sustainable soil and climate management strategies.

3.3.5 Soil properties

Soil texture, pH, and organic carbon content critically shape earthworm-mediated greenhouse gas (GHG) emissions. Liu et al. (2024) demonstrated that initial soil properties, particularly pH, soil organic carbon (SOC), total nitrogen (TN), and microbial biomass carbon (MBC), varied significantly with elevation and vegetation type. SOC and dissolved organic carbon (DOC) generally declined across zones after 71 days of earthworm and litter

treatment, except in tundra soils. These changes were attributed to increased microbial activity and nutrient turnover. Notably, nitrate nitrogen (NO_3^- -N) was a strong predictor of both CO_2 and N_2O emissions, explaining 35.34% and 42.83% of their variability, respectively. MBC also significantly influenced N_2O fluxes, highlighting the importance of microbial biomass and nitrogen availability in regulating GHG dynamics.

Organic carbon serves as a vital substrate for microbial respiration and GHG production. In tropical soils, *Rhinodrilus alatus* alters soil characteristics through its casts, which showed higher moisture (51%), pH (4.03), and nutrient content, total nitrogen (1.98 g kg^{-1}) and organic carbon (20.42 g kg^{-1}), compared to control soils (Santos et al., 2021). Although CO_2 emissions were comparable to non-ingested soil, N_2O emissions in fresh casts were markedly higher (up to $1.61 \text{ nmol g}^{-1} \text{ day}^{-1}$), driven by elevated NH_4^+ concentrations and denitrification. Occasional CH_4 emissions were also observed, marking the first report of methane flux from *R. alatus* casts. These findings underscore the role of soil properties, especially pH, ammonium, and organic carbon, in shaping microbial processes and GHG fluxes in earthworm-influenced tropical ecosystems.

3.3.6 Agricultural management practices

Agricultural practices such as tillage and fertilization significantly influence earthworm populations and their associated greenhouse gas (GHG) emissions. No-till systems enhance soil structure and organic matter, promoting earthworm abundance. However, these systems may increase nitrous oxide (N_2O) emissions due to higher moisture and nitrogen levels, particularly in earthworm casts that act as microbial hotspots. Ardeni et al. (2024) showed that conservation practices like minimum tillage (MT) and strip tillage (ST) increased soil carbon sequestration ($1.06\text{--}1.21 \text{ Mg C ha}^{-1} \text{ y}^{-1}$), reduced CO_2 emissions, and boosted earthworm populations by up to 133% in clay soils. These practices also improved soil structure, nutrient content, and tomato yields, indicating their potential for sustainable crop production. Further studies are needed to clarify the long-term dynamics of N_2O under such systems.

Earthworm activity is also influenced by residue management. In a short-term trial, Li et al. (2024) reported that straw incorporation and earthworm bioturbation elevated CO_2 emissions by up to 436% in compact soils due to increased macroporosity and surface residue decomposition. However, this effect declined over time as soil quality improved and burrowing decreased.

Fertilizer type plays a critical role in shaping earthworm populations and GHG emissions. Deru et al. (2023) found that organic fertilizers with high C:N ratios, such as the solid fraction of cattle slurry, increased earthworm abundance by 35% in drained peat soils, whereas inorganic nitrogen fertilizers reduced populations by 24%. Although inorganic inputs increased microbial activity and nitrogen uptake, they also lowered soil pH and accelerated peat decomposition. In contrast, organic amendments supported carbon retention and biodiversity, aligning with regenerative agriculture goals.

Overall, the evidence suggests that the environmental role of earthworms is context-dependent. In systems with balanced nutrient inputs, organic amendments, and reduced soil disturbance, earthworms promote soil aggregation, humus formation, and plant productivity, thereby functioning predominantly as climate mitigators (Kumar et al., 2025; Lu et al., 2025; Wang et al., 2024b). Conversely, under high nitrogen fertilization, compacted soils, or waterlogged environments, earthworm-induced hotspots may elevate N_2O and CO_2 emissions. These findings underscore the importance of integrating earthworm ecology into climate-smart agricultural strategies, emphasizing precision fertilization, organic amendments, and sustainable tillage practices to optimize ecological benefits while minimizing greenhouse gas emissions (Forey et al., 2023; Meng et al., 2021; Wang et al., 2023).

Moreover, the consistency of findings across controlled experiments and field studies emphasizes the relevance of earthworm-driven processes in real agricultural landscapes. Yet, considerable variability remains due to species-specific behavior, soil-crop interactions,

and climatic variability (Liao et al., 2024; Vidal et al., 2023; Zi et al., 2025). For instance, tropical agroecosystems with high soil temperatures and rapid organic matter turnover often demonstrate more substantial priming effects and elevated respiratory CO₂ fluxes compared to temperate systems. Conversely, temperate conservation agriculture systems appear to benefit from higher aggregate stability and carbon storage, driven by anecic and endogeic species (Das et al., 2025; King & Hungria, 2002; Wang et al., 2024b). Future refinement of mechanistic models should explicitly incorporate earthworm functional diversity and soil microhabitat heterogeneity. Integrating earthworm parameters into national greenhouse gas inventory methodologies and life-cycle assessments of agricultural production may provide more accurate climate accounting (Burton & Eggleton, 2016; Korboulewsky et al., 2016; Torppa et al., 2024; Vion-Guibert et al., 2024). Furthermore, there is an emerging interest in whether earthworm management through inoculation strategies, plant-soil-biota engineering, or selective habitat manipulation can be used to optimize ecosystem services in agroecological and regenerative farming systems. These approaches require interdisciplinary collaboration that spans soil ecology, microbiome science, agronomy, climate modelling, and socioeconomic policy (Azhar et al., 2024; Capowiez et al., 2021; Coulis, 2021; Emmerling et al., 2021; Gong et al., 2018).

Furthermore, earthworm-mediated soil improvements contribute not only to nutrient cycling but also to the long-term resilience of agroecosystems. Their role in enhancing porosity and moderating moisture availability becomes increasingly relevant under climate variability, where episodic drought and heavy rainfall events can compromise soil function (Dang et al., 2025; Kooch et al., 2025; Toor et al., 2024; Wang et al., 2024a). In such situations, earthworm burrowing improves water infiltration and storage, while stable aggregates resist erosion and compaction. These benefits demonstrate that earthworms are ecosystem engineers whose influence extends beyond biochemical cycling to broader ecological stability (Ahmed & Al-Mutairi, 2022; Ojha & Devkota, 2014; Wang et al., 2024b). Thus, understanding and managing earthworm populations can help strengthen soil buffering capacity and secure food production under changing climate scenarios (Akhila & Entoori, 2022; Kooch et al., 2025; Siebert et al., 2019).

Table 1. Summary of research findings: the role of earthworms in greenhouse gas emissions and climate mitigation

No.	Aspect	Key Findings	Key References
1	CO ₂ Emissions	Earthworms contribute an estimated 1–2% of total soil CO ₂ emissions, depending on population density and activity level. The priming effect induced by earthworm digestion of organic matter accelerates microbial activity, leading to elevated CO ₂ and N ₂ O release. Temperature sensitivity of soil respiration ($Q_{10} = 2-3$) suggests that global warming may amplify earthworm-mediated CO ₂ emissions. Model projections indicate soil respiration could increase by 30% under future warming scenarios, creating a positive climate feedback loop.	Lubbers et al. (2013) Linden & Clapp (2018) Lloyd & Taylor (1994); Li (2008) Davidson & Janssens (2006); Ren et al. (2024)
2	N ₂ O Emissions	Earthworm activity can increase soil N ₂ O emissions by up to 42% compared to earthworm-free soils. Aerobic conditions in earthworm burrows enhance nitrification, while anoxic microsites in casts promote denitrification — both are hotspots for N ₂ O production. Lumbricus terrestris increases N ₂ O emissions in temperate soils even under reduced fertilizer inputs, driven by stimulated denitrifiers and efficient residue–soil mixing.	Depkat-Jakob et al. (2013); Wu et al. (2015) Lubbers et al. (2013); Manono (2016) Maslov et al. (2022)

		Reduced tillage, organic amendments, and precision fertilization can lower N ₂ O emissions by 15–20%.	Lubbers et al. (2013); Van Groenigen et al. (2014) Kang et al. (2024)
3	CH ₄ Emissions	Eisenia fetida and Moniligastrer japonicus significantly reduced soil CH ₄ uptake at 14.2°C and 17.2°C, attributed to enhanced methanogen diversity and reduced methanotroph abundance. Earthworms increased total dissolved nitrogen by 30.1% and microbial biomass carbon by 9.4%, indirectly affecting CH ₄ dynamics.	Li et al. (2023)
4	Carbon Sequestration	The impact of earthworms on CH ₄ fluxes is highly context-dependent, governed by soil temperature, moisture levels, and nutrient status. Earthworms increase stabilized carbon pools by promoting macroaggregate formation while decreasing potentially mineralizable fractions. Vermicompost application can boost soil organic carbon (SOC) by up to 52% in salt-affected soils, improving soil fertility and long-term carbon storage.	Dean et al. (2018); Maccanti et al. (2017) Fonte et al. (2010) Farooqi et al. (2024)
5	Soil Structure and Water Infiltration	Earthworm activity creates a biogenic 'carbon trap' in which stabilization outweighs mineralization, enhancing long-term soil carbon retention, particularly in no-till systems. Earthworm burrowing can increase soil macroporosity by up to 30%; casts (containing 50–70% organic matter) form stable aggregates with a mean diameter of 2–4 mm. Macropores created by earthworms increase rainwater infiltration rates by 25–40%, reduce surface runoff by 20–35%, and improve plant water availability by 10–20% during dry periods.	Lago et al. (2020); Zhang et al. (2013) Tiwari et al. (2022) Bertrand et al. (2015)
6	Plant Growth and Productivity	Earthworm populations increased from 120 to 620 individuals/m ² over four years under permanent pasture; water infiltration rates doubled after the second year. Earthworms increase crop yields by ≥25% and aboveground biomass by 23%, particularly in low-nitrogen soils amended with crop residues. Earthworm activity fosters beneficial microbial communities that produce phytohormones and enhance nutrient mineralization, thereby supporting plant growth.	McLenaghan et al. (2017) Van Groenigen et al. (2014) Hodson et al. (2023)
7	Functional Groups and Population Density	Nutrient-rich earthworm casts function as natural fertilizers, reducing the need for synthetic inputs and forming the basis of vermitechnology development. <i>Anecic earthworms (Lumbricus terrestris) increased CO₂ emissions by 22%; soil inversion further raised N₂O emissions by 188%.</i> Endogeic earthworms or their combination with anecic species reduced N ₂ O emissions by up to 44.8%, especially under drying–wetting cycles, due to increased soil macroporosity. At high earthworm density (450 ind/m ²), CH ₄ emissions decreased by 71% and overall global warming potential (GWP) declined by up to 55% in upland rice systems.	Pan & Huang (2024); Terefe et al. (2024) Engell et al. (2021) Ganault et al. (2024) John et al. (2020)

8	Soil Moisture and Aeration	CO ₂ emissions peaked at 25% soil moisture; CH ₄ emissions increased significantly at 50–75% moisture, with earthworms further amplifying emissions at the highest moisture level. At optimal moisture (~25%), earthworms promote carbon reincorporation into soil; at higher moisture levels, elevated CH ₄ emissions may offset the benefits of carbon sequestration.	Gorbunova et al. (2020) Gorbunova et al. (2020)
9	Agricultural Management Practices	Minimum tillage (MT) and strip tillage (ST) increased carbon sequestration (1.06–1.21 Mg C ha ⁻¹ yr ⁻¹) and earthworm populations by up to 133% in clay soils. Organic fertilizers with high C:N ratios increased earthworm abundance by 35%, while inorganic nitrogen fertilizers reduced populations by 24% and lowered soil pH. In systems with balanced nutrient inputs and minimal soil disturbance, earthworms act as climate mitigators; under high nitrogen fertilization or waterlogged conditions, they may function as GHG emitters.	Ardenti et al. (2024) Deru et al. (2023) Kumar et al. (2025); Forey et al. (2023)

Note: SOC = Soil Organic Carbon; GWP = Global Warming Potential; N₂O = Nitrous Oxide; CO₂ = Carbon Dioxide; CH₄ = Methane; SOM = Soil Organic Matter; ind = individuals.

4. Conclusions

While earthworms contribute to greenhouse gas (GHG) emissions, particularly CO₂ and N₂O, their overall impact on climate change is more beneficial as climate mitigators. Their activities enhance carbon sequestration in soils by promoting the formation of stable aggregates and humus, which store carbon for extended periods. Studies indicate that earthworms can significantly increase soil carbon stocks and improve water-holding capacity, reducing soil erosion and enhancing drought resistance. Although earthworms increase soil CO₂ emissions by 1–2% of total soil flux and may elevate N₂O emissions in certain conditions (up to 42% in agricultural soils), their contribution to carbon storage and overall soil health remains a more significant benefit. Their ability to enhance soil structure, water infiltration, and plant productivity makes them crucial for sustainable agriculture and climate change adaptation. Conservation practices, such as reduced tillage and the use of organic amendments, are essential for optimizing earthworm populations to maximize their climate mitigation potential. The net effect of earthworms as climate mitigators far exceeds their role as contributors to emissions, underscoring their importance in strategies for sustainable land management and climate change mitigation.

The integration of ecological knowledge, field-based measurements, and advanced analytical tools will be crucial for refining our understanding of earthworm-driven processes under real-world agricultural constraints. Promoting farmer-centered soil biodiversity management, strengthening soil-health-based incentive schemes, and linking earthworm indicators to sustainability certification programs could accelerate the adoption of earthworm-friendly practices. Ultimately, recognizing earthworms as biological assets within climate mitigation frameworks reinforces their importance in developing sustainable agricultural landscapes and resilient ecosystems.

Future research should focus on quantifying long-term greenhouse gas balances of earthworm-managed soils across climatic zones, crop systems, and soil types, particularly under regenerative agriculture and reduced-input systems. Policymakers and agricultural stakeholders should integrate earthworm-friendly practices, such as minimal soil disturbance, organic amendments, and biodiversity-based fertilization, into national climate-smart agriculture frameworks. These strategies are essential for maximizing earthworm-mediated soil carbon sequestration while mitigating potential nitrogen-related emissions, thereby supporting both food security and global climate targets.

In addition to scientific advances, the global movement toward sustainable farming frameworks, such as the FAO's Soil Health Agenda, the EU Green Deal, and regenerative agriculture initiatives, creates opportunities to embed earthworm ecology into policy instruments. Incentive-based programs, such as carbon credits, payment for ecosystem services, and nature-positive agriculture schemes, could explicitly integrate soil biota indicators, including earthworm diversity and biomass. Such policy mechanisms would encourage farmers to adopt practices that support soil biodiversity, reduce their dependency on synthetic nitrogen, and enhance carbon sequestration. However, standardized monitoring protocols and threshold values must be established to avoid ambiguity in implementation. Remote sensing, machine learning, and in-field biosensors may serve as emerging technologies to quantify soil biological indicators at scale. Bridging scientific knowledge with policy design will ensure that the benefits of earthworms are recognized and safeguarded within agricultural transformation pathways.

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Informed Consent Statement

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Data Availability Statement

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

Conflicts of Interest

The author declares no conflict of interest.

Declaration of Generative AI Use

During the preparation of this work, the author used ChatGPT (OpenAI, San Francisco, CA, USA) to assist in improving the clarity, organization, and academic tone of the manuscript. After using this tool, the author reviewed and edited the content as needed and took full responsibility for the content of the publication.

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Biography of Author

Syarifinnur, Department of Agrotechnology, Faculty of Agriculture, Universitas Nahdlatul Wathan Mataram, Mataram, West Nusa Tenggara 83125, Indonesia.

- Email: syarifinnur@gmail.com
- ORCID: 0000-0002-9078-5360
- Web of Science ResearcherID: KAL-9822-2024
- Scopus Author ID: 57221752244
- Homepage: <https://sinta.kemdiktisaintek.go.id/authors/profile/6966763/?view=googlescholar>