

EARTHWORMS UNDER PESTICIDE STRESS: ECOTOXICOLOGICAL RESPONSES, BIOMARKER ALTERATIONS, AND IMPLICATIONS FOR SUSTAINABLE AGRICULTURE

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ABSTRACT

Earthworms are crucial contributors to soil processes, supporting ecosystem services such as nutrient cycling, organic matter decomposition, and soil structure enhancement. As bioindicators of chemical toxicity, they reflect soil health and contaminant effects. However, intensive agricultural practices, particularly pesticide usage, can negatively impact earthworm populations and their ecological functions. Pesticides interfere with enzymatic activity, increase mortality, reduce reproduction and growth, alter feeding behavior, and decrease population biomass and density. Among chemical classes, insecticides and fungicides are the most detrimental to survival and reproduction, respectively. Recent studies emphasize the importance of sensitive testing methods, such as reproduction assays, to evaluate sublethal effects, as acute mortality tests may underestimate ecological risk. This review synthesizes literature from 2020–2025 on pesticide impacts on earthworms, highlighting knowledge gaps, and emphasizing the role of earthworms and vermicomposting in sustainable soil management.

KEYWORDS: Earthworms, Pesticides, Soil management

INTRODUCTION

The uncontrolled use of pesticides has resulted in widespread environmental contamination, prompting the need for environmental risk assessments to evaluate their toxicity on soil and aquatic organisms (Choudhary et al., 2021; Ramesh & Singh, 2022). Earthworms, comprising up to 92% of soil invertebrate biomass, play a vital role in nutrient cycling, organic matter decomposition, and vermicomposting, making them excellent bioindicators of soil health (Mehta et al., 2023; Singh & Kumar, 2021). Earthworms convert organic waste into nutrient-rich vermicast, improving soil fertility, structure, porosity, water retention, and microbial diversity (Zhang et al., 2022; Patel et al., 2021). Vermicompost has been shown to enhance crop productivity by 20–35% and reduce pathogen prevalence in soil (Sharma et al., 2022). Their burrowing activity promotes aeration and humus formation, while their digestion stabilizes organic residues into bioavailable nutrients (Kaur & Rani, 2020; Verma et al., 2024).

Modern agriculture relies heavily on chemical herbicides, insecticides, and fertilizers to increase yield, but long-term application has led to declining soil health, biodiversity loss, and environmental pollution (Choudhary et al., 2021; Ramesh & Singh, 2022). Pesticides persist in soil longer than many organic pollutants, leach into water bodies, bioaccumulate in food chains, and generate harmful byproducts during degradation (Liu et al., 2023; Mehta et al., 2023). Studies show that pesticides affect earthworms at multiple levels: enzyme inhibition, behavioral changes, growth retardation, reproduction decline, and population reduction (Sharma et al., 2022; Verma et al., 2024). Insecticides and fungicides are most toxic to survival and reproduction, while herbicides have sublethal but significant effects (Kaur & Rani, 2020). Heavy metals and other contaminants also exacerbate soil toxicity, complicating assessments of chemical combinations (Patel et al., 2021). Bioremediation using earthworms and vermicomposting has emerged as an effective approach for pesticide degradation, achieving up to 80–85% removal of certain herbicides, including lambda cyhalothrin and folpet, under controlled studies (Zhang et al., 2022; Mehta et al., 2023). Implementing sustainable agricultural practices that support earthworm populations is essential to maintain soil fertility, enhance crop production, and reduce environmental risks (Liu et al., 2023; Verma et al., 2024).

Pesticide Production and Consumption in the World and India Global Scenario

Currently, approximately 2.1 million tons of pesticides are used worldwide annually, with 44% herbicides, 27% fungicides, 22% insecticides, and 7% other types (FAO, 2022). Global pesticide consumption has increased more than 1.5 times over the last three decades, reflecting the intensification of agriculture (Zhang et al., 2021). The top five pesticide-consuming

countries are China, the USA, Argentina, Thailand, and Brazil. China alone accounts for ~30–35% of global pesticide consumption, while the USA represents nearly 15% of the global market in recent years (Li et al., 2023; FAO, 2022).

India

Pesticide production in India began in 1952 with benzene hexachloride (BHC), followed by DDT (Kumar et al., 2021). Production rose from 5,000 metric tons in 1958 to 85,000 metric tons in the 1990s, with insecticides dominating the output. India is currently ranked 12th globally, producing ~217,000 metric tons of insecticides in 2019 and contributing substantially to Asia's pesticide market (Sharma et al., 2024).

Pesticide use in India has increased over time. The gross cropped area (GCA) usage rose from 0.29 kg/ha in 2014–15 to ~0.6 kg/ha in 2024, still significantly lower than other countries like China (13 kg/ha) and Japan (12 kg/ha) due to small landholdings and limited purchasing capacity of farmers (Patel et al., 2022; Singh & Mehta, 2023). The growing use of herbicides is largely attributed to rising labor costs for manual weed management.

Persistent organic pollutants such as DDT and endosulfan remain detectable in Indian soils despite bans, posing risks to ecosystems and human health (Kumar et al., 2021; Sharma et al., 2024). Globally, illegal pesticide use persists, especially in developing countries. For instance, some Latin American nations continue to apply chemicals banned elsewhere, increasing environmental contamination (Valenzuela et al., 2020). Similarly, in Ukraine, ~50 of 170 used pesticides are highly persistent, with DDT and hexachlorocyclohexane contaminating ~24% of agricultural land (Ivanov et al., 2021).

Excessive use of herbicides like acetochlor and glyphosate has led to detectable residues in soil, water, and food, challenging their assumed safety for non-target organisms (Sun et al., 2021; Oliveira et al., 2022). Studies from China, Brazil, and Canada report high pesticide residues in agricultural soils, emphasizing that improper use contributes to environmental contamination and ecological risks (Li et al., 2023; Oliveira et al., 2022).

Ecological Classification of Earthworms

Earthworms are classified into three ecological groups based on feeding, burrowing habits, and soil strata: epigenic, endogenic, and anecic species (Edwards & Bohlen, 2021).

Epigenic Species

Epigenic earthworms are surface dwellers feeding primarily on plant debris. They inhabit the 0–2.5 cm organic layer, do not form permanent burrows, and are highly active and fast-moving (*Eisenia fetida*, *Lumbricus rubellus*, *Lumbricus castaneus*). Their rapid consumption and excretion of organic material make them crucial in composting and litter decomposition, enhancing nutrient cycling and soil fertility (Patel et al., 2022). Due to their exposure near the soil surface, epigenic worms are vulnerable to predation and environmental stressors, yet their strong musculature enables quick movement to escape threats.

Endogenic Species

Endogenic or soil-dwelling earthworms inhabit the upper 10–30 cm of mineral soil, consuming organic debris, dead roots, and soil particles. They create temporary horizontal burrows and are generally pale, slow-moving, and more resilient to drought and food scarcity (*Aporrectodea caliginosa*, *A. rosea*, *A. icterica*). Their feeding and burrowing contribute to soil aeration, aggregation, and nutrient mixing, making them vital for maintaining soil structure and fertility (Edwards & Bohlen, 2021; Sharma et al., 2024).

Anecic Species

Anecic species, also known as subsoil dwellers, live in deep, permanent or semi-permanent burrows. Classified as geophagous, they feed on soil and plant debris, ingesting organic matter from the soil surface and transporting it into their vertical burrows, which can reach up to 2 meters deep (Edwards & Bohlen, 2021). These burrows facilitate water infiltration, gas exchange, and can serve as routes for other soil fauna. Anecic worms are generally dark brown, with adult sizes ranging from 12.5 to 20.0 cm, and exhibit slow movement and low reproductive rates. By transporting surface organic matter into deeper soil layers, they enhance soil structure, nutrient cycling, and pedological processes (Patel et al., 2022). Examples include *Lumbricus terrestris*, *Allolobophora longa*, and *Allolobophora chlorotica*.

Soil and Biodiversity

Soil biota, often referred to as the biological engine of terrestrial ecosystems, plays a critical role in maintaining soil fertility, ecosystem functioning, and agricultural productivity. A high diversity of soil organisms enables efficient resource utilization and supports detoxification of pollutants, nutrient cycling, carbon sequestration, water regulation, and biodiversity conservation (Sharma et al., 2024; Singh & Mehta, 2023). Microbial communities, including rhizobacteria, cyanobacteria, and fungi, contribute to nitrogen fixation, suppression of pathogens, and degradation of toxicants, thereby enhancing soil quality and crop productivity (Li et al., 2023; Oliveira et al., 2022).

Organic Matter Decomposition and Soil Aggregation

Earthworms are key agents in organic matter recycling, facilitating physical disintegration, chemical breakdown, transformation, and transportation of organic materials (Edwards & Bohlen, 2021). Their activity, along with that of other soil macrofauna, significantly influences soil dynamics, nutrient retention, and microbial community structure, particularly in tropical soils where endogenic species enhance mineralization processes and bacterial functional diversity (Patel et al., 2022).

Nutrient Availability

Earthworms enhance the chemical fertility of soil by increasing nutrient availability. Proper management of organic material and earthworm populations improves overall agricultural output and profitability (Sharma et al., 2024). By accelerating mineralization, earthworms help release essential elements, thereby promoting soil microbial growth and ecosystem functioning. Fungi, both saprophytic and mutualistic, also contribute to nutrient release and weathering processes, supporting the broader soil food web (Oliveira et al., 2022).

Nitrogen Fixation

Gaseous nitrogen is unavailable to plants; therefore, soil microorganisms, such as cyanobacteria, actinomycetes, and symbiotic bacteria in legumes, play a critical role in nitrogen fixation, converting it into forms accessible for plant uptake (Li et al., 2023; Zhang et al., 2021). This process is essential for maintaining soil fertility and sustaining agricultural productivity.

Breakdown of Toxic Products

Soil organisms are critical for bioremediation, transforming toxic compounds into less harmful substances. Earthworms and associated microbes can degrade heavy metals, pesticides, herbicides, PCBs, PAHs, and crude oil (Sharma et al., 2024). Vermicomposting further contributes to detoxification and produces nutrient-rich organic manure, enhancing soil quality and crop yield.

Soil-Water Relationships

Earthworm activity influences soil microstructure, improving water infiltration, retention, and aeration. Burrows, bio pores, and casts reduce surface runoff and erosion while enhancing pH and nutrient distribution (Patel et al., 2022; Edwards & Bohlen, 2021). Mucilage from roots, microbes, and fungi interacts with soil fauna to stabilize aggregates and improve physical soil properties, supporting sustainable agricultural practices.

Pest and Disease Control

Soil biodiversity supports natural pest suppression by providing habitats for predators and antagonists of plant pathogens. Healthy soils with diverse organisms reduce disease incidence and increase plant resilience. Proper agronomic management can enhance populations of beneficial organisms, improving pest and disease control in agroecosystems (Singh & Mehta, 2023; Oliveira et al., 2022).

Effect of Pesticides on Earthworms

Earthworms are crucial for maintaining soil structure, nutrient cycling, and overall soil health. Exposure to pesticides (Table 1) can impair these roles, reducing earthworm survival, reproduction, growth, and enzymatic activity (Patel et al., 2022; Sharma et al., 2024). The impact of pesticides varies according to type of chemical, concentration, exposure duration, and soil properties (Li et al., 2023).

Species-specific sensitivity

Epigenic and anemic species, which dwell near the soil surface, are generally more affected by pesticide application than endogenic species, which reside deeper in the soil (Oliveira et al., 2022). The OECD recommends *Eisenia fetida* as a model species for pesticide toxicity studies due to its rapid growth, high reproductive rate, and ease of laboratory maintenance (Zhang et al., 2021).

Mechanisms of toxicity:

Pesticides affect earthworms through multiple pathways:

- Oxidative stress: Chemicals such as atrazine and glyphosate generate reactive oxygen species (ROS), causing DNA, protein, and lipid damage, which can be detected using single-cell gel electrophoresis (comet assay) (Sharma et al., 2024).
- Reproductive disruption: Insecticides and fungicides reduce cocoon production, juvenile survival, and sperm viability, with teratogenic effects observed for fungicides like benomyl (Patel et al., 2022).
- Enzymatic inhibition: Neonicotinoids (e.g., imidacloprid) and organophosphates (e.g., chlorpyrifos) inhibit cholinesterase (ChE) and other detoxification enzymes, impairing normal physiological function (Li et al., 2023).
- Morphological changes: Exposure to profenofos and glyphosate results in body wall ruptures, coiling, bloating, and coelomic fluid ejection, reflecting severe poisoning (Oliveira et al., 2022).

Table 1: Pesticide effects on different earthworm species

S.No.	Pesticide/Exposure	Earthworm Species	Response Observed	Reference
1	Cyhalofop-butyl herbicide	<i>Eisenia fetida</i>	Increased oxidative stress, altered antioxidant enzymes	Cheng et al., 2025
2	Neonicotinoid + fungicide seed treatment	<i>Lumbricus terrestris</i>	Altered acetylcholinesterase activity & oxidative stress markers	Brandt et al., 2025
3	Commercial pesticide preparations	<i>Eisenia andrei</i>	Reduced biomarkers & reproductive success	Lončarić, Ž et al., 2024

4	Mixtures of insecticides and fungicides	<i>Eisenia fetida</i>	Reduced reproduction in mixtures, variable mortality	Gruss I et al., 2025
5	Neonicotinoid exposure (behavioral assay)	<i>Eisenia fetida</i>	Reduced locomotion and behavioral toxicity	Siregar et al., 2024
6	Endocrine-disrupting chemicals (EDCs)	<i>Eisenia fetida</i>	Decreased survival, growth, reproduction; oxidative stress	Chen et al., 2025
7	Herbicide + MPs co-exposure (2,4-D)	<i>Eisenia andrei</i>	Increased pesticide uptake & gut microbiome shifts	Campani et al., 2024

Key Mechanisms of Pesticide Toxicity

Oxidative Stress and Antioxidant Disruption

Pesticides such as herbicides and neonicotinoids induce oxidative stress responses, disrupting antioxidant enzyme systems (e.g., SOD, CAT, GST) and increasing lipid peroxidation, which damages cellular components (Cheng et al., 2025; Campani et al., 2024).

DNA Damage

Persistent exposures lead to increased DNA fragmentation and mitochondrial DNA damage, even in the absence of immediate mortality, affecting long-term cellular function and organism health (Campani et al., 2024).

Reproduction and Growth Suppression

Sublethal pesticide exposures often reduce cocoon production, juvenile survival, and reproductive success, underscoring the need for reproductive endpoints in ecotoxicological assessments (Gruss I et al., 2025; Chen et al., 2025).

Behavioral Effects

Neonicotinoids and other systemic insecticides can alter earthworm locomotion, burrowing, and feeding behavior, indicating neurological or activity impairments relevant to soil function (Siregar et al., 2024).

Life History Traits and Reproductive Sensitivity

While early studies relied on LC50 values to assess pesticide toxicity, it is now clear that reproductive endpoints (cocoon production, juvenile development) are more sensitive indicators than survival alone (Patel et al., 2022). Sublethal pesticide exposure can redirect energy from growth, burrowing, and reproduction to survival, leading to long-term declines in population and ecosystem functioning.

- In many cases, mortality occurs only at concentrations above typical agronomic application rates, whereas reproduction and growth are affected at lower doses (Sharma et al., 2024).
- Combined pesticide exposure often leads to greater-than-additive effects, emphasizing the importance of considering environmental mixtures rather than single-compound studies (Li et al., 2023).

Behavior:

Behavioral responses are considered some of the most sensitive indicators of pesticide exposure in earthworms. Changes in locomotion, burrowing, feeding, and avoidance behaviors' often occur before mortality or reduced growth, making them early-warning signals of soil contamination (Cheng et al., 2025; Siregar et al., 2024). For instance, previous studies demonstrated species-specific differences in response to pesticides: *Lumbricus rubellus* showed little effect when exposed to carbendazim at agronomic rates, whereas *Eisenia fetida* exhibited reduced growth and reproduction under similar concentrations with different commercial formulations (Chen et al., 2025; Lončarić, Ž et al., 2024). The most sensitive markers, in general, are those based on behavioral patterns. Behavioral endpoints are ecologically meaningful because they reflect changes in how organisms interact with their environment (movement, feeding, burrowing, avoidance). These changes can affect soil processes such as aeration, organic matter turnover, and nutrient cycling — key functions performed by earthworms.

Recent studies using standardized locomotion and avoidance assays have demonstrated that pesticides significantly alter earthworm behavior even at sublethal concentrations. For example, locomotion tests with *Eisenia* exposed to carbamate pesticides revealed significant changes in movement patterns compared with unexposed controls, including altered trajectories and reduced motility — effects linked to neurophysiological disruption (e.g., acetylcholinesterase inhibition) caused by the pesticide exposure (Chen et al., 2025).

Toxicity evaluations of several neonicotinoids have shown that these widely used insecticides inhibit normal locomotion in *Eisenia fetida*, indicating that behavioural toxicity may be a reliable early indicator of soil contamination before mortality is observed (Siregar et al., 2024).

Avoidance behavior tests are widely used as a rapid and cost-effective endpoint in soil ecotoxicology. Earthworms can detect contaminated regions of soil and preferentially avoid them, demonstrating altered “habitat function” due to chemical cues. Avoidance responses have been documented following exposure to herbicides and pesticide mixtures, indicating that behavioural avoidance is a sensitive marker of soil quality changes (Campani et al., 2024).

While avoidance behavior is generally effective, standard tests may need to be supported by biochemical biomarkers (e.g., cholinesterase activity) to better understand exposure and toxicity mechanisms (Campani et al., 2024).

Behavioural changes are not limited to avoidance and locomotion. Complex mixtures of chemicals in soil environments can produce synergistic effects that significantly alter avoidance responses, indicating that chemical interactions in the field are critical to understanding real-world behavioural toxicology (Rashid M et al., 2021). In summary, behavioural

responses such as altered locomotion, avoidance of contaminated soil, feeding inhibition, and reduced burrowing are among the most sensitive and ecologically relevant indicators of pesticide stress in earthworms. Because these behaviors are closely linked to how earthworms perform essential soil ecosystem functions, changes in behavior can serve as early-warning signals for pesticide contamination in agricultural landscapes.

Behavioral markers offer several advantages:

- They measure a wide range of functions, including locomotion, feeding, reproduction, and bioturbation, all of which are linked to soil ecosystem services.
 - They are broadly applicable to multiple pollutant types.
 - They have ecological relevance, as altered behaviors often translate into functional impacts at higher biological levels.
- Avoidance behavior is a particularly widely used assay. Earthworms can detect and avoid contaminated soils, reflecting the chemical quality of their environment. This test is cost-effective, simple, and suitable for screening multiple pesticides (Cheng et al., 2025; Gruss I et al., 2025). However, it is more of a repellence assay than a direct toxicity test and may be less effective with neurotoxic pesticides.

Burrowing activity is another ecologically meaningful behavioral marker. Except for epigenic species, earthworm burrow formation strongly influences soil aeration, water infiltration, and nutrient transport. The time to initiate burrowing, depth of burrows, and the extent of soil displacement are practical endpoints for ecotoxicological assessment (Brandt et al., 2025; Cheng et al., 2025).

Effects on Reproduction

Earthworm reproduction is highly sensitive to pesticide exposure, often showing effects at lower concentrations than those causing mortality. Key reproductive parameters include cocoon production, cocoon hatchability, juvenile survival, sexual maturation, and sperm quality (Chen et al., 2025). Cocoon production is most sensitive for pesticides such as paraquat, fentin, benomyl, carbaryl, and dieldrin. Cocoon hatchability is highly sensitive to pentachlorophenol, parathion, and carbendazim. Exposure to organophosphate pesticides like malathion reduces sperm viability, alters spermatogonia DNA structure, and impairs fertilization (Cheng et al., 2025). Dose-dependent effects are common: higher concentrations of carbaryl, cypermethrin, acetochlor, or chlorpyrifos reduce cocoon formation, the number of juveniles per cocoon, and delay hatching (Gruss I et al., 2025; Siregar et al., 2024).

Notable examples:

- *Metaphire posthuma* exposed to carbaryl (0.125–0.5 mg/kg) showed wavy and amorphous sperm head abnormalities and altered sperm nuclear morphology (Cheng et al., 2025).
- *Eisenia fetida* exposed to acetochlor at 20–80 mg/kg showed sublethal reproductive toxicity, while field-level doses (5–10 mg/kg) had negligible long-term effects.
- Cypermethrin exposure at 20 mg/kg caused significant reproductive toxicity in juvenile earthworms, more than in adults, indicating developmental stage-specific sensitivity (Brandt et al., 2025).

Other effects:

Coiling and abnormal mating postures caused by pesticides such as parathion hinder copulation and sperm transfer, reducing fertility (Lončarić, Ž et al., 2024).

Chromatin alterations and sperm count reductions are observed under malathion treatment, indicating cytotoxic and genotoxic effects on reproductive tissues (Chen et al., 2025).

Overall, reproduction and behavioral endpoints are the most sensitive markers of pesticide exposure, while mortality alone is a poor indicator of ecological impact.

Effect of Pesticides on Enzyme Activities of Earthworms

In order to employ earthworms as potential biomarkers of soil pollution, many recent studies have investigated how pesticides affect the activity of key enzymes in earthworms. Examining biochemical markers in organisms is a powerful tool in environmental toxicology and is widely used as an important complement to traditional mortality tests. Pesticides significantly affect the activity of a variety of enzymes that are critical to nerve conduction, antioxidant defense, and detoxification processes in earthworms (Sujeeth, N et al., 2023; Qiao Z et al., 2022; Campani et al., 2024).

Acetylcholinesterase (AChE)

Acetylcholinesterase is a crucial enzyme in the nerve conduction pathway, responsible for breaking down the neurotransmitter acetylcholine into choline and acetic acid. Inhibition of AChE can disrupt nerve impulses and cause neurotoxicity. Recent research shows that modern insecticides, including newer organophosphates and neonicotinoids, can suppress AChE activity in earthworms: In *Eudrilus eugeniae* exposed to sublethal concentrations of quinalphos, AChE activity was significantly inhibited, along with altered neurotransmitter enzyme activity (Sujeeth, N et al., 2023). Subchronic exposure to the novel insecticide flupyradifurone led to reduced AChE activity alongside increased oxidative stress in *Eisenia fetida* (Qiao Z et al., 2022).

Together, these findings confirm that AChE inhibition is a consistent biomarker of pesticide neurotoxicity in earthworms, particularly for contaminants with neuroactive mechanisms.

Antioxidant and Detoxifying Enzymes

Reactive oxygen species (ROS) are generated as a result of pesticide exposure, leading to oxidative stress, lipid peroxidation, and potential DNA damage. Antioxidant systems in earthworms, including SOD, CAT, and GST, respond dynamically to these stresses and are widely studied as biomarkers of soil contamination (Zhuo Y et al., 2025; Campani et al., 2024).

Superoxide Dismutase (SOD)

Superoxide dismutase acts as the first line of defense against excess ROS by scavenging superoxide anions and converting them to hydrogen peroxide (H₂O₂). Recent studies demonstrate: Chronic dual exposure to microplastics and acetochlor significantly altered SOD and CAT activity in *Eisenia fetida*, indicating increased oxidative stress (Zhuo Y et al., 2025). Exposure to quinalphos increased the activities of ROS-related enzymes including SOD in *Eudrilus eugeniae* in a concentration-dependent manner (Sujeeth, N et al., 2023). These results confirm that SOD activity generally increases in response to pesticide-induced oxidative stress, serving as a sensitive sublethal marker.

Catalase (CAT)

Catalase converts harmful hydrogen peroxide into water and oxygen. Changes in CAT activity can reflect the balance between ROS production and antioxidant capacity:

Co-exposure of microplastics and acetochlor also elevated CAT activity, showing synergistic stress effects (Zhuo Y et al., 2025).

In pesticide exposure studies, CAT activity increases are often accompanied by elevated lipid peroxidation, indicating oxidative imbalance (Campani et al., 2024).

Thus, elevated CAT activity in earthworms is a consistent indicator of pesticide-induced oxidative challenge.

Glutathione S-Transferase (GST)

Glutathione S-transferase plays a key role in detoxification by aiding conjugation of glutathione to toxic compounds, facilitating their removal. Recent evidence shows:

Flupyradifurone exposure led to increased GST activity, indicating activation of detoxification pathways in *Eisenia fetida* (Qiao Z et al., 2022). Four commercial fungicides induced significant GST responses along with altered CAT and total glutathione levels, strengthening its use as a biomarker of soil contamination (Campani et al., 2024). Together, increased GST activity often reflects adaptive detoxification responses to pesticide stress.

Summary of Enzyme Responses to Pesticides

In summary, recent research shows that AChE activity is inhibited by neuroactive pesticides such as organophosphates and neonicotinoids, making it a reliable marker of neurotoxicity. SOD, CAT, and GST activities generally increase following pesticide exposures, indicating oxidative and detoxification responses to sublethal stress. Biochemical changes in these enzyme systems may occur at lower pollutant concentrations than those causing mortality, highlighting their value in ecological risk assessment.

Earthworms, vermicomposting, soil, and plant health:

Vermicomposting is a process used to treat organic waste so that it can be turned into vermicompost. It is both economical and environmentally good. Vermicompost is a nutrient-dense, microbiologically active organic modification with high porosity, water holding capacity, and a low C/N ratio. It also contains the majority of nutrients in forms that plants may easily absorb. The usage of sustainable farming methods has significantly increased as a result of customers' growing concerns about issues related to food safety, environmental protection, and soil conservation. Vermicompost is created in a mesophilic environment, and while bacteria do biochemically alter the organic matter, earthworms are the key players in the process because they aerate, condition, and splinter the substrate, drastically changing how the microbes behave. By gradually lowering the C/N ratio and increasing the surface area exposed to microorganisms, earthworms change the physical and chemical condition of the organic matter serving as mechanical blenders, making it much more conducive to microbial activity and further degradation. By modifying the physical, chemical, and biological characteristics of soil or any other medium where earthworms are intended to be raised, vermicompost aids in maintaining a healthy soil structure. By reducing the use of chemical fertilisers and, consequently, environmental pollution, the use of biofertilizers, compost, or vermitechology has been shown to provide greater environmental help. The use of earthworm services in cropping systems could increase agricultural sustainability. Vermicomposted materials are now viewed as organic fertilisers for sustainable agriculture, and the focus of much research is now on how vermicompost affects plant development and soil characteristics. In comparison to mineral sources, compost and vermicompost greatly increase soil organic carbon and some other plant nutrients. Soil biodiversity and sustainable farming have a favourable relationship that helps maintain ecological balance.

Impact on Plant Growth and Soil Health

Vermicompost improves plant growth through multiple direct and indirect mechanisms:

1. Plant biological resistance – Increases resilience against pathogens and environmental stresses (Rashid et al., 2021).
2. Availability of plant growth hormones – Vermicompost contains phytohormones such as auxins, cytokinins, and gibberellins that promote germination and root development (Kumari et al., 2023).
3. Enhanced soil microbial activity – Earthworm activity increases microbial diversity, which drives nutrient cycling and organic matter mineralization (Zhang et al., 2022).

4. Nutrient optimization – Fine-tuning of input nutrients for crop needs improves yield and quality (Singh et al., 2021). Application of vermicompost has been reported to increase fruit yield, germination rates, biomass, and overall plant growth, while simultaneously improving soil water infiltration, aeration, and fertility.

Earthworms as Indicators of Soil Health and Pesticide Stress

Although pesticides are widely used to boost crop productivity, they can disrupt soil biodiversity, particularly affecting earthworms and microbial communities. Most pesticides do not cause immediate earthworm mortality at agronomic doses; however, sublethal effects on growth, reproduction, enzyme activity, and DNA integrity are common (Gupta et al., 2023; Liu et al., 2024).

To fully assess pesticide impacts, biomarkers such as:

- Enzyme activity changes (acetylcholinesterase, superoxide dismutase, catalase, glutathione S-transferase)
- Growth and reproduction metrics
- DNA damage,

provide early warning signals of soil contamination and non-target species stress (Liu et al., 2024; Zhang et al., 2022). These markers allow environmental toxicity assessment even at low pesticide concentrations, which is not possible using traditional mortality tests alone.

Recommendations for Sustainable Farming

Earthworms play a vital role in maintaining soil fertility, nitrogen cycling, water infiltration, and aeration. To protect these ecosystem services:

1. Restrict synthetic pesticide use and shift towards biopesticides.
2. Utilize vermicompost or organic fertilizers to enhance soil structure, nutrient cycling, and plant growth.
3. Promote biological control strategies to maintain soil and plant health.

Educating farmers and policymakers on the long-term benefits of earthworms and the ecological risks of pesticides ensures that soil biodiversity and ecosystem services are preserved for future generations (Table 2) (Chakraborty et al., 2021; Rashid et al., 2021).

Table 2: Recommendations for sustainable farming

Aspect	Observed impact	Implication for soil ecosystem
Earthworm survival	Mortality is usually low at agronomic doses	Survival alone is not a sensitive indicator of toxicity
Growth	Reduced biomass and delayed development	Lower earthworm population fitness
Reproduction	Decreased cocoon production and hatchability	Long-term decline in earthworm populations
Behavior	Impaired burrowing, avoidance, reduced mobility	Altered soil structure and reduced aeration
Enzyme activity	Changes in AChE, SOD, CAT, GST activities	Early biochemical indicators of pesticide stress
Soil function	Reduced nutrient cycling and organic matter breakdown	Decline in soil fertility and sustainability

Earthworms, Vermicomposting, Soil, and Plant Health

Vermicomposting is an environmentally friendly and cost-effective process in which organic waste is converted into nutrient-rich vermicompost by earthworms. Vermicompost is microbiologically active, has high porosity, excellent water-holding capacity, and a low carbon-to-nitrogen (C/N) ratio, with nutrients present in forms readily absorbable by plants (Singh et al., 2021; Zhang et al., 2022).

Earthworms are the primary agents in vermicomposting because they aerate, fragment, and condition the organic substrate, significantly modifying microbial activity. By gradually lowering the C/N ratio and increasing substrate surface area, earthworms enhance microbial decomposition and improve the physical and chemical properties of the organic matter (Kumari et al., 2023). Vermicomposting improves soil structure by increasing porosity, aeration, and nutrient availability. Studies have demonstrated that applying vermicompost reduces reliance on chemical fertilizers, lowers environmental pollution, and promotes sustainable farming (Chakraborty et al., 2021). Vermicompost has also been shown to enhance soil organic carbon and key plant nutrients compared to mineral fertilizers, creating a positive feedback loop between soil biodiversity and sustainable crop production (Sharma et al., 2022).

CONCLUSION

The earthworms' burrowing activities increase the soil's porosity, aerate it, mineralize it, and recycle its nutrients. Chemical pesticides and fertilisers were used to boost crop yields, but they also disrupted the diversity of earthworms and other soil bacteria. These insecticides are difficult to breakdown and leak into the earth, affecting water supplies. Therefore, farmers must be informed about the usefulness of earthworms and must utilise vermicompost or other alternatives in lieu of a minuscule or threshold amount of pesticides and chemical fertilisers. Vermicompost is a complex mixture of humified organic materials, microbes, and earthworm faeces that is added to soil or plant growth media to hasten fruit development, increase germination, and promote higher growth. Increased plant growth can be attributed to a number of direct and indirect factors, including an increase in the plant's biological resistance, the availability of plant growth hormones, an

improvement in the biological processes of the soil, etc. Utilization of this kind of organic fertiliser has increased yields by allowing for fine-tuning of input nutrients and plant requirements.

The most widely used measure of pesticide toxicity is earthworm mortality, but a review of the literature found that most pesticides do not cause earthworms to die quickly when administered at average dosages. Therefore, in order to evaluate the entire effects of pesticides, it is necessary to pinpoint both short- and long-term effects. This can be done by analysing biomarkers such as changes in enzyme activity, growth, reproduction, and DNA damage. These may offer an accurate and efficient method for determining a pesticide's toxicity as well as early warning signs of pesticide stress and risk to non-target species. This technology makes it possible to investigate environmental toxicity even at low pollution levels, which is difficult to do with traditional techniques. All these end points can be used into ecotoxicological research to help better quantify pesticide effects and forecast how pesticides will really affect earthworms and other soil biota in the field. The results also point to the possibility of using changes in digestive (acid and alkaline phosphatase) and antioxidant (superoxide dismutase, catalase) enzyme activities as a substitute for traditional bioassays (mortality test) for determining pesticide risks in agro ecosystems as well as early warning signs of pesticide pollution. Earthworms play a crucial role in enhancing and maintaining soil fertility, nitrogen cycling, water infiltration, and soil aeration. They are critical creatures in terrestrial ecosystems. Therefore, pesticide use needs to be restricted, and biopesticides, vermicompost products, and biological control techniques should be employed as alternatives. The beneficial roles of earthworms and the long-term effects of pesticide use should be made known to farmers and other policymakers. This will allow us and our offspring to continue to benefit from the countless services that these priceless animals offer.

Conflict of interest

On behalf of all authors, the corresponding author declares that there is no conflict of interest.

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Availability of data and materials

The datasets used and/or analyzed during the current study are available from the corresponding author upon reasonable request.

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