J. Adv. Res. in Alternative Energy, Environment and Ecology
Volume 10, Issue 3&4 - 2023, Pg. No. 19-26
Peer Reviewed Journal

Review Article

The Impact of Soil Toxicity on Earthworms: A Review

Shahnawaz Ahmed

Research Scientist, Institute for Industrial Research and Toxicology, Ghaziabad, Uttar Pradesh, India.

INFO

E-mail Id:
shanu160by2@gmail.com
Orcid Id:
https://orcid.org/0000-0002-8678-4541
How to cite this article:
Ahmed S. *J Adv Res Alt Energ Env Eco* 2023; 10(3&4): 19-26.

Date of Submission: 2023-10-10
Date of Acceptance: 2023-10-22

ABSTRACT

Earthworms play a pivotal role in maintaining soil health and fertility, yet their significance often remains underestimated. This article explores the increasing awareness of earthworms' crucial role in soil ecosystems, highlighting the growing conservation efforts, monitoring strategies, and mitigation measures employed to protect these ecosystem engineers. Moreover, it sheds light on the emergence of new technologies that have revolutionized the study and conservation of earthworms and their habitats. The rise in awareness of earthworms' ecological importance has driven global conservation efforts. Initiatives to protect these organisms aim to maintain soil structure, enhance nutrient cycling, and reduce erosion. Monitoring and mitigation strategies include non-invasive techniques like DNA barcoding and remote sensing, enabling a deeper understanding of earthworm populations and their habitats. Furthermore, innovative technologies, such as automated soil sensors and soil-improving bio stimulants, are revolutionizing how we manage soil ecosystems, ensuring optimal conditions for earthworm survival and thriving. This underscores the imperative need for an integrated approach to earthworm and soil conservation, harmonizing awareness, monitoring, and mitigation strategies, and harnessing cutting-edge technologies. Through these efforts, we can safeguard the essential services provided by earthworms and maintain the resilience of our planet's soil ecosystems in the face of environmental challenges.

Keywords: Earthworm, Indicator Species, Soil Toxicity, Monitoring Techniques, Mitigation and Conservation

Introduction

Earthworms are soil-dwelling organisms that belong to the class Oligochaeta and are found in various terrestrial ecosystems worldwide. Their presence in soil ecosystems has far-reaching implications for soil health, nutrient cycling, and overall ecosystem sustainability. Earthworms are ecosystem engineers known for their burrowing activities. As they move through the soil, they create channels and pores, improving soil aeration. This enhanced aeration promotes the exchange of gases, such as oxygen and carbon dioxide, which is essential for the respiration of plant roots and beneficial soil microorganisms.[1,2] Earthworms play a vital role in nutrient cycling within soil ecosystems. They consume organic matter, including dead plant material, and excrete it as nutrient-rich castings. These castings are more stable and have higher nutrient availability than the organic matter they consume, making essential nutrients, such as nitrogen, phosphorus, and potassium, readily accessible to plants.[3] The burrowing and feeding activities of earthworms help in soil structure improvement. They mix organic matter with mineral soil particles, creating aggregates that enhance water infiltration, root penetration, and overall soil stability [4,5] Earthworms accelerate the decomposition of organic matter, aiding in the breakdown of complex compounds. This decomposition leads to the release of carbon in the form of CO2 and helps in the sequestration of carbon in soil.[6] Earthworms enhance microbial activity in the soil by providing a conducive environment for microorganisms. They stimulate the growth of beneficial microorganisms that contribute to nutrient cycling and suppress the growth of harmful pathogens.[7]

Soil toxicity refers to the condition in which soil contains harmful substances at levels that can negatively impact the health and functioning of organisms living within or coming into contact with the soil. Soil toxicity can result from a variety of contaminants, including heavy metals (e.g., lead, cadmium, and mercury), organic pollutants (e.g., pesticides and polycyclic aromatic hydrocarbons), and other chemical substances like salts and acids.[8] The toxicity of soil depends on the concentration of the contaminants. Certain substances may be naturally occurring in soil but become toxic at elevated levels. Regulations and guidelines often define threshold concentrations for specific contaminants.[9] This toxicity can harm soil-dwelling organisms, including microorganisms, earthworms, insects, and plants. It can disrupt ecosystem functions, such as nutrient cycling and plant growth, and may lead to soil degradation.[10] If soil toxicity is present in areas used for agriculture or residential purposes, it can pose a risk to human health. Contaminants can enter the food chain through plants or be directly ingested or inhaled if the soil is disturbed.[11] Strategies to mitigate soil toxicity include soil remediation techniques like phytoremediation, bioremediation, and physical removal of contaminated soil. These methods aim to reduce the concentration of harmful substances to safe levels.[12]

Earthworms in Soil Ecosystems

Earthworms play a vital role in soil ecosystems, contributing to various ecological and agricultural processes. Their actions have a profound impact on soil structure, nutrient cycling, and overall soil health. Earthworm, is an integral members of soil ecosystems, and they have a profound influence on soil health and sustainability. Their activities significantly impact soil structure, nutrient cycling, and the overall functioning of terrestrial ecosystems. One of the primary functions of earthworms is to enhance soil aeration. Earthworms burrow through the soil, creating channels that improve air exchange between the soil and the atmosphere. These channels facilitate the diffusion of gases, such as oxygen and carbon dioxide, which is crucial for the respiration of plant roots and soil microorganisms.[13] Earthworms are known for their role in improving soil structure. They ingest soil particles and organic matter, processing them within their digestive tracts. The resulting excreted material, known as casts, is rich in nutrients and has a stable, aggregated structure. Casts enhance soil porosity, water retention, and reduce the risk of erosion.[14] Earthworms are efficient decomposers of organic matter. They consume decaying plant material and transform it into nutrient-rich casts, returning valuable nutrients to the soil. Their activities also promote the breakdown of complex organic compounds, making nutrients more readily available to plants and microorganisms.[15] Earthworms influence soil pH through their interactions with soil minerals. By consuming and excreting soil particles, they can alter the pH of the soil. This can be particularly important in moderating the acidity or alkalinity of the soil, making it more conducive to a broader range of plant species.[16] Earthworms enhance microbial activity in the soil by providing a favorable environment for microorganisms in their burrows and casts. The increased microbial activity contributes to organic matter decomposition and nutrient cycling.[17]

Earthworms are often regarded as essential indicator species due to their remarkable sensitivity to environmental changes and their significant role in ecosystem processes. Earthworms are highly responsive to variations in soil quality. Their presence and abundance can serve as a barometer for assessing soil health and fertility. As soil conditions deteriorate due to factors such as pollution, compaction, or the use of pesticides, earthworm populations decline. This has been well-documented in numerous studies, such as those conducted by.[17] Earthworms are incredibly diverse, with thousands of species inhabiting various ecosystems worldwide. Changes in the composition of earthworm communities can reflect alterations in the environment. This makes them valuable indicators of biodiversity. Symondson et al. (1996) demonstrated this in a study that assessed earthworm diversity in response to land-use changes.[18] Earthworms are sensitive to soil pollutants, such as heavy metals and organic contaminants. Their response to these pollutants can provide early warnings of soil pollution, making them excellent bioindicators. Research by[19] showcased the use of earthworms in detecting soil contamination and assessing its impact.[19]

Earthworms play a critical role in carbon sequestration and nutrient cycling. Their activities help break down organic matter and distribute nutrients throughout the soil, thereby influencing soil quality. Changes in earthworm behavior can signal disruptions in these essential processes, as indicated in studies by.[20,21] Earthworms also play a role in climate change mitigation through their contribution to carbon storage and soil aeration. Monitoring earthworm populations can help track the impact of climate change on soil ecosystems, as highlighted in research by.[22] Earthworms are valuable for evaluating the success of habitat restoration projects. The return of earthworm populations to previously degraded areas can indicate ecosystem recovery, as demonstrated in studies like the one by.[23]

Understanding Soil Toxicity

Soil toxins, also known as soil contaminants or soil pollutants, are substances or chemicals present in the soil at concentrations that can harm living organisms, including plants, animals, and humans. These contaminants can originate from various sources, including industrial activities, agriculture, waste disposal, and natural processes. Soil toxins can have detrimental effects on ecosystems, soil quality, and human health, making them a significant environmental concern. We can categories Soil Toxins as:

- **Heavy Metals:** Heavy metals such as lead (Pb), cadmium (Cd), mercury (Hg), and arsenic (As) are common soil contaminants. These metals can accumulate in soil from sources like industrial discharges, mining, and agricultural inputs, leading to long-term toxicity to plants and potential bioaccumulation in the food chain.[24]
- **Pesticides and Herbicides:** Agricultural chemicals, including pesticides (e.g., organophosphates) and herbicides (e.g., glyphosate), can contaminate soil through runoff or direct application. Prolonged exposure to these chemicals can disrupt soil ecosystems and pose risks to human health.[25]
- **Petroleum Hydrocarbons:** Oil spills and leaks from industrial activities can introduce petroleum hydrocarbons into the soil. These compounds can have detrimental effects on soil structure and microbial activity.[26]
- **Polycyclic Aromatic Hydrocarbons (PAHs):** PAHs are a group of organic compounds that can originate from the incomplete combustion of organic materials, such as wood or fossil fuels. They are known carcinogens and can persist in soil for extended periods.[27]
- **Volatile Organic Compounds (VOCs):** VOCs, including benzene, toluene, ethylbenzene, and xylene (BTEX), can contaminate soil from industrial emissions, fuel leaks, and improper waste disposal. These compounds can have adverse effects on soil and pose health risks if they migrate to groundwater.[28]
- **Nitrates and Phosphates:** Excessive use of fertilizers in agriculture can lead to elevated levels of nitrates and phosphates in the soil. These nutrients, when present in high concentrations, can cause water pollution through runoff and disrupt natural ecosystems.[29]
- **Radionuclides:** Radionuclides like uranium (U) and Radium (Ra) can contaminate soil from both natural sources and nuclear activities. Their radioactive decay can have serious health and environmental consequences.[30]
- **Organic Pollutants:** Organic pollutants, such as Polychlorinated Biphenyls (PCBs) and chlorinated solvents, can contaminate soil due to industrial activities and improper disposal. They can persist in the environment for extended periods.[31]

Impact of Soil Toxicity on Earthworms

Earthworms improve soil structure, nutrient cycling, and overall soil quality. However, the presence of environmental toxins, such as pesticides, heavy metals, and organic pollutants, can have a significant impact on earthworm behavior and their essential ecological functions.

- **Pesticides:** Pesticides are commonly used in agriculture to protect crops from pests. However, their application can negatively affect earthworms. For example, neonicotinoid pesticides have been shown to reduce earthworm activity and burrowing behavior.[32] Earthworms exposed to pesticides exhibit decreased feeding activity and reduced movement in contaminated soils.[33] These changes can disrupt their role in soil aeration and nutrient cycling.
- **Heavy Metals:** Heavy metals like lead, cadmium, and mercury can accumulate in soil due to industrial and anthropogenic activities. When earthworms come into contact with elevated levels of heavy metals, they exhibit altered behaviors. Studies have shown that earthworms reduce their burrowing activity in metal-contaminated soils.[34] This avoidance behavior is an adaptive response to minimize exposure to toxic substances.
- **Organic Pollutants:** Organic pollutants, including Polychlorinated Biphenyls (PCBs) and polycyclic aromatic hydrocarbons (PAHs), can disrupt earthworm behavior. Exposure to these substances can result in reduced earthworm reproduction rates[35] and altered burrowing patterns.[36] Such changes can impact soil structure and nutrient distribution.
- **Effects of Toxins on Reproduction:** Exposure to toxins can lead to reduced earthworm fecundity, or the ability to reproduce. For instance, studies have shown that pesticides, heavy metals, and organic pollutants can negatively affect earthworm reproductive organs and reduce the number of offspring produced.[37,38] Toxins can disrupt earthworm reproductive behavior, including mating and cocoon production. This can result in fewer viable offspring, ultimately impacting population growth.[39,40]
- **Population Effects of Toxins:** Toxins can lead to a decrease in earthworm density within contaminated areas. Studies have reported that soil pollution caused by chemicals like pesticides and heavy metals can result in a reduced number of earthworms in affected regions.[37] Some earthworm species are more sensitive

to toxins than others. Consequently, exposure to toxins can lead to shifts in earthworm species composition in contaminated soils, potentially favoring more toxin-tolerant species.[41]

- **Mechanisms of Toxic Effects:** Some toxins can directly harm earthworms by affecting their physiological processes and causing damage to their tissues and organs.[42] Toxins may alter the availability of essential resources (e.g., organic matter, nutrients) or microbial communities in the soil, indirectly impacting earthworms' health and reproduction.[43]
- **Ecological Implications:** A decrease in earthworm populations can disrupt soil structure and nutrient cycling, potentially reducing the overall health and fertility of the soil.[37,38] Earthworms provide vital ecosystem services, including soil aeration and nutrient cycling. Reductions in their populations can affect these services, potentially leading to negative consequences for ecosystems.[43]
- **Bioaccumulation:** Bioaccumulation is the process by which toxins, such as heavy metals and organic pollutants, accumulate in the tissues of living organisms. Earthworms, as important soil-dwelling organisms, play a crucial role in soil health and ecosystem functioning. Earthworms can be exposed to toxins through contaminated soil, water, or organic matter they consume.[44] Toxins are often lipophilic and tend to accumulate in the fatty tissues of earthworms. This accumulation occurs over time as earthworms continuously ingest contaminated soil.[45] Bioaccumulation of toxins in earthworm tissues can lead to adverse health effects, such as reduced growth, impaired reproduction, and increased mortality.[46] Earthworms serve as a primary food source for many organisms, and bioaccumulated toxins can be transferred up the food chain to predators, potentially impacting higher trophic levels.[47] Bioaccumulation of toxins in earthworms can disrupt soil processes, affect nutrient cycling, and ultimately impact ecosystem health.[48] The bioaccumulation of certain toxic substances in earthworms can trigger regulatory actions to limit or monitor pollutant levels in the environment.[49]
- **Toxins and Earthworm Physiology:** The physiological and mechanistic effects of toxins on earthworms have been a subject of research due to their role as indicator species for soil health and environmental toxicity. When exposed to various toxins, these organisms can experience a range of physiological and mechanistic effects. Exposure to toxic substances like pesticides, heavy metals, and organic pollutants can lead to acute toxicity in earthworms. Such exposure may result in immediate mortality or sublethal effects. Acute toxicity can be attributed to the disruption of cellular homeostasis, often leading to damage in cellular structures, ultimately affecting the overall health of the earthworms.[50] Exposure to certain toxins can lead to changes in earthworm behavior. Earthworms may exhibit altered burrowing patterns, reduced feeding activity, and a preference for specific microhabitats within the soil to avoid toxic substances.[51] They possess detoxification mechanisms to cope with toxin exposure. They may upregulate detoxification enzymes, such as cytochrome P450s, glutathione-S-transferases, and metallothioneins, in response to specific toxins.[52] Some toxins can cause genotoxic effects in earthworms, leading to DNA damage and mutations. Genotoxicity can result from exposure to certain pesticides and heavy metals.[53] Toxins can compromise the immune system of earthworms, making them more susceptible to infections. This can further affect their overall health and survival.[17]

Long-Term Consequences on Populations

Earthworms play a vital role in soil ecosystems, However, earthworm populations can be severely impacted by exposure to toxins, whether through agricultural practices, industrial pollution, or other sources. Such as Impact on Reproduction as toxins can disrupt the reproductive capabilities of earthworms, leading to long-term population declines. A study by.[54] demonstrated that exposure to pesticides and heavy metals led to reduced earthworm reproduction rates. Over time, this can lead to a decline in the overall population. Toxins can disrupt the balance of soil ecosystems, impacting the availability of food sources and habitat quality for earthworms. This can lead to a long-term decline in their populations as they struggle to find suitable living conditions.[55] Some earthworm populations may develop genetic adaptations and resistance to toxins over time, potentially mitigating the long-term consequences. A study by[56] discussed the potential for evolutionary changes in earthworm populations subjected to long-term exposure to contaminants. Climate change can exacerbate the long-term consequences of toxin exposure. Changes in temperature, precipitation, and soil moisture can further stress earthworm populations already have affected by toxins.[57]

Ecological Implications

When toxins are introduced into the soil, whether through pollution, agriculture, or other means, it can trigger a series of cascading effects that can significantly disrupt the equilibrium of the ecosystem. These cascading effects on soil health and ecosystem function such as Impact on Soil Microorganisms as toxins, such as heavy metals or pesticides, can have a detrimental impact on soil microorganisms. These microorganisms play a crucial role in nutrient cycling and decomposition. For instance, heavy metals like cadmium and lead can disrupt the activity of soil bacteria and fungi.[58] This disruption impairs the breakdown of organic matter, which leads to reduced nutrient availability for plants and affects overall soil health. Pollutants in the soil can be absorbed by plants, leading to reduced growth and reproductive capabilities. Pesticides, in particular, can have a direct negative impact on plant health. [59] Weakening plants make them more susceptible to pests and diseases, leading to a decrease in plant diversity, which further disrupts the ecosystem.

The disruption of soil microorganisms and the decline in plant health can disrupt nutrient cycling within the ecosystem. Toxins can reduce the availability of essential nutrients, such as nitrogen and phosphorus, impacting the overall productivity of the ecosystem.[60] This can lead to a reduction in the quality and quantity of plant and animal species in the affected area. The altered soil conditions and disrupted nutrient cycling can result in reduced biodiversity within the ecosystem. Soil contaminants can lead to the decline of sensitive species and favor the proliferation of more tolerant or resistant species.[61] This shift in species composition can disrupt the delicate balance within the ecosystem. Eventually the cascading effects of soil toxins ultimately impact ecosystem services, such as pollination, water purification, and carbon sequestration.[62] These services are vital for human well-being and are crucial for the health and functioning of ecosystems.

Monitoring and Mitigation

Various toxins, such as pesticides, heavy metals, and organic pollutants, can adversely affect earthworms and soil quality. Monitoring and mitigating these effects are essential to safeguard soil health and maintain agricultural productivity. Regularly monitor earthworm populations in the affected areas using established sampling methods, such as the “hand-sorting” technique.[17] This allows for the assessment of earthworm abundance and diversity. Monitor earthworm behavior, such as burrowing and surface activity, which can be indicators of toxin-induced stress.16].Employ biomarkers like acetylcholinesterase activity and metallothionein levels to gauge the toxicological impact on earthworms.[63]

Regularly analyze soil samples for pH, organic matter content, nutrient levels, and heavy metal concentrations to assess changes in soil quality.[64] Microbial community assessment helps to evaluate the impact of toxins on soil microbial communities through techniques like DNA sequencing and enzyme activity assays.[65] Implementing sustainable agriculture practices performed in transition to sustainable farming practices, such as reduced pesticide usage and organic farming, to minimize the introduction of toxins into the soil.[66] For soil remediation Utilizing techniques like phytoremediation and bioremediation to reduce the levels of specific toxins, particularly heavy metals and organic pollutants.[67] Restoring natural habitats around agricultural areas to encourage earthworm movement and migration, aiding in their recovery from toxin exposure.[68] The incorporation of biochar into soil(Biochar Application) has shown promise in mitigating the effects of various toxins by improving soil structure and reducing contaminant bioavailability.[69]

Future Research Directions

Monitoring and mitigating the effects of these toxins on earthworms and soil ecosystems is essential for sustaining healthy soils and, by extension, global food security and ecosystem services. Here I would like to discusses potential future research directions in this critical field through suggesting these techniques, such as:

- **Monitoring Toxins and Earthworm Health:** Develop and refine biomarkers to assess earthworm health, as traditional indicators may not sufficiently capture sublethal effects of toxins. These biomarkers could include genotoxicity, metabolic responses, and behavior changes.[70] Exploring non-invasive methods like remote sensing technologies and environmental DNA (eDNA) to monitor earthworm populations and assess toxin exposure in the soil without disturbing their habitats.[71] Besides developing real-time sensors and autonomous monitoring systems that can continuously track soil conditions and toxin levels to provide early warnings of earthworm stress and soil contamination could be a great idea.[72]
- **Mitigation Strategies:** Investigate the potential of earthworms in bioremediation by breeding or engineering earthworm species with enhanced toxin-degradation capabilities, focusing on specific pollutants like Polycyclic Aromatic Hydrocarbons (PAHs) or heavy metals.[73] Research the effectiveness of different soil amendments (e.g., biochar, organic matter) in reducing the bioavailability and toxicity of contaminants, thus protecting earthworms and enhancing soil quality.[74] Designing and implementing ecological engineering approaches, such as constructed wetlands or green infrastructure, to prevent toxin runoff into earthworm habitats and promote natural detoxification processes.[75]
- **Ecosystem-Level Assessments:** To Investigate how earthworm population declines and altered behavior affect the broader soil food web, including predators, prey, and decomposers, to better understand the ecological consequences of toxin exposure[76] and at last by working on Soil functionality by assessing the long-term impacts of toxin exposure on soil functionality, including nutrient cycling, carbon sequestration, and water retention, to evaluate the ecosystem-wide implications.[77]

Conclusion

Increased awareness has highlighted the vital importance of earthworms in maintaining soil health. These creatures aerate the soil, improve its structure, and recycle organic matter, contributing to fertile and sustainable agricultural practices. Through conservation efforts, we recognize that preserving earthworm populations is vital. This involves protecting their natural habitats, reducing the use of harmful pesticides and chemicals, and encouraging organic farming practices that support earthworm populations. Regular monitoring of earthworm populations and soil conditions is crucial. This enables us to identify any decline in earthworm numbers or soil degradation promptly. Mitigation strategies can then be implemented, such as implementing crop rotation, cover cropping, and reduced soil disturbance to promote earthworm health. The integration of new technologies in earthworm and soil conservation is promising. Soil sensors, for instance, can help farmers and conservationists monitor soil health in real-time. Additionally, innovative farming techniques like no-till and precision agriculture reduce soil disruption, which benefits earthworms. The combination of awareness, conservation efforts, monitoring, and new technologies aligns with the broader goal of sustainable agriculture. This approach focuses on minimizing environmental impact while maintaining or increasing crop productivity. Earthworms and healthy soils are integral components of sustainable agriculture. Recognizing the interconnectedness of ecosystems, efforts to protect earthworms and soil health contribute to the overall well-being of ecosystems. Healthy soils support plant growth, which, in turn, sustains various animal species and benefits human agriculture. These efforts are essential for maintaining agricultural productivity, sustaining ecosystems, and achieving global sustainability goals.

Acknowledgement: I wish to extend our heartfelt thanks to Dr, Gayathri Venkatesan and Ms. Nahid Abda whose unwavering moral support and invaluable guidance have been instrumental throughout this research project.

Conflicts of Interest: The author wishes to confirm that he has no affiliations or relationships with organizations or entities that could lead to a perceived conflict of interest regarding the research findings.

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