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Earthworms as Integrative Bioindicators of Soil Health in Agroecosystems under Chemical and Plastic Stress

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Abstract

Agricultural soil health assessment continues to focus heavily on chemical fertility despite the fact that soil functioning is highly mediated by biological communities and the structures they form. The earthworms are the only useful indicators in that they are sensitive to disturbance and also control aggregation, porosity, residue turnover, nutrient mineralization, and microbial habitats. This review is a synthesis of evidence on earthworms as integrative bioindicators of the state of agroecosystems under synthetic pesticides, plastic residues and microplastics, and biopesticide-based management. Web of Science, Scopus, PubMed, and Google Scholar were searched systematically to identify studies published between 2000 and early 2026 that correlated earthworm measures with soil functions. Recent synthesis shows that earthworms are involved in approximately 6.5 percent of the world grain production and 2.3 percent of the legume production, highlighting their agronomic importance (Fonte et al., 2023). In pesticide research, the most common negative effects are reproduction, behavior, growth, and biochemical biomarkers; a general hazard assessment found negative responses in 87.7% of earthworm survival parameters, 82.7% of reproduction parameters, and 80.6% of behavioral parameters in laboratory exposure conditions (Gunstone et al., 2021). In the case of microplastics, a recent meta-analysis of 2,124 observations of 102 articles revealed a decrease in survival and growth, increased oxidative stress, and impaired gut microbial diversity, and biodegradable polymers were not necessarily less harmful than conventional plastics (Zhong et al., 2026). In comparison, existing data on biopesticides tends to indicate reduced non-target interference at recommended concentrations, but formulation impacts and multiple applications are not well-investigated. The literature suggests that abundance and biomass continue to be valuable field diagnostics, but reproduction, avoidance behavior, and function-related measures like aggregate stability and enzyme activity give earlier and more mechanistic warning signals. It is suggested to use an earthworm-based indicator panel in intensified tropical and subtropical agroecosystems, especially in the context of Indian agroecosystems where pesticide inputs and agricultural plastics are becoming more and more co-located.

Keywords: earthworms; soil health; bioindicators; agroecosystems; pesticides; microplastics; biopesticides; soil biodiversity

1. Introduction

The concept of soil health is becoming the ability of soil to act as a living system that maintains productivity, controls water and nutrient movement, and promotes ecological resilience instead of a purely chemical manifestation of fertility (Bünemann et al., 2018; Lehmann et al., 2020). This theoretical change has significant implications on the choice of indicators. Chemical parameters are still required, but do not entirely describe the formation of soil structure, residue turnover, biological regulation, and the interactions between soil fauna, microbes, and plants. Biological indicators are thus inevitable where the objective is to identify functional degradation at an early stage to inform the management before the productivity deterioration becomes irreversible (Doran and Zeiss, 2000).

Earthworms are in a uniquely informative position among candidate biological indicators since they are both responders to soil disturbance and soil formers. Their feeding, burrowing, and casting behaviors alter pore continuity, macroaggregation, water infiltration, nutrient release, and microbial hotspots distribution, which is why they are commonly considered ecosystem engineers (Blouin et al., 2013). Their agronomic importance is no longer anecdotal: a global synthesis estimated that earthworms contribute about 6.5% of grain production and 2.3% of legume production globally (Fonte et al., 2023). Earthworms also organize soil biota in long-term field systems to promote multifunctionality instead of single ecosystem processes in isolation (Liu et al., 2019).

However, the ecological characteristics that render earthworms useful are the same that render them susceptible to agricultural intensification. Synthetic pesticides have the potential to compromise survival, growth, cocoon development, juvenile hatching, and behavior, frequently at levels lower than those necessary to cause significant mortality (Pelosi et al.,

2014; Yasmin and D'Souza, 2010; Kumar et al., 2024). Simultaneously, agricultural plastics are creating a land-based pollution issue via mulch fragmentation, tunnel films, irrigation parts, polluted composts, and diffuse residue deposition. Earthworms consume and redistribute them, which makes them not only the indicators of plastic pollution but also the carriers of contaminants in the soil (Rillig et al., 2017; de Souza Machado et al., 2018). The use of biopesticides is being actively encouraged as less risky options, but their effects on soil fauna are determined by active ingredients, formulations, co-formulants, and exposure history, not by the category of the product (Copping and Menn, 2000; Kilani-Morakchi et al., 2021; Pereira et al., 2025).

Although the literature is growing rapidly, the evidence base is still disjointed. Most studies are done on a single stressor group, a single endpoint, or a standard test species in artificial soil conditions, whereas field-based studies tend to confound agrochemical exposure with tillage, residue management, and soil organic matter depletion. Consequently, a universally accepted framework that elucidates how earthworm responses can be used as soil-health indicators in chemical stress, plastic stress, and biologically-based pest management remains lacking. This is of particular concern to tropical and subtropical agroecosystems, such as the Indo-Gangetic region, where intensification, vegetable production, and mixed-input management are becoming more and more co-occurring.

The gap in this paper is filled by a systematic critical analysis of the ecological foundation and indicator value of earthworms in agroecosystems subjected to synthetic pesticide, microplastic, and biopesticide stress. The aims were four-fold: to explain why earthworms are integrative indicators, not simple abundance indicators; to compare the patterns of dominant responses across the three classes of

stressors; to determine the most diagnostic endpoints in soil-health assessment; and to suggest a practical monitoring framework that is suitable to field assessment, mesocosm testing, and management decision-making in intensified farming systems.

2. Review methodology

The review was developed as a structured critical synthesis based on PRISMA 2020 reporting logic, but it was acknowledged that the heterogeneity of endpoints, species, soils, and exposure measures preclude formal pooled meta-analysis beyond the mentioned published syntheses in the current paper (Page et al., 2021). Web of Science, Scopus, PubMed, and Google Scholar were searched and updated until February 2026. Blocks of keywords were used to combine earthworm* with soil health, bioindicator, agroecosystem, pesticide, insecticide, fungicide, herbicide, microplastic, plastic mulch, biopesticide, botanical pesticide and microbial pesticide.

Peer-reviewed studies and regulatory guidance that related earthworm endpoints to agricultural management or soil-function variables were prioritized. Articles included field surveys, manipulative field experiments, mesocosm

experiments, standardized ecotoxicology assays, meta-analyses, and critical reviews. The studies were included in the study when they reported at least one earthworm response variable including abundance, biomass, reproduction, avoidance, growth, oxidative or neurophysiological biomarkers, or community composition, and when the agricultural or soil-quality relevance of the response could be interpreted. Articles that were solely on aquatic exposure, wastewater toxicology with no agricultural soil relationship, or irrelevant annelid taxa were not included in the core synthesis.

Evidence was categorized into five domains: earthworms as ecosystem-function indicators; land-use and management gradients; synthetic pesticide effects; microplastic and plastic-residue effects; and biopesticide compatibility. Broad effect patterns were defined by foundational reviews and recent meta-analyses, and representative experimental and field studies were used to demonstrate mechanisms, endpoint sensitivity, and extrapolation limits. The ultimate interpretation is thus intended to be decision-oriented: it focuses on the most informative earthworm metrics to diagnose soil habitat quality in the face of realistic agricultural stress.

| Review element | Operationalization in this paper |
|---------------------|--|
| Review design | Structured critical review informed by PRISMA 2020, emphasizing interpretive synthesis rather than a new pooled effect-size meta-analysis. |
| Search window | Peer-reviewed literature and regulatory guidance published from 2000 to February 2026. |
| Databases searched | Web of Science, Scopus, PubMed, and Google Scholar. |
| Core keyword blocks | Earthworm* AND soil health/bioindicator/agroecosystem; earthworm* AND pesticide/insecticide/fungicide/herbicide; earthworm* AND microplastic/plastic mulch; earthworm* AND biopesticide/botanical pesticide/microbial pesticide. |
| Inclusion criteria | Agricultural soils or standardized soil tests; at least one earthworm endpoint; direct relevance to management, contamination, or soil-function interpretation. |
| Synthesis domains | Ecological basis of indicator value; land-use gradients; synthetic pesticides; plastics and microplastics; biopesticides; integrative monitoring. |

Table 1. Review design and evidence-selection framework used for the present synthesis.

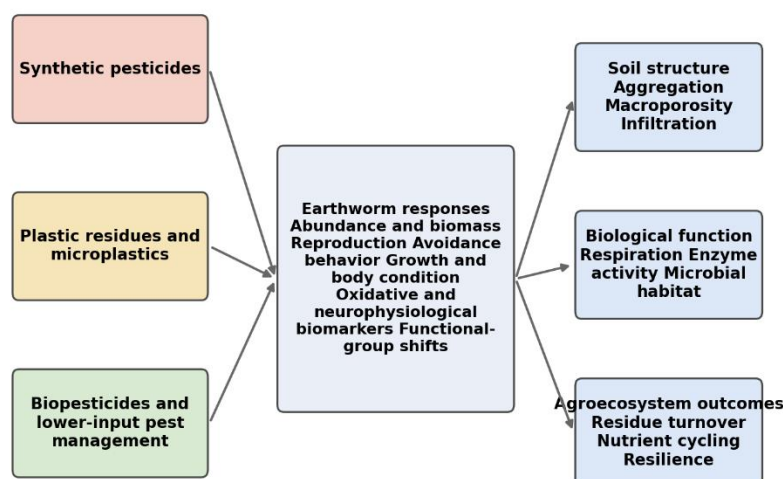
3. Why earthworms function as integrative bioindicators

Earthworms are integrative indicators because they occupy the intersection of biological response and functional consequence. Unlike many microbial metrics that are sensitive but difficult to interpret ecologically, earthworm responses can often be linked directly to soil processes that matter to farmers and land managers, including aggregation, infiltration, residue incorporation, nutrient mineralization, and habitat creation for microbial communities (Blouin et al., 2013; Bertrand et al., 2015). When earthworm communities decline, the loss is therefore not simply taxonomic; it often implies reduced engineering capacity in soil.

This interpretive value depends partly on functional-group ecology. Epigeic earthworms are associated with litter layers and tend to respond quickly to surface-applied chemicals and residue quality. Endogeic species integrate disturbance within

agricultural systems, while anecic species provide vertically oriented burrows that strongly influence infiltration, gas exchange, and residue incorporation. A useful earthworm-based diagnosis therefore benefits from more than one metric. Abundance and biomass remain practical field indicators, but they become far more informative when combined with functional-group composition, reproductive performance, or behavior.

Recent large-scale evidence supports this integrative view. A global meta-analysis of 113 publications across 44 countries found that arable cropland supported 18% lower earthworm density, 15% lower biomass, and 27% lower species richness than undisturbed reference systems, whereas pastures, agroforestry, and less intensive rotational systems were comparatively favorable (Betancur-Corredor et al., 2024). Likewise, a global meta-analysis showed that conventional tillage systematically reduces earthworm abundance and biomass while altering community structure (Briones & Schmidt, 2017).



Earthworms integrate exposure history and habitat quality while simultaneously influencing the soil functions that soil-health frameworks seek to protect.

FIGURE 1. CONCEPTUAL PATHWAYS LINKING SYNTHETIC PESTICIDES, PLASTIC RESIDUES/MICROPLASTICS, AND BIOPESTICIDE-BASED MANAGEMENT TO EARTHWORM RESPONSES AND SOIL-HEALTH OUTCOMES. FIGURE CREATED FOR THIS REVIEW.

the mineral topsoil and frequently dominate. Conversely, recent work in no-tillage agroecosystems

highlights earthworms as useful indicators of biological improvement where residue retention, reduced disturbance, and habitat continuity are maintained (Bartz et al., 2024; Bertoneclj et al., 2025).

Earthworm indicators are strongest when interpreted together with soil-function metrics. Field studies and long-term experiments consistently show positive associations between earthworm abundance and aggregation, mineral nitrogen turnover, microbial activity, and multifunctionality, although the magnitude and direction of specific responses can vary with climate, texture, and management intensity (Liu et al., 2019; Reis et al., 2025). For this reason, earthworm monitoring should not be framed as a substitute for biochemical indicators, but as a biologically interpretable anchor that helps integrate them.

4. Earthworm reactions to synthetic pesticide stress

Artificial pesticides are still one of the most apparent chemical dangers to the soil health of earthworms. The mechanistic pathways are varied: neurotoxic insecticides may disrupt movement and feeding, fungicides may alter associated microbial food resources, herbicides may alter residue inputs and indirectly alter habitat quality, and repeated mixtures may produce chronic exposure patterns that are not well reflected in acute mortality tests (Pelosi et al., 2014; Yasmin and D'Souza, 201). A general hazard evaluation of soil invertebrates revealed that pesticides adversely impacted earthworm survival in 87.7% of laboratory parameters, reproduction in 82.7, growth in 79.4, and behavior in 80.6, which showed that non-lethal impairment is the most common toxicological indicator, not catastrophic mortality.

The hierarchy of endpoints is important. Standardized approaches like OECD Test No. 222 explicitly acknowledge reproductive output as a primary chronic endpoint of *Eisenia fetida* and *Eisenia*

andrei, and not an optional complement to mortality assessment (OECD, 2016). In the same vein, ISO 17512-1 codified avoidance as a quick screening method of the habitat role of soils, as earthworms can discriminate between contaminated and uncontaminated substrates behaviorally, prior to attaining lethal levels (ISO, 2008). This methodological development is in line with the ecotoxicology literature, in which cocoon production, juvenile emergence, biomass change and avoidance are used to detect chronic soil stress earlier than survival.

Field interpretation is more complex yet more applicable. Pesticides had a negative impact on earthworm mortality, abundance, and biomass in 77.8, 38.2, and 39.6 of the parameters tested in field and semi-field studies reviewed by Gunstone et al. (2021), and reproduction was negatively impacted in 81.8% of the smaller reproduction evidence base. These reduced percentages of abundance and biomass are not to be interpreted as indicators of safety, but are indicators of seasonal variability, recolonization, and the confounding influence of tillage, moisture, residue return, and soil organic carbon on achieved exposure. In fact, the 2024 review by Kumar et al. highlighted that oxidative stress, gut disturbance, and reproductive impairment are common even in cases where visible population collapse is not imminent.

In the case of indicator practice, the most justifiable interpretation is that synthetic pesticide pressure produces a multidimensional earthworm signal. Short-term assays measure bioavailability by avoidance and growth responses, medium-term chronic tests by reproductive inhibition, and field surveys by whether repeated exposure is transferring into reduced abundance, community structure, or weakening of earthworm-soil interactions. Count-based monitoring programs thus run the risk of underestimating

ecologically significant damage in intensively managed soils.

5. Earthworm behavior in plastic and microplastic stress

Plastic residues and microplastics are another stress regime. Polyethylene mulches, greenhouse films, nursery trays, irrigation infrastructure, sewage sludge or compost amendments, and increasingly fragmented packaging residues are the main sources of contamination in agroecosystems. Plastics are physically heterogeneous and unlike most pesticides, they are persistent. They are able to change the bulk density of soil, pore structure, water retention, and aggregate dynamics and are consumed by soil fauna or serve as vectors of sorbed chemicals (de Souza Machado et al., 2018; Boots et al., 2019).

Earthworms are at the heart of this issue since they do not simply react to microplastics; they redistribute them. Experimental studies have shown that earthworms are able to move microplastics through the soil profile, suggesting that earthworm activity affects the burial, mixing, and bioavailability of plastic particles in agricultural soils (Rillig et al., 2017). This duality makes interpretation of indicators difficult. Reduction in earthworm activity is an indicator of habitat degradation, yet the continued activity in polluted soils could also aid in the transport of particles into biologically active layers.

The prevailing biological trend when exposed to microplastic is chronic and sublethal instead of acutely fatal. Cui et al. (2022) critically reviewed the literature and found that microplastics generally affect growth, feeding, oxidative status, enzyme activity, reproduction, and behavior in earthworms, and that effects depend on polymer type, shape, particle size, concentration, and co-contaminants. In a 2026 meta-analysis, this conclusion was extended with 2,124 observations in 102 articles and found overall survival

and growth reductions, augmented oxidative stress and DNA damage, and diminished gut bacterial diversity and richness; biodegradable microplastics were found to have different but not necessarily lower ecological risk than traditional polymers (Zhong et al., 2026)

Microplastics are particularly problematic in terms of soil-health as they cause organism-level stress, structural and microbial disturbance. The reaction of earthworms to plastic is thus usually most effectively explained in conjunction with aggregate stability, soil respiration, and enzyme activity. In places where synthetic pesticides can generate a more distinct toxicological signal, microplastics increasingly undermine habitat quality by creating low-visibility, cumulative alterations in the feeding environment, gut processing and soil physical architecture. This renders reproductive performance, growth, oxidative biomarkers, and function-related soil indicators especially useful in diagnosis.

6. Biopesticides and the issue of perceived safety

Bio-pesticides are somewhere in between in the literature: they are typically positioned as less-toxic alternatives, yet the data is not sufficient to consider them universally harmless. Lower persistence, reduced target spectrum, or accelerated environmental dissipation of microbial products, fermentation-derived actives, or botanical pesticides may also lead to less non-target exposure compared to conventional broad-spectrum chemicals (Copping & Menn, 2000). Meanwhile, toxicity is formulation-dependent, and the ecological profile of a product can change significantly when solvents, adjuvants, encapsulation materials, or repeated application schedules are taken into account (Kilani-Morakchi et al., 2021; Pereira et al., 2025).

Nevertheless, the current agricultural evidence is promising. Marcinkevičienė et al. (2022) found that the application of biopesticides in an organic rapeseed system did not have a significant effect on the number

or biomass of earthworms, and certain biopesticide-cover crop combinations enhanced macroaggregate-related properties. That observation is in line with the larger agronomic anticipation that biologically based pest management may be more compatible with soil-fauna conservation when applied at recommended rates and integrated into systems that retain residue inputs and cause minimal severe disturbance.

Caution remains necessary. Neem-derived azadirachtin formulations, such as, are frequently preferred due to faster degradation and reduced persistence, yet the same characteristics can

necessitate more frequent applications, and newer encapsulated formulations might not have the same non-target profile as conventional products (Kilani-Morakchi et al., 2021). On the same note, certain essential-oil and fermentation products can impact non-target invertebrates at high doses or in unsuitable formulations. The evidence of the review thus suggests a comparative and not categorical conclusion: biopesticides tend to cause less earthworm stress than conventional pesticides, but they too need ecotoxicological investigation. using the same endpoint hierarchy applied to synthetic inputs.

| Evidence domain | Representative source(s) | Study scope | Main implication for indicator use |
|-----------------------------------|---|--|--|
| Soil function and crop production | Fonte et al. (2023); Liu et al. (2019) | Global synthesis and long-term field experiment | Earthworms influence production and multifunctionality, so their responses have direct agronomic meaning. |
| Land-use intensification | Betancur-Corredor et al. (2024); Briones & Schmidt (2017); Bartz et al. (2024) | Global meta-analyses and no-tillage indicator study | Density, biomass, and richness decline with tillage and intensive arable use; lower-disturbance systems preserve the biological signal. |
| Synthetic pesticides | Pelosi et al. (2014); Gunstone et al. (2021); Kumar et al. (2024) | Critical reviews and hazard assessment | Reproduction, behavior, and growth are generally more sensitive than mortality; field abundance alone can underdetect chronic stress. |
| Microplastics | Rillig et al. (2017); Cui et al. (2022); Zhong et al. (2026) | Mechanistic experiment, critical review, and meta-analysis | Chronic sublethal effects, oxidative stress, and gut perturbation dominate; biodegradable polymers are not automatically safer. |
| Biopesticides | Marcinkevičienė et al. (2022); Kilani-Morakchi et al. (2021); Pereira et al. (2025) | Field evidence and formulation-oriented reviews | Non-target disruption is usually lower at recommended rates, but formulation details and repeated exposure remain important uncertainties. |
| Soil-function coupling | Burns et al. (2013); Six et al. (2004); Reis et al. (2025) | Process reviews and field study | Enzyme activity and aggregate stability strengthen interpretation by linking earthworm responses to soil function. |

Table 2. Representative literature streams that underpin the comparative argument of this review.

7. Toward an earthworm-centered monitoring framework

The practical question is not whether earthworms are useful indicators, but how they should be used. The literature strongly suggests that earthworm-based soil-health assessment is most robust when it combines population metrics, early-warning ecotoxicological endpoints, and function-linked soil measures. Abundance and biomass remain essential because they are accessible in field surveys and communicate clearly to farmers. However, they are seasonally variable and often lag behind sublethal impairment. Reproduction integrates chronic energetic stress, avoidance captures short-term habitat quality and bioavailability, and biochemical markers such as catalase, glutathione-related enzymes, acetylcholinesterase, malondialdehyde, and reactive

population decline becomes obvious (Pelosi et al., 2014; Cui et al., 2022; Zhong et al., 2026).

An additional strength of earthworms as indicators is that they can be linked directly to soil functions that are already recognized in soil-health frameworks. Dehydrogenase, beta-glucosidase, phosphatase, respiration, and aggregate stability are especially useful complements because they reflect the microbial and structural consequences of the same disturbances that alter earthworm performance (Burns et al., 2013; Six et al., 2004). When earthworm responses and soil-function metrics move in the same direction, inference is much stronger than when either is interpreted in isolation.

A tiered monitoring design is therefore appropriate for agroecosystems. The first tier is field diagnosis through abundance, biomass, and visible ecological

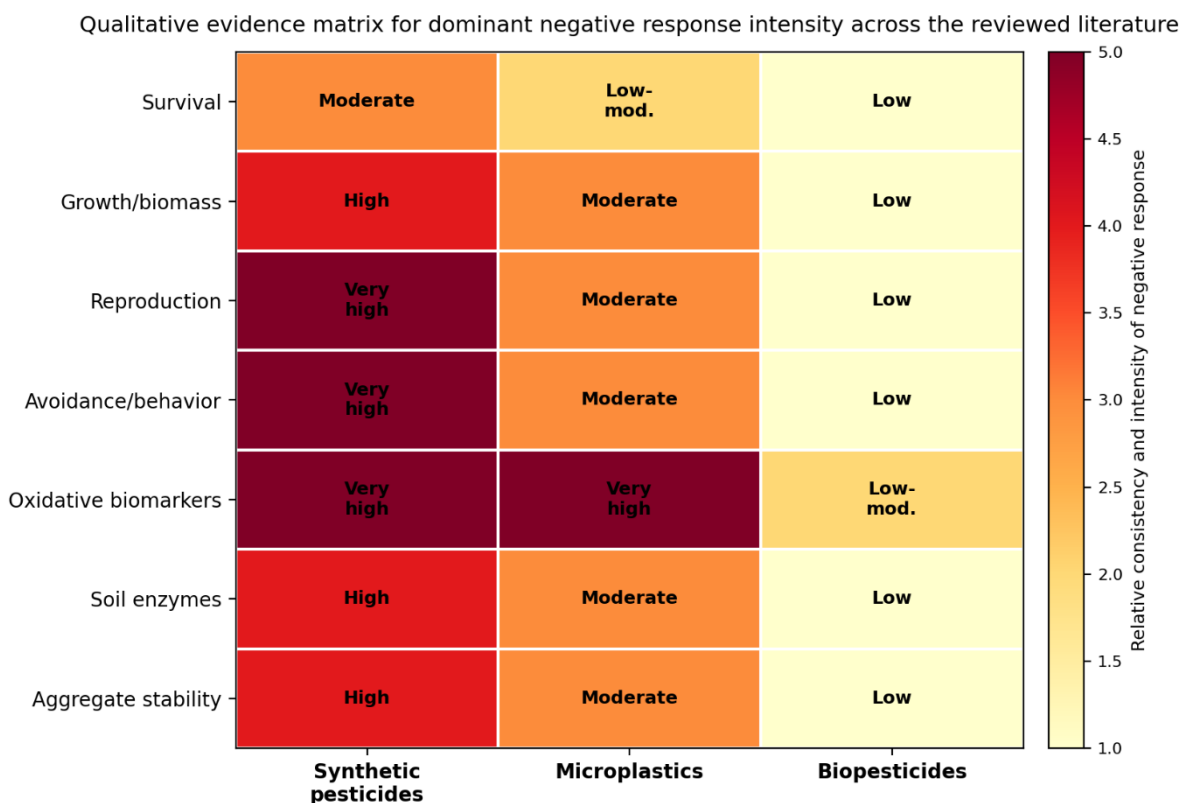


FIGURE 2. QUALITATIVE EVIDENCE MATRIX SUMMARIZING THE RELATIVE CONSISTENCY AND INTENSITY OF NEGATIVE RESPONSES REPORTED FOR MAJOR EARTHWORM AND SOIL-FUNCTION ENDPOINTS ACROSS THE REVIEWED LITERATURE. HIGHER VALUES INDICATE MORE CONSISTENTLY ADVERSE RESP

oxygen species help reveal mechanism before categories during biologically active periods. The

second tier adds standardized laboratory or mesocosm assays for avoidance, growth, and reproduction to evaluate chronic or suspected contaminant stress under controlled conditions. The third tier links the biological results to soil-function metrics and management history so that diagnostic conclusions can be translated into practice. This tiered approach also creates a bridge between regulatory ecotoxicology and soil-health monitoring, two fields that often remain unnecessarily separate.

For tropical and subtropical agriculture, baseline calibration is particularly important. Species pools,

seasonal moisture patterns, temperature regimes, and residue management differ substantially from temperate reference systems where many standard methods were developed. That does not invalidate earthworm testing, but it does mean that interpretation should prioritize relative comparison among management regimes, repeated seasonal measurements, and the use of complementary soil-function metrics. Where possible, regionally common field species should be considered alongside standard test species so that indicator frameworks remain ecologically grounded.

| Metric | Diagnostic timescale | Primary strength | Main limitation | Recommended use |
|---|-------------------------------------|---|---|--|
| Abundance and biomass | Seasonal to annual | Field-realistic and easy to communicate | Strongly influenced by moisture and season | Baseline monitoring and comparison among management systems |
| Functional-group composition | Seasonal to annual | Identifies which soil compartment is most affected | Requires ecological expertise | Diagnosis of tillage, residue, and surface contamination effects |
| Growth or biomass change in assay | Days to weeks | Sensitive early sublethal response | Needs controlled exposure | Follow-up testing when contamination is suspected |
| Reproduction (cocoon or juveniles) | Weeks | Most robust chronic ecotoxicology endpoint | Longer duration and higher labor | Regulatory and ecological diagnosis of long-term stress |
| Avoidance behavior | 48 hours | Rapid signal of habitat quality and bioavailability | Cannot replace chronic endpoints | Screening of hotspots and contaminated field soils |
| Oxidative or neurophysiological biomarkers | Hours to days | Mechanistic early warning | Laboratory capacity and species variability | Mechanistic follow-up and stressor discrimination |
| Respiration, enzymes, and aggregate stability | Concurrent with biological sampling | Links biological response to soil function | Not earthworm-specific | Integrated interpretation of |

| Metric | Diagnostic timescale | Primary strength | Main limitation | Recommended use |
|--------|----------------------|------------------|-----------------|-----------------------------|
| | | | | earthworm indicator signals |

Table 3. Proposed earthworm-centered indicator panel for soil-health assessment in agroecosystems

7.1 Interpretation of mixed-stressor and gaps in evidence

One of the longstanding problems in agroecosystems is that soils rarely face a single stressor. Pieces of mulch, pesticide programs, tillage, removal of residues, drought events, and uneven organic inputs tend to co-occur and form exposure sequences not reflected by one-factor assays. The fact that earthworms combine these pressures over time is what makes them useful; but the same integrative property implies that a decrease in abundance or biomass cannot alone determine the driver behind it. The interpretation is best when biological observations are combined with management history, visible plastic loading, and complementary soil-function metrics that can differentiate between cumulative degradation and short-lived disturbance (Gunstone et al., 2021; de Souza Machado et al., 2018).

Thresholds are relative as well. Species pools differ with climates, and the sensitivity of a field population is sensitive to soil texture, moisture regime, pH, residue inputs, and contaminant sorption. Standard assays using *Eisenia fetida* or *Eisenia andrei* are still essential to provide comparability, but should be used as reference tools, not as full ecological surrogates of diverse tropical and subtropical field communities. Regional calibration of baselines, seasonal repetition, and explicit attention to tillage and land-use context are thus necessary in case earthworm indicators should be used to support operational decisions in monsoonal or irrigated systems (OECD, 2016; ISO, 2008; Betancur-Corredor et al., 2024; Jat et al., 2022).

Future studies would also enhance the evidence base by reporting exposure descriptors more consistently. In the case of plastics, polymer type, particle size, weathering condition, additives and co-contaminants must be standardized; in the case of pesticides and biopesticides, formulation, adjuvants, application intervals, and repeated exposure histories should be documented with active ingredients. Simultaneously measuring earthworm endpoints, soil enzymes, respiration, and aggregate stability will be especially informative as it will enable the diagnosis to shift towards toxicity description to ecosystem-function interpretation (Cui et al., 2022; Zhong et al., 2026; Kilani-Morakchi et al., 2021; Marcinkevičienė et al., 20)

8. Research implications and priorities in Indian agroecosystems

The consequences to Indian agroecosystems are direct. The use of pesticides, intermittent plastic mulch or greenhouse film inputs, transition to residue-management, and variable organic-matter return are increasingly integrated in intensified cereal and vegetable systems across the Indo-Gangetic plains. In this case, chemical soil tests are ill-equipped to detect the arising biological degradation. Indian climate-smart agricultural systems research has recently demonstrated that earthworm abundance is a predictor of more general increases in soil physico-biochemical properties with less disruptive management (Jat et al., 2022), which is why earthworm-based metrics should be considered in soil-health assessment outside of research contexts.

There are three research priorities. To begin with, mixed-stressor research is urgently required since real farms are not exposed to pesticides, fertilizers, tillage, and plastic residues in isolation. Second, more attention should be paid to tropical field species and natural soils, as sensitivity to climate and soil may be overlooked when extrapolating a limited range of standard organisms and artificial substrates. Third, the evaluation of biopesticides must shift beyond the simplistic product categories to formulation-conscious ecotoxicology that considers adjuvants, repeated application, and nano-enabled delivery systems.

8.1 Evidence translation into management programs

To implement it, an earthworm-based framework can be incorporated into the current soil-health and extension programs without undue analytical load. Field campaigns may be planned to coincide with

systems (Bünemann et al., 2018; Burns et al., 2013; Lehmann et al., 2020).

At the management level, the evidence reviewed justifies a pyramid of interventions: decreasing reliance on broad-spectrum synthetic pesticides by using integrated pest management, decreasing persistent plastic inputs and field-retrieval before fragmentation, retaining organic matter, and assessing reduced-risk products with the same non-target rigor as conventional chemicals. This framework is particularly applicable to the fast-growing Indian agroecosystems, where biological deterioration may go unnoticed until structural degradation and yield instability have progressed. Earthworm indicators are best applied in cases where they are integrated into management programs that relate diagnosis to residue management, input replacement, and soil-restorative measures (Copping and Menn, 2000; Marcinkevičienė et al., 2022; Bartz et al., 2024; Bertoncelj et al., 2025).

Tiered earthworm-centered workflow for diagnosis and management of stressed agroecosystems

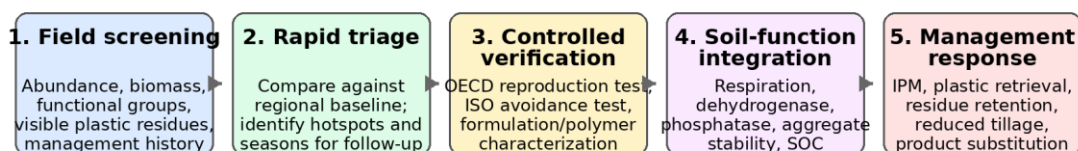


FIGURE 3. PROPOSED TIERED EARTHWORM-CENTERED WORKFLOW LINKING FIELD SCREENING, TARGETED VERIFICATION, SOIL-FUNCTION INTEGRATION, AND MANAGEMENT RESPONSE IN

biologically active intervals, monolith or mustard-extraction techniques of standardized abundance and biomass, and visible mulch residues, tillage intensity, residue cover, and recent pest-management history may be recorded during the same visit. In the presence of laboratory capacity, a small panel of complementary assays, including respiration or dehydrogenase to assess biological activity and aggregate stability to assess structural condition, can significantly enhance inference and still be compatible with larger soil-health

One last practical lesson of the literature reviewed is that communication is important. Farmers and extension officers tend to react more to an observable biological indicator than to an independent laboratory value. The abundance of earthworms, cocoon generation in simple mesocosm demonstrations, and evident shifts in soil friability or aggregate stability can render soil-health degradation palpable and can also be used to convey the advantages of less disruptive management. That is why earthworm-based monitoring is not only a scientific instrument but also

a potentially useful interface between ecological evaluation and on-farm decision-making.

stressed agroecosystems. Figure created for this review.

9. Conclusions

Earthworms are among the most informative biological indicators available for diagnosing soil habitat quality in agroecosystems because they unite sensitivity to disturbance with direct functional importance. The literature reviewed here shows a consistent gradient of stress: synthetic pesticides usually generate the strongest and most multifaceted adverse responses, microplastics produce chronic and often sublethal impairment that can be underestimated by mortality-based assessment, and biopesticides are generally more compatible with earthworm conservation but are not automatically risk free.

For practical soil-health assessment, abundance and biomass should be retained as core field metrics, but they should be interpreted together with reproduction, avoidance behavior, and soil-function indicators such as enzyme activity and aggregate stability. An earthworm-centered, multi-metric framework offers a realistic way to connect ecotoxicology, soil biology, and management decisions. In intensifying agricultural regions, especially those where pesticide inputs and agricultural plastics increasingly co-occur, such an approach can strengthen both ecological diagnosis and the design of more resilient farming systems.

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