Journal of
Environment
(JE)

Earthworms as Soil-Health Bioindicators in Mogadishu Greenhouses: A Comparative Study Under Contrasting Managements

Journal of Environment

ISSN 2789-3863 (Online)

Vol. 5, Issue No. 5, pp 51 – 66, 2025

Earthworms as Soil-Health Bioindicators in Mogadishu Greenhouses: A Comparative Study Under Contrasting Managements

Ibrahim Jamal Ahmed[1]*, Yasin Sheikh Amir Sheikh Ibrahim[1], Abdullahi Adan Salah[1], Abdirahman Jamal Ahmed[2], Hibo Abdinasir Mohamud[3], Abdisamad Abdidahir Adan[1], Abdisalan Mohamud Sheikh Isak[1], Abdulkadir Abdullahi Ibrahim[1]

[1]Somali National University, Faculty of Agriculture and Environmental Science, Department of General Agriculture, Mogadishu, Somalia.

[2]Civil & Environmental Engineering Department, King Fahd University of Petroleum & Minerals, Dhahran, Kingdom of Saudi Arabia.

[3]Faculty of Agriculture, Environment and Food Systems, Department of Crop Science, University of Zimbabwe, Harare, Zimbabwe.

Accepted: 7th Dec, 2025, Received in Revised Form: 23rd Dec, 2025, Published: 28th Dec, 2025

Abstract

Purpose: Greenhouse farming is rapidly expanding in Mogadishu due to water scarcity and increasing demand for vegetables in the market. However, widespread dependence on chemical inputs raises concerns about the long-term health of soils. This study investigated the influence of management systems, Good Agricultural Practices (GAP) versus non-GAP, on plant and soil biological health across 30 greenhouse farms located on the outskirts of Mogadishu and along the Afgoye corridor.

Methodolo Abdisalan Mohamud Sheikh Isak gy: A cross-sectional observational design was applied across 30 greenhouses (9 GAP, 21 non-GAP), with 300 plant-rhizosphere units assessed using non-destructive visual indicators. Metrics included Plant Health Score (PHS), leaf color, turgor, surface soil condition, and the Visual Earthworm Abundance Index (V-EAI). Data collection was undertaken from July through September 2025. Data was analyzed using SPSS V.27. Mann. Whitney U tests and Independent Samples t-Tests assessed differences.

Findings: Results revealed significantly higher biological activity and plant vigor in GAPmanaged greenhouses ($p < 0.05$), with visible earthworms mainly present in GAP greenhouses. Despite similar irrigation and bed formation practices, non-GAP systems showed reduced earthworm presence, lower plant health scores, and greater reliance on chemical inputs.

Unique Contribution Theory, Policy and Practice: The study demonstrates that visual earthworm monitoring is a feasible and effective proxy for soil biological health, offering a scalable method for smallholder farmers and extension agents. It also highlights the ecological benefits of GAP management, emphasizing the role of organic inputs and reduced fumigation in promoting soil life. These findings support integrating bioindicators into sustainable greenhouse agriculture in fragile, water-limited environments. Overall, the study advances SDG 12 (Responsible Consumption and Production) and SDG 15 (Life on Land) by promoting sustainable greenhouse management and safeguarding soil biodiversity.

Keyword: *Soil health, Greenhouse, Earthworm, Gap, Non-Gap, Somalia*

1. Introduction

Soil health, a critical determinant of agricultural productivity and ecosystem functionality, is fundamentally shaped by the biological communities within it. In semi-arid systems like those around Mogadishu, soil biological health plays a pivotal role in sustaining crop productivity under pressures from chemical inputs and water scarcity. Soil health is vital for sustaining life on Earth. Healthy soil supports food production, regulates climate, manages water, and provides energy while hosting countless living organisms. It also recycles nutrients, replenishes groundwater, maintains fertility, and helps break down organic matter.. The importance of soil health goes far beyond farming; it also affects the environment, the economy, and society. (Yadav et al., 2021). Healthy soils create strong, productive ecosystems by giving plants a stable place to grow and supplying essential nutrients, organic matter, and beneficial microorganisms. (Gupta & Kumar, 2024). Soil organisms and their interactions play a key role in various ecosystem processes and functions, such as the provision of nutrients (Lang et al., 2023). In most terrestrial ecosystems, earthworms represent the largest animal biomass (Lavelle & Spain, 2004). They serve as catalysts for two crucial supporting services: soil formation (Darwin, 2009) and nutrient cycling (Edwards, 2004), both of which are fundamental to other services. Earthworms are vital soil organisms that support soil fertility and overall ecosystem sustainability (Liu et al., 2019). Often called "farmers' friends" or "ecological engineers." (A & Entoori, 2022). They improve soil structure, aeration, and drainage through their burrowing. By enhancing nutrient cycling and influencing microbial communities, earthworms boost plant growth and act as natural soil conditioners (Ahmed & AlMutairi, 2022).

Earthworms and other soil fauna, along with rhizosphere microbial communities, are vital bioindicators of soil quality and human impact (Bhaduri et al., 2015; Patel et al., 2020). These organisms regulate essential ecosystem processes such as organic matter decomposition, nutrient cycling, soil structure formation, and water infiltration, all of which support sustainable agriculture and land rehabilitation (Ayangbenro et al., 2022). Earthworms are key ecosystem engineers, vital for soil ecosystems, and are widely recognized as indicators of soil quality, health, and functions. Earthworm activity significantly affects the soil structure and nutrient cycling (Kooch et al., 2025). Earthworms are especially recognized for their role in ecosystem functions and services. They shape soil structure, protect organic material from mineralization as it mixes with soil particles, promote water infiltration, facilitate litter decomposition, and support nitrogen mineralization (Blouin et al., 2013). They also dominate the biomass of soil fauna in most biomes (Fierer et al., 2009). Their activity promotes soil aeration, microbial diversity, and the stabilization of soil aggregates, making them crucial allies in sustainable farming systems (A & Entoori, 2022).

Because of their sensitivity to soil disturbance, moisture, pH, and chemical residues, earthworm abundance and diversity have become valuable bioindicators for assessing soil biological health in agricultural settings (Fründ et al., 2011). Studies consistently show that earthworm populations are significantly higher in organically or biologically managed soils compared to chemically fertilized or intensively tilled ones (Cenci & Sena, 2006; Szilágyi et al., 2021). Managing the rhizosphere through composting, reduced agrochemical use, and biological monitoring can improve soil fertility and crop outcomes, particularly in urban greenhouses, where varying practices, such as Good Agricultural Practices (GAP) and non-GAP approaches, can alter soil biological communities (Prasad et al., 2017). Although quantifying soil health remains challenging for policy implementation, it provides a valuable tool for research and for tracking ecological changes over time. The soil microbiome is essential for recycling nutrients and supplying plants with key macro- and micronutrients. But environmental stress and excessive chemical use can disrupt microbial diversity, ultimately altering soil biochemistry (Purohit et al., 2024). In greenhouse systems, where soil conditions are artificially maintained, earthworm visibility and activity can be strongly influenced by irrigation, organic amendments, and avoidance of chemical fumigation. Their presence offers a rapid, visual proxy for farmers and extension agents to assess soil biological health, particularly in resource-limited contexts like Somali greenhouse agriculture (Schon et al., 2023). The significance of incorporating eco-friendly methods that involve earthworms in modern agriculture and environmental sustainability is immense. These practices produce a high-quality, nutrient-dense biofertilizer that greatly enhances soil health, boosts crop yields, and improves waste management (Ali et al., 2015; Boruah & Deka, 2023; Rupani et al., 2023)

Greenhouse cultivation is rapidly expanding in semi-arid regions as a strategic response to erratic rainfall, degraded soils, and rising market demand for year-round vegetable production. By enabling controlled irrigation, temperature buffering, and protection from environmental stressors, greenhouses have become central to resilient farming in water-scarce areas like Somalia, Mexico, and northwest India. (Sharan & Madhavan, 2010). However, the sustainability of these systems depends not just on yield, but also on maintaining healthy, biologically active soils, an aspect often neglected under intensive greenhouse regimes. Despite their promise, greenhouse systems in semiarid zones face specific soil health challenges due to high evapotranspiration, salinity buildup, and over-reliance on synthetic inputs. Studies have shown that, over time, the intensive use of fertilizers and poor replenishment of organic matter in such settings lead to microbial decline and reduced soil function (Rodríguez-Berbel et al., 2022). These constraints are particularly acute in Somalia, where fragile soils and limited access to training or composting infrastructure hinder the adoption of soil-regenerative practices (SWALIM, 2013).

While greenhouse productivity is typically measured by yields or input efficiency, soil biological health, especially in the rhizosphere, remains largely overlooked, particularly in many smallholder systems (Kaushal et al., 2025). Most existing monitoring approaches are either laboratoryintensive or rely on chemical proxies, leaving farmers and extension workers without accessible tools for assessing soil life (Zeng et al., 2025). This gap is especially problematic in semi-arid greenhouses, where management intensity often disrupts microbial and faunal communities but goes undetected due to the lack of biological indicators. Recent commentary highlights that visual soil evaluation, including basic observation of structure, rooting depth, and fauna like earthworms, can be a powerful, scalable approach to assessing biological soil health in the field (Ruf, 2025). Yet this simple method is utilized in developing country contexts, where agricultural extension services often lack both resources and technical training. Incorporating visual bioindicators, such as earthworm presence, offers an immediate, non-destructive, and educational method to engage growers in sustainable soil stewardship.

Journal of Environment

ISSN 2789-3863 (Online)

Vol. 5, Issue No. 5, pp 51 – 66, 2025

This study aims to assess the biological health of soils in greenhouse vegetable production systems around Mogadishu by comparing Good Agricultural Practices (GAP) and non-GAP management through the lens of earthworm abundance and basic rhizosphere indicators. The core research question asks: Do GAP-managed greenhouses show higher levels of visible earthworm activity and healthier soil-plant conditions than their non-GAP counterparts? A secondary goal is to explore which management practices, such as compost use, pesticide reduction, or irrigation scheduling, correlate with stronger biological outcomes in the field. We hypothesize that GAP greenhouses support significantly greater soil biological activity, as indicated by surface-visible earthworm presence and associated plant health scores. The null hypothesis assumes no measurable difference between GAP and non-GAP systems. By introducing a visual, farmerfriendly observation method grounded in local practice, this study contributes a replicable and cost-effective approach for evaluating soil life in semi-arid, smallholder greenhouse environments.

2. Material And Methods

2.1 Study Area and Design

The study was conducted in 30 soil-based greenhouse farms located in Mogadishu and along the Afgoye corridor (See Figure 1). These greenhouses typically use drip irrigation and raised beds under a hot, semi-arid climate. Farms were intentionally selected to represent two contrasting management types: 9= under Good Agricultural Practices (GAP) and non-GAP management. In this study, GAP greenhouses are defined as production units complying with FAO Good Agricultural Practices, characterized by reduced use of synthetic fertilizers, application of compost or well-managed organic manures, responsible pesticide use, protection of worker health, environmentally sustainable cultivation, and proper postharvest handling. In contrast, non-GAP greenhouses are conventionally managed systems that rely predominantly on synthetic fertilizers and chemical pesticides, with limited organic inputs and no formal adherence to GAP-based environmental, safety, or soil management standards (FAO, 2003). A comparative cross-sectional observational design was applied to assess differences in soil biological health. In each greenhouse, ten plants were chosen using a systematic sampling method (selecting every kth plant or evenly spaced across beds), avoiding edge positions and headlands to reduce edge effects. Sampling was done in one round, scheduled to minimize temporal bias by collecting samples during similar irrigation times, and conducted in the morning when plant water status and visible rhizosphere cues were most comparable. Verbal informed consent was obtained from all participating growers, and only surface-level, non-destructive observations were made to ensure minimal disruption to crops and soils.

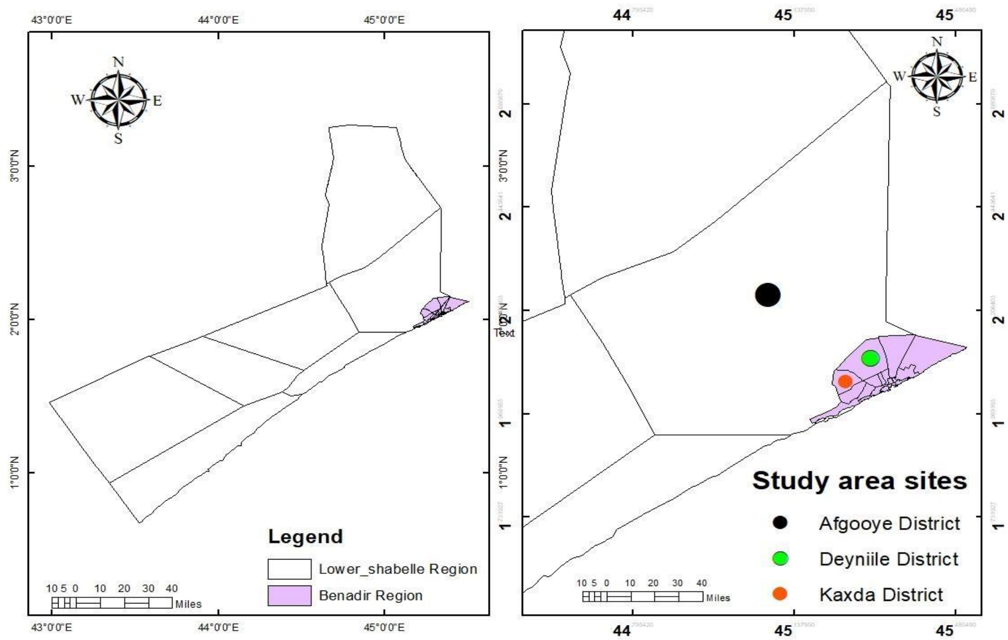

Figure 1: Study area

2.2 Field Observation and Data Collection

The main sampling unit was the plant and its immediate rhizosphere (5–10 cm from the stem). At each plant, a standardized protocol was used to assess:

- Plant Health Score (PHS) (0–4)
- Leaf Color Score (0–3), Turgor Score (0–2), and Surface Soil Condition Score (0–3)
- Visual Earthworm Abundance Index (V-EAI) ranging from 0 (none) to 3 (>5 worms)
- Binary indicators: mulch present (Y/N) and visible worm (Y/N)
- Environmental context: days since irrigation/fertigation, crop stage, and pest/disease observations

Structured interviews (10–15 minutes) were conducted with each grower to gather information on demographics, soil preparation, chemical use, compost/mulch application, irrigation, and bed management. Data collection was undertaken from July through September 2025.

2.3 Data Management and Analysis

Descriptive statistics were used to summarize management practices and field observations. Differences between GAP and non-GAP greenhouses were assessed using Mann–Whitney U tests and Independent Samples t-Tests via SPSS V.27**.** Given the limited number of GAP samples and the clustering of observations within 30 greenhouses, results were interpreted conservatively. Logistical and financial constraints made it difficult to visit more greenhouses; therefore, the sampled sites were used as a snapshot to represent broader greenhouse farming practices. The study emphasizes the need for larger, balanced sampling in future research to enable more robust inferential analysis.

3. Results

3.1 Demographics of the respondents and Greenhouse Management Practices

The demographic profile of the 30 greenhouse farmers (See Table 1) shows a predominantly young farming population. The majority (60%, n = 18) were between 18–25 years, while 30% (n = 9) were 26–35 years. Only a small proportion were older adults, with 3.3% (n = 1) aged 36–45 and 6.7% (n = 2) aged above 46 years. Educational attainment varied, but most respondents had a basic education: 36.7% (n = 11) completed primary school, 33.3% (n = 10) reached secondary school, while 23.3% (n = 7) attained tertiary education. Only 6.7% (n = 2) reported informal education, indicating that the majority of greenhouse adopters have at least a foundational level of schooling. Greenhouse production appears male-dominated, with 83.3% (n = 21) of respondents being men compared to 16.7% (n = 5) women. Regarding farming experience, 30% (n = 9) had farmed for 0–1 year, and another 30% (n = 9) for 2–3 years. Slightly more experienced farmers, those with 4–7 years, made up 26.7% (n = 8), while only 13.3% (n = 4) had farmed for 8–10 years. Regarding livelihood dependency, almost half of the households (63.3% n = 19) relied primarily on farming as their main source of income, while 36.7% (n = 11) reported mixed income sources. This distribution suggests that greenhouse farming is becoming an important part of household economic strategies.

Journal of Environment

ISSN 2789-3863 (Online)

Vol. 5, Issue No. 5, pp 51 – 66, 2025

Table 1: Demographics of the respondents (n = 30)

Variable	Category	%
Education Level	Informal	6.7%
	Primary	36.7%
	Secondary	33.3%
	Tertiary	23.3%
Gender	Female	30.0%
	Male	70.0%
Age Group	18–25	60.0%
	26–35	30.0%
	36–45	3.3%
	46+	6.7%
Farming Experience	0–1 year	30.0%
	2–3 years	30.0%
	4–7 years	26.7%
	8–10 years	13.3%
Main Household Income	Farming	63.3%
	Mixed	36.7%

According to Table 2, greenhouse management experience varied considerably among respondents. Half of the farmers (50%, n = 15) had managed greenhouses for less than one year, demonstrating a relatively new and rapidly expanding adoption of this technology. More established users, those with 4–6 years of experience, accounted for 33.3% (n = 10), whereas only 3.3% (n = 1) had more than seven years of experience. Soil preparation practices were dominated by manual tillage, reported by 86.7% (n = 26), highlighting limited mechanization within the study area. Mechanized tillage was used by only 13.3% (n = 4). Similarly, soil fertility management practices showed varied adoption among respondents. While 40% (n = 12) reported applying compost, the remaining 60% (n = 18) did not use compost at all. Mulching practices were also limited, with 83.3% (n = 25) indicating they did not apply mulch, whereas only 16.7% (n = 5) reported using mulch. Biological soil health indicators appeared weak, as 70% (n = 21) of farmers stated they "never" observed earthworms, compared with only 30% (n = 9) who saw them often. This aligns with the widespread use of soil fumigation or sterilization, reported by 70% (n = 21), which may reduce beneficial soil organisms. Only 30% (n = 9) stated they did not use fumigation or sterilization. Together, these practices suggest a greenhouse sector characterized by early adoption, intensive soil management, and varying levels of adherence to sustainable soil health practices.

Table 2: Greenhouse Management Practices of Respondents (n = 30)

Variable	Category	%
Years Managing Greenhouse	<1 year	50.0%
	1–3 years	13.3%
	4–6 years	33.3%
	7+ years	3.3%
Soil Preparation Method	Manual tillage	86.7%
	Mechanized tillage	13.3%
Compost Application	No	60.0%
	Yes	40.0%
Mulch Application	No	83.3%
	Yes	16.7%
Earthworm Observation	Often	30.0%
	Never	70.0%
Fumigation / Soil Sterilization	No	30.0%
	Yes	70.0%

3.2 Data Comparative Analysis of Plant and Soil Health Indicators

A comprehensive statistical evaluation was conducted to determine how greenhouse management practices (GAP vs non-GAP) influenced plant performance, foliar attributes, soil condition, and soil biological activity. Descriptive statistics, percentile distributions, and inferential tests were integrated to provide a robust assessment. Across all measured indicators, GAP-managed plots consistently exhibited higher central tendency values**,** narrower dispersion, and more favorable

Journal of Environment

ISSN 2789-3863 (Online)

Vol. 5, Issue No. 5, pp 51 – 66, 2025

www.carijournals.org

biological conditions compared to non-GAP plots. Median plant health was higher in GAP (Median = 4.0) than in NGAP (Median = 3.0), accompanied by improved leaf color, turgor, and surface soil structure. The Visible Worm Index—a proxy for soil biological activity showed a complete contrast between systems, with consistently high scores in GAP and near-zero values in NGAP.

Table 3: Consolidated Descriptive and Percentile Statistics by Management System (n = 300)

Variable	Group	Mean	SD	25th	Median	75th	IQR	N
Plant health score (0–4)	GAP	4.00	0.00	4.00	4.00	4.00	0.00	90
	NGAP	2.67	0.72	2.00	3.00	3.00	1.00	210
Leaf color score (0–3)	GAP	2.93	0.25	3.00	3.00	3.00	0.00	90
	NGAP	2.42	0.63	2.00	2.50	3.00	1.00	210
Turgor score (0–2)	GAP	2.00	0.00	2.00	2.00	2.00	0.00	90
	NGAP	1.73	0.54	2.00	2.00	2.00	0.00	210
Surface soil condition (0–3)	GAP	3.00	0.00	3.00	3.00	3.00	0.00	90
	NGAP	2.08	0.55	2.00	2.00	2.00	0.00	210
Visible worm index (0–3)	GAP	2.41	0.78	3.00	3.00	3.00	0.00	90
	NGAP	0.04	0.19	0.00	0.00	0.00	0.00	210

3.3 Comparative and Inferential Analysis of Plant and Soil Health Indicators

Inferential statistics (See Table 4A and B) strongly supported these differences. All Mann–Whitney U tests were highly significant ($p < .001$), indicating systematic and non-random differences in plant and soil attributes between management groups. These findings were corroborated by Independent Samples t-tests, which revealed large effect sizes and significant mean differences, indicating that GAP management substantially improved plant vigor, leaf physiology, soil condition, and earthworm presence. Correlation analysis further reinforced these patterns. Plant health, leaf color, turgor, surface soil condition, and earthworm abundance all demonstrated strong positive intercorrelations, indicating synergistic relationships among plant vigor, foliar traits, and soil biological functioning. Importantly, Management was strongly negatively correlated with most biophysical indicators (ρ ranging from −.28 to −.95), reflecting that shifting from NGAP to GAP was associated with marked improvements in all measured outcomes. Overall, the combined evidence demonstrates that GAP management produces more favorable greenhouse plant and soil health conditions, supporting higher physiological quality, improved soil structure, and greater biological activity. These patterns highlight the ecological and agronomic relevance of adopting improved management interventions such as balanced fertigation, mulching, sanitation, irrigation scheduling, and integrated pest control.

Table 4: Inferential Tests and Correlation Summary (n = 300)

A. Mann–Whitney U Tests

Variable	U	Z	p-value
Plant health	585.000	−13.772	.000
Leaf color	5307.000	−7.101	.000
Turgor	7380.000	−4.806	.000
Surface soil condition	1710.000	−12.631	.000
Visible worm index	64.000	−16.430	.000

B. Independent Samples t-Tests

Variable	t	df	p	Mean Diff	95% CI (Lower, Upper)
Plant health	26.742	209	.000	1.329	1.231 – 1.427
Leaf color	9.999	297	.000	0.510	0.409 – 0.610
Turgor	7.149	209	.000	0.267	0.193 – 0.340
Surface soil	24.426	209	.000	0.924	0.849 – 0.998
Visible worms	28.587	94	.000	2.373	2.208 – 2.538

3.4 Reliability Analysis

Internal consistency among the five plant and soil health indicators (Plant Health Score, Leaf Color, Turgor, Surface Soil Condition, and Visible Worm Index) was assessed using Cronbach's Alpha, see Table 5. The scale showed acceptable reliability ($\alpha = 0.809$), indicating that the indicators are sufficiently correlated to justify their combined interpretation as a composite measure of overall plant and soil health.

Journal of Environment

ISSN 2789-3863 (Online)

Vol. 5, Issue No. 5, pp 51 – 66, 2025 www.carijournals.org

Table 5: Reliability Statistics

Reliability Statistics	
Cronbach's Alpha	**N of Items**
0.809	**5**

4. Discussions

The findings from this study offer compelling evidence that greenhouse management practices significantly affect soil biological health, particularly as measured by visible earthworm activity. Earthworms were largely observed in GAP-managed greenhouses, reinforcing their role as sensitive indicators of soil ecological integrity. This mirrors findings from semi-arid systems in South Africa, where earthworm richness and abundance increased significantly under conservation practices such as residue retention and crop rotation with organic inputs (Mcinga et al., 2020). The statistically significant differences across all plant and soil health indicators underscore the ecological benefits of GAP practices, specifically compost use, minimal tillage, and reduced chemical load. Cardarelli et al. (2022) and Mohite et al. (2024) agree that the presence of earthworms enhances crop resistance against diseases, stimulates seed germination, and improves overall plant vigor. Despite structural similarities (e.g., bed layout, drip irrigation), nonGAP systems exhibited diminished soil earthworms, likely due to frequent fumigation and synthetic fertilizer use. Comparable trends were documented in long-term African field trials, where intensive cropping and reduced soil carbon inputs led to suppressed earthworm and termite populations (Ayuke et al., 2011).

The strong internal consistency across indicators (Cronbach's $\alpha = 0.809$) validates the visual methodology as a composite tool for rapid soil health assessment. This supports calls for visual soil evaluation in smallholder agriculture as an accessible alternative to lab-intensive testing (Ruf, 2025). While the limited GAP sample size restricts broader inference, the results affirm the value of integrating biological indicators into participatory soil monitoring. As stated by Bartz et al., (2024) farmers can easily assess the health of their soil by examining the abundance and diversity of earthworm species. Soil earthworms, known for their eco-friendly qualities, are considered crucial for greatly boosting the growth and productivity of a variety of crops, including vegetables, flowering plants, and fruit trees (Aalok et al., 2008; Ali et al., 2015). Jat et al., (2022) also highlighted that earthworms are a reliable indicator of soil biological health, with their abundance increasing under sustainable management practices.

The exclusive presence of earthworms in GAP-managed soils is consistent with their recognized role as highly sensitive bioindicators of soil health. Earthworms respond rapidly to environmental changes, and their presence, abundance, and species composition provide direct insight into soil ecological functioning (Fründ et al., 2011). Their ecological roles, including organic matter decomposition, nutrient mineralization, soil aeration, and microbial activation, explain why they thrive in biologically enriched GAP soils. Conversely, their absence in non-GAP soils likely reflects chemical stress, and exposure to pesticides is known to disrupt key physiological systems in earthworms, including neurotransmission and energy metabolism (Tiwari et al., 2016), while toxic environments trigger avoidance behaviors that cause earthworms to migrate away from polluted soils (Fründ et al., 2011). Biochemical and metabolomic studies further demonstrate that earthworm metabolic profiles vary significantly under different land management systems, reflecting underlying soil health conditions (Rochfort et al., 2009). Moreover, their broad sensitivity to endocrine-disrupting compounds and other anthropogenic chemicals (Azevedo et al., 2024) emphasizes their value as comprehensive sentinels of soil contamination, ecological stress, and long-term sustainability (Ghosh, 2018; Hirano & Tamae, 2011).

5. Conclusion

This study demonstrates that earthworm presence is a valid and accessible bioindicator of soil biological health in greenhouse systems. In the semi-arid conditions of Mogadishu, greenhouses managed under Good Agricultural Practices (GAP) consistently exhibited higher earthworm abundance, superior plant health, and improved rhizosphere conditions compared to non-GAP systems. These findings highlight the ecological advantages of organic inputs, mulching, and reduced synthetic chemical use in supporting soil biological function. The exclusive detection of earthworms in GAP-managed plots underscores their sensitivity to soil management, reinforcing their value as practical and farmer-observable indicators of soil life. Visual metrics such as the Plant Health Score and Earthworm Abundance Index proved effective, low-cost tools for assessing greenhouse soil quality, particularly in low-resource farming environments where laboratory testing is not feasible. This approach offers a scalable solution for integrating soil biological monitoring into smallholder agriculture, bridging the gap between scientific knowledge and fieldlevel practice. The study highlights the value of integrating biological indicators into routine greenhouse management, particularly in resource-limited and water-stressed environments such as Mogadishu. By showing how sustainable practices strengthen both productivity and ecological resilience, the study aligns with global priorities under SDG 12 (Responsible Consumption and Production) and SDG 15 (Life on Land).

6. Recommendation

The study reinforces the need to protect soil biodiversity while advancing more responsible and sustainable agricultural systems. Future research should validate these findings across diverse seasons, soil types, and microbial communities to strengthen generalizability. Policymakers and development programs are encouraged to incorporate bioindicator-based training into extension services to support sustainable intensification. In fragile agroecosystems, visual bioindicators could offer a pathway to enhancing productivity, resilience, and long-term soil health.

Acknowledgments

We gratefully acknowledge the faculty of Agriculture and Environmental Science at Somali National University, along with the technical staff and students, for their valuable support throughout this experiment. Their assistance during data collection and greenhouse assessments greatly strengthened this work.

Declaration of competing interests

The authors declare that they have no known competing financial interests or personal relationships that could appear to influence the work reported in this paper. We also assert that this article is original, has not been published before, and is not under consideration for publication elsewhere.

Data availability

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

References

A, A., & Entoori, K. (2022). Role of earthworms in soil fertility and its impact on agriculture: A review. *International Journal of Fauna and Biological Studies*, *9*(3), 55–63. https://doi.org/10.22271/23940522.2022.v9.i3a.907

Aalok, A., Tripathi, A. K., & Soni, P. (2008). Vermicomposting: A Better Option for Organic Solid Waste Management. *Journal of Human Ecology*, *24*(1), 59–64. https://doi.org/10.1080/09709274.2008.11906100

Ahmed, N., & Al-Mutairi, K. A. (2022). Earthworms Effect on Microbial Population and Soil Fertility as Well as Their Interaction with Agriculture Practices. *Sustainability*, *14*(13), 7803. https://doi.org/10.3390/su14137803

Ali, U., Sajid, N., Khalid, A., Riaz, L., Rabbani, M. M., Syed, J. H., & Malik, R. N. (2015). A review on vermicomposting of organic wastes. *Environmental Progress & Sustainable Energy*, *34*(4), 1050–1062. https://doi.org/10.1002/ep.12100

Ayangbenro, A. S., Chukwuneme, C. F., Ayilara, M. S., Kutu, F. R., Khantsi, M., Adeleke, B. S., Glick, B. R., & Babalola, O. O. (2022). Harnessing the Rhizosphere Soil Microbiome of Organically Amended Soil for Plant Productivity. *Agronomy*, *12*(12), 3179. https://doi.org/10.3390/agronomy12123179

Ayuke, F. O., Pulleman, M. M., Vanlauwe, B., De Goede, R. G. M., Six, J., Csuzdi, C., & Brussaard, L. (2011). Agricultural management affects earthworm and termite diversity across humid to semi-arid tropical zones. *Agriculture, Ecosystems & Environment*, *140*(1–2), 148–154. https://doi.org/10.1016/j.agee.2010.11.021

Azevedo, T., Gonçalves, M., Silva-Reis, R., Medeiros-Fonseca, B., Roboredo, M., Sousa, J. R., Oliveira, P. A., Pinto, M. D. L., Peixoto, F., Gaivão, I., Matos, M., & Coimbra, A. M. (2024). Do endocrine-disrupting compounds impact earthworms? A comprehensive evidence review. *Reviews in Environmental Science and Bio/Technology*, *23*(3), 633–677. https://doi.org/10.1007/s11157-024-09698-z

Bartz, M. L. C., Dudas, R. T., Demetrio, W. C., & Brown, G. G. (2024). Earthworms as soil health indicators in no-tillage agroecosystems. *European Journal of Soil Biology*, *121*, 103605. https://doi.org/10.1016/j.ejsobi.2024.103605

Bhaduri, D., Pal, S., Purakayastha, T. J., Chakraborty, K., Yadav, R. S., & Akhtar, Mohd. S. (2015). Soil Quality and Plant-Microbe Interactions in the Rhizosphere. In E. Lichtfouse (Ed.), *Sustainable Agriculture Reviews* (Vol. 17, pp. 307–335). Springer International Publishing. https://doi.org/10.1007/978-3-319-16742-8_9

Blouin, M., Hodson, M. E., Delgado, E. A., Baker, G., Brussaard, L., Butt, K. R., Dai, J., Dendooven, L., Peres, G., Tondoh, J. E., Cluzeau, D., & Brun, J. -J. (2013). A review of earthworm impact on soil function and ecosystem services. *European Journal of Soil Science*, *64*(2), 161–182. https://doi.org/10.1111/ejss.12025

Boruah, T., & Deka, H. (2023). Comparative investigation on synergistic changes in enzyme activities during vermicomposting of cereal grain processing industry sludge employing three epigeic earthworm species. *Environmental Science and Pollution Research*, *30*(59), 123324–123334. https://doi.org/10.1007/s11356-023-31043-0

Cardarelli, M., Woo, S. L., Rouphael, Y., & Colla, G. (2022). Seed Treatments with Microorganisms Can Have a Biostimulant Effect by Influencing Germination and Seedling Growth of Crops. *Plants*, *11*(3), 259. https://doi.org/10.3390/plants11030259

Cenci, R. M., & Sena, F. (Eds.). (2006). *Bio-Bio Project: Based on conclusions from the International Workshop on Biodiversity-Bioindication to evaluate soil health, ISPRA 22 June 2006 Sala Michelangelo - ed. 26*. Office for Official Publications of the European Communities.

Darwin, C. (2009). *The Formation of Vegetable Mould through the Action of Worms: With Observations on their Habits* (1st ed.). Cambridge University Press. https://doi.org/10.1017/CBO9780511703850

Edwards, C. A. (Ed.). (2004). *Earthworm Ecology* (0 ed.). CRC Press. https://doi.org/10.1201/9781420039719

Fierer, N., Strickland, M. S., Liptzin, D., Bradford, M. A., & Cleveland, C. C. (2009). Global patterns in belowground communities. *Ecology Letters*, *12*(11), 1238–1249. https://doi.org/10.1111/j.1461-0248.2009.01360.x

Fründ, H.-C., Graefe, U., & Tischer, S. (2011). Earthworms as Bioindicators of Soil Quality. In A. Karaca (Ed.), *Biology of Earthworms* (Vol. 24, pp. 261–278). Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-14636-7_16

FAO (2003). *Development of a Framework for Good Agricultural Practices*. Food and Agriculture Organization of the United Nations, Rome.

Ghosh, S. (2018). Environmental pollutants, pathogens and the immune system in earthworms. *Environmental Science and Pollution Research*, *25*(7), 6196–6208. https://doi.org/10.1007/s11356-017-1167-8

Gupta, S., & Kumar, S. (2024). Earthworms as Biological Tools for Assessing Soil Pollutants. *Environment and Ecology*, *42*(4C), 2004–2014. https://doi.org/10.60151/envec/SLAN9416

Hirano, T., & Tamae, K. (2011). Earthworms and Soil Pollutants. *Sensors*, *11*(12), 11157–11167. https://doi.org/10.3390/s111211157

Jat, H. S., Choudhary, M., Kakraliya, S. K., Gora, M. K., Kakraliya, M., Kumar, V., Priyanka, Poonia, T., McDonald, A. J., Jat, M. L., Sharma, P. C., & Abdallah, A. M. (2022). A Decade of Climate-Smart Agriculture in Major Agri-Food Systems: Earthworm Abundance and

Soil Physico-Biochemical Properties. *Agronomy*, *12*(3), 658. https://doi.org/10.3390/agronomy12030658

Kaushal, M., Kolombia, Y. A., Alakonya, A. E., & Masso, C. (2025). Comparing soil microbial diversity in smallholder plantain backyard gardens and main farms in Western and Central Africa. *Scientific Reports*, *15*(1), 30220. https://doi.org/10.1038/s41598-025-14533-8

Kooch, Y., Heydari, M., Parsapour, M. K., & Valkó, O. (2025). Earthworm: A keystone species of soil quality, health, and functions. *Acta Oecologica*, *128*, 104106. https://doi.org/10.1016/j.actao.2025.104106

Lang, B., Betancur-Corredor, B., & Russell, D. J. (2023). *Earthworms increase soil mineral nitrogen content – a meta-analysis*. https://doi.org/10.25674/SO95ISS1ID308

Lavelle, P., & Spain, A. V. (2004). *Soil Ecology*. Kluwer Academic Publishers. https://doi.org/10.1007/0-306-48162-6

Liu, T., Chen, X., Gong, X., Lubbers, I. M., Jiang, Y., Feng, W., Li, X., Whalen, J. K., Bonkowski, M., Griffiths, B. S., Hu, F., & Liu, M. (2019). Earthworms Coordinate Soil Biota to Improve Multiple Ecosystem Functions. *Current Biology*, *29*(20), 3420-3429.e5. https://doi.org/10.1016/j.cub.2019.08.045

Mcinga, S., Muzangwa, L., Janhi, K., & Mnkeni, P. N. S. (2020). Conservation Agriculture Practices Can Improve Earthworm Species Richness and Abundance in the Semi-Arid Climate of Eastern Cape, South Africa. *Agriculture*, *10*(12), 576. https://doi.org/10.3390/agriculture10120576

Mohite, D. D., Chavan, S. S., Jadhav, V. S., Kanase, T., Kadam, M. A., & Singh, A. S. (2024). Vermicomposting: A holistic approach for sustainable crop production, nutrient-rich bio fertilizer, and environmental restoration. *Discover Sustainability*, *5*(1), 60. https://doi.org/10.1007/s43621-024-00245-y

Patel, H. K., Vyas, R. V., Ramesh, A., & Solanki, J. P. (2020). Rhizosphere Microbes: Driver for Soil Health Management. In S. K. Sharma, U. B. Singh, P. K. Sahu, H. V. Singh, & P. K. Sharma (Eds.), *Rhizosphere Microbes* (Vol. 23, pp. 235–258). Springer Singapore. https://doi.org/10.1007/978-981-15-9154-9_9

Prasad, M., Chaudhary, M., Choudhary, M., Kumar, T. K., & Jat, L. K. (2017). Rhizosphere Microorganisms Towards Soil Sustainability and Nutrient Acquisition. In V. S. Meena, P. K. Mishra, J. K. Bisht, & A. Pattanayak (Eds.), *Agriculturally Important Microbes for Sustainable Agriculture* (pp. 31–49). Springer Singapore. https://doi.org/10.1007/978-98110-5589-8_2

Purohit, H. J., Pandit, P., Pal, R., Warke, R., & Warke, G. M. (2024). Soil microbiome: An intrinsic driver for climate-smart agriculture. *Journal of Agriculture and Food Research*, *18*, 101433. https://doi.org/10.1016/j.jafr.2024.101433

Rochfort, S. J., Ezernieks, V., & Yen, A. L. (2009). NMR-based metabolomics using earthworms as potential indicators for soil health. *Metabolomics*, *5*(1), 95–107. https://doi.org/10.1007/s11306-008-0140-4

Rodríguez-Berbel, N., Soria, R., Villafuerte, A. B., Ortega, R., & Miralles, I. (2022). Short-Term Dynamics of Bacterial Community Structure in Restored Abandoned Agricultural Soils under Semi-Arid Conditions. *Agronomy*, *13*(1), 86. https://doi.org/10.3390/agronomy13010086

Ruf, T. (2025). Look at our soil! Visual soil evaluation is more important than ever. *Soil Use and Management*, *41*(1), e70049. https://doi.org/10.1111/sum.70049

Rupani, P. F., Embrandiri, A., Garg, V. K., Abbaspour, M., Dewil, R., & Appels, L. (2023). Vermicomposting of Green Organic Wastes Using Eisenia Fetida Under Field Conditions: A Case Study of a Green Campus. *Waste and Biomass Valorization*, *14*(8), 2519–2530. https://doi.org/10.1007/s12649-022-02004-4

Schon, N. L., Fraser, P. M., & Mackay, A. D. (2023). Earthworms for inclusion as an indicator of soil biological health in New Zealand pastures. *New Zealand Journal of Agricultural Research*, *66*(3), 208–223. https://doi.org/10.1080/00288233.2022.2041676

Sharan, G., & Madhavan, T. (2010). Cropping in Semi-arid North-west India in Greenhouse with Ground Coupling Shading and Natural Ventilation for Environmental Control. *International Journal for Service Learning in Engineering, Humanitarian Engineering and Social Entrepreneurship*, *5*(1), 148–169. https://doi.org/10.24908/ijsle.v5i1.2228

SWALIM, F. (2013). *Status Needs and Priorities for Status Needs and Priorities for Sustainable Soil Management in Somalia*. https://www.fao.org/fileadmin/user_upload/GSP/docs/South_east_partnership/Somalia.pdf

Szilágyi, A., Plachi, E., Nagy, P., Simon, B., & Centeri, C. (2021). Assessing Earthworm Populations in Some Hungarian Horticultural Farms: Comparison of Conventional, Organic and Permaculture Farming. *The 1st International Electronic Conference on Biological Diversity, Ecology and Evolution*, 11. https://doi.org/10.3390/BDEE202109416

Tiwari, R. K., Singh, S., Pandey, R. S., & Sharma, B. (2016). Enzymes of Earthworms as Indicators of Pesticide Pollution in Soil. *Advances in Enzyme Research*, *04*(04), 113–124. https://doi.org/10.4236/aer.2016.44011

Yadav, A. N., Singh, J., Singh, C., & Yadav, N. (Eds.). (2021). *Current Trends in Microbial Biotechnology for Sustainable Agriculture*. Springer Singapore. https://doi.org/10.1007/978-981-15-6949-4

Zeng, Y., Verhoef, A., Vereecken, H., Ben-Dor, E., Veldkamp, T., Shaw, L., Van Der Ploeg, M., Wang, Y., & Su, Z. (2025). Monitoring and Modeling the Soil-Plant System Toward Understanding Soil Health. *Reviews of Geophysics*, *63*(1), e2024RG000836. https://doi.org/10.1029/2024RG000836