Author Response and Revision

Dear Reviewer,

Thank you for the constructive and detailed feedback.

We read the reviewer's assessment carefully; we hope that the manuscript will benefit significantly from clearer conceptual foundation, aim, objectives, structure, methodological transparency, and sharper articulation of scope and contributions. Below we address each comment point-by-point and present an updated version with description on what we have revised:

We, the authors, summarised key findings (including the conceptual framework linking soil contamination → ecosystem services → restorative mitigation → SDGs) in the abstract. We specified the unique contribution e.g. integration of case-based evidence with policy-oriented framing, and identification of SDG-aligned pathways for mitigation.

We integrated case studies with conceptual framework.

[Abstract] Revised as per the third reviewer's comment:

Soil is a critical terrestrial resource whose physicochemical and biological integrity underpins agricultural productivity, ecosystem functioning, and socio-ecological resilience. Contemporary agricultural practices and pollution – particularly the widespread and unregulated application of synthetic pesticides – are accelerating the chemical degradation of soils, disrupting soil organic matter, diminishing microbial biomass, impairing respiration and enzymatic activity, and altering nutrient cycling processes essential for soil fertility. This conceptual synthesis develops an integrated framework linking contaminants like heavy metals and more specifically pesticide driven soil degradation to losses in ecosystem services and explores restorative mitigation strategies within the context of sustainability governance. Drawing on current scientific knowledge, it examines how contaminants influence soil structure, modulate microbial community composition, affect contaminant mobility under changing climatic conditions, and interact with co-occurring stressors such as land-use change, hydrological dynamics, and biodiversity loss. The manuscript further evaluates emerging remediation approaches – including physicochemical, biological, and integrated strategies – and places them within a broader nexus of environmental sustainability, research priorities, and policy development aligned with the Sustainable Development Goals (SDGs). By integrating scientific, socio-ecological, and governance perspectives, this study conceptualizes soil restoration as a multi-level process requiring not only technical interventions but also systemic transformations in agricultural practices, environmental management, and green-chemistry innovations. At a mechanistic level, this synthesis clarifies how contaminant–soil interactions regulate sorption, mobility, microbial inhibition, and elemental cycling, highlighting specific processes that both drive soil degradation and determine the efficacy of mitigation strategies.

[1]. Improved Introduction

The revised introduction is more focused and aligns better with the conceptual framing. It includes: Context & problem definition; Transboundary nature; Knowledge gaps; Aim, scope,

contaminants, objectives, and the conceptual framework.

[i]. Clearer Aim

In order for us to meet reviewer comment, we added a more explicit aim, and clarified the focus on contaminants.

This conceptual synthesis aims to integrate scientific and socio-ecological knowledge at the interface of soil contamination, ecosystem services, and restorative mitigation, and to analyse how these link to SDGs.

…. To translate this conceptual foundation into clearly defined research aims, this study examines:

1. The mechanisms through which agrochemicals alter soil physicochemical properties, microbial functions, and overall soil quality.
2. The implications of pesticide-induced degradation for nutrient cycling, microbial activity, soil fertility, ecosystem resilience, and associated environmental and human-health risks.
3. Emerging restorative mitigation strategies – physico-chemical, biological, and integrated – and their scalability and long-term sustainability.
4. The role of research and policy frameworks in advancing sustainable soil management aligned with the SDGs.
5. The sustainability nexus linking soil health, agricultural practices, environmental governance, and broader socio-ecological resilience.

(ii). Objectives

Building on these objectives, this conceptual synthesis integrates scientific, mechanistic, and socio-ecological perspectives to explain how pesticide-driven soil contamination reshapes soil physicochemical properties, microbial functions, and ecosystem services. Accordingly, the scope of the article is to:

• Conceptualize the processes through which contaminants degrade soil quality and disrupt key soil functions.

• Explain the interactions among contaminants, soil structure, microbial communities, and climate-related stressors.

• Identify the implications of soil degradation for ecosystem services, agricultural sustainability, and human well-being.

• Examine restorative mitigation strategies – including physico-chemical, biological, and integrated approaches – within the broader context of sustainability governance and the SDGs.

• Provide a coherent, integrative framework to guide research, policy, and field-level interventions aimed at restoring soil quality in modern agricultural systems.

(iii). The Unique Contribution

This manuscript addresses these critical gaps by advancing a new conceptual synthesis structured around three interconnected analytical threads:

1. How major soil contaminants – pesticides and heavy metals in particular – impair soil functions and the ecosystem services derived from them.

2. Which restorative mitigation approaches operate across physico-chemical, biological, ecological, and socio-technical domains, and how they can be deployed effectively.
3. How these mitigation strategies intersect with and influence progress toward key SDG targets.

To unify these elements, the manuscript introduces a conceptual framework that traces the continuum from contamination → soil processes → ecosystem-service outcomes → mitigation pathways → SDG relevance. This framework organizes the synthesis, provides a coherent basis for integrating disparate knowledge domains, and highlights the multi-scalar linkages essential for sustainable soil management.

[2]. Methods confirms the type of research article and highlights the use of PRISMA (although not categorised as a systematic review *per-say*), databases and search strings, inclusion/exclusion, screening (no specific protocol), data extraction categories, and includes a "flow diagram" as well.

The manuscript has been prepared for submission to this research journal – a key resource for disseminating knowledge within the soil and agricultural science communities. We examine the effects of agricultural soil contamination on ecosystem services and global sustainable development. This study adopts a narrative and integrative article design, guided by PRISMA principles to enhance transparency in the secondary research while not constituting a full systematic review. The methodology comprises four components: search strategy, screening criteria, data extraction, and synthesis approach. Findings were integrated using a conceptual framework that links contaminant pathways to soil process disruption, ecosystem-service impacts, mitigation strategies, and SDG alignment. A quantitative meta-analysis was not undertaken due to heterogeneity in study designs and measurement metrics.

Literature was sourced from Scopus, Web of Science, Sci-Finder, Google Scholar, ScienceDirect, and other trustworthy platforms.

Inclusion criteria: Peer-reviewed articles, scientific reports, and authoritative agency documents (FAO, UNEP, IPBES); Studies examining pesticides, heavy metals, or microplastics in soil systems; Studies reporting impacts on soil processes or ecosystem services; Research on mitigation or remediation strategies; Publications in English.

Exclusion criteria: Non-agricultural soils unless conceptually relevant; Studies focused exclusively on air or water contamination without soil interactions; Duplicates or non-scientific commentaries.

[3]. Results as the Thematic Synthesis includes Soil contamination pathways (pesticides, heavy metals); Impacts on ecosystem services; Restorative mitigation approaches; SDG alignment

The authors made sure the contents in Results & the following section Discussion does not overlap or become redundant.

[4]. Discussion includes integrated synthesis, policy implications, and research needs. We expanded discussion of global policy context and or the SDG relevance / framework.

This section integrates themes, synthesize cross-cutting insights, identify knowledge gaps and research needs.

Technical Response from Authors:

The manuscript has been tightened to retain the content, to enhance coherence, and to facilitate seamless transitions across sections.

Although the previous manuscript design of ours seems to categorise the content correctly (considered by the Editor as an original article), the reviewer 3 proposed an optimised manuscript structure. We are ready to re-structure the manuscript as per the Editorial advice or the *Instructions for Authors* without losing our focus on the key areas studied.

The re-structuring, if any, shall support an original conceptual synthesis and also a non-systematic (despite use of PRISMA) and exhaustive secondary research, while integrating cross-cutting themes.

1. Introduction

- Soil as a socio-ecological foundation
- Mechanistic links between contaminants and soil functions
- Pesticide contamination as an accelerating driver of degradation
- Importance of integrating ecological, chemical, and governance perspectives

Conceptual Foundations

- Components of soil quality and ecosystem services
- Key microbial indicators of contamination (Gómez-Sagasti et al., 2012)
- Climate interactions with contaminant fate (also discussed earlier in different-light by others: Köhler & Triebskorn, 2013; Biswas et al., 2018)

2. MATERIALS AND METHOD

Detailed in length.

3. RESULTS AS CONCEPTUAL SYNTHESIS

- Integrative framework

4. DISCUSSION

Mechanisms of Heavy Metals and Pesticide-Driven Soil Degradation

Implications for Ecosystem Services

Restorative Mitigation Strategies

Sustainability Governance and SDG Nexus

- Soil pollution in global policy and decision-making
- Soil restoration as part of socio-ecological resilience

- Linking scientific innovation, green chemistry, and governance

5. FUTURE SCOPE

- Research gaps
- Pathways toward resilient agricultural systems

6. Conclusions

References

Hope that we answered the community and reviewers' feedback appropriately.

Thanking you,

Sincerely,

Dr. ISAK R. SHAIKH (on behalf of myself and the other co-author Dr. Parveen R. Shaikh)