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Restorative Mitigation of Contaminated Soil for Ecosystem Services: Influences from Research Enterprise and Sustainable Development Goals

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Abstract. Soil is a critical terrestrial resource whose physico-chemical and biological integrity underpins agricultural productivity, ecosystem functioning, and socio-ecological resilience. However, intensive agricultural practices, particularly the widespread and often unregulated use of synthetic pesticides and other agrochemicals, are accelerating soil degradation and disrupting essential ecosystem services. Although previous studies have examined individual contaminants and remediation techniques, limited attention has been given to integrating mechanistic soil processes, ecosystem-service decline, remediation strategies, and sustainability governance within a unified analytical framework. This study develops a systems-based conceptual synthesis linking soil contaminants – particularly pesticide residues as dominant agrochemical stressors and heavy metals as co-contaminants – with soil-process disruption, ecosystem-service degradation, and restorative mitigation strategies within broader research and Sustainable Development Goal (SDG) frameworks. The synthesis examines how contaminants influence soil organic matter, microbial biomass, respiration, enzymatic activity, nutrient cycling, microbial community composition, and contaminant mobility under changing climatic conditions. Particular emphasis is placed on the interaction between soil contamination and co-occurring stressors, including land-use change, hydrological variability, biodiversity loss, and climate change, which collectively intensify soil degradation and ecosystem instability. The study further

evaluates biological, physico-chemical, and integrated remediation approaches in terms of effectiveness, scalability, ecological functionality, and long-term sustainability. By integrating mechanistic, socio-
30 ecological, and governance perspectives, this work conceptualizes soil restoration as a multi-level process requiring not only technical remediation but also systemic transformation in agricultural practices, environmental governance, research priorities, and green chemistry innovation. This integrated perspective provides a stronger analytical basis for understanding soil degradation pathways, informing sustainable land-management strategies, and advancing soil functionality and ecosystem
35 resilience under accelerating global environmental change.

Keywords: Soil contamination; Soil restoration; Pesticide residues; Heavy metals; Agrochemical pollution; Soil health; Soil microbial communities; Ecosystem services; Soil degradation; Remediation; Sustainable Development Goals.

40 **1 Introduction**

Soil is a fundamental natural resource that underpins terrestrial life by providing the physical, chemical, and biological conditions essential for plant growth, ecosystem functioning, and environmental stability (Bünemann et al., 2018). Fertile soils regulate water and gas exchange to roots, supply nutrients, sustain diverse microbial communities, and support ecosystem services critical for food production,
45 biodiversity conservation, and climate regulation (Bünemann et al., 2018). However, these functions are increasingly threatened by anthropogenic pressures, including intensive agriculture, land-use change, and widespread agrochemical application (Köhler & Triebkorn, 2013; Biswas et al., 2018). As these pressures intensify, soils are progressively exposed to contaminants that interfere with biological and physico-chemical processes, reduce fertility, and impair overall soil functionality. Understanding the
50 mechanisms through which soil quality deteriorates – particularly under pesticide contamination, heavy metal exposure, and related chemical stressors – is therefore essential for safeguarding ecosystem services and sustaining agricultural productivity (Šmejkalová et al., 2003; Kenarova et al., 2014; Xiong, 2015).

The emergence of agriculture marked a transformative stage in human civilization, with fertile soils and
55 freshwater availability enabling permanent settlements and early agricultural societies (Montgomery,
2008). Soil is a highly dynamic and complex system composed of: (i) a solid phase containing minerals
and organic matter, including soil organic matter (SOM) and soil organic carbon (SOC); (ii) a soil
solution enriched with dissolved nutrients; (iii) pore spaces occupied by atmospheric gases such as
nitrogen, oxygen, and carbon dioxide; and (iv) living biomass dominated by bacteria, archaea, and
60 fungi. Soil quality depends not only on the absence or presence of contaminants but also on interactions
among these components, which collectively regulate biogeochemical cycling, microbial activity,
contaminant transformation, and structural stability (Bünemann et al., 2018).

Chemical contaminants can severely disrupt these interactions. At a mechanistic level, pollutants reduce
microbial biomass, alter microbial community composition, and suppress enzymatic activities
65 associated with organic matter decomposition and nutrient cycling (Šmejkalová et al., 2003; Kenarova
et al., 2014; Xiong, 2015). Three major microbial indicators of soil contamination – microbial biomass,
microbial activity, and microbial diversity – effectively capture these degradation effects (Gómez-
Sagasti et al., 2012). These biological responses are further intensified by climate change, which
influences nutrient cycling, nutrient-use efficiency, soil moisture, contaminant mobility, and persistence
70 (Köhler & Triebkorn, 2013; Biswas et al., 2018). When contaminant loads exceed soil buffering
capacity, soil functions decline, increasing the risks of eutrophication, phytotoxicity, water pollution,
and long-term fertility loss (Shaikh et al., 2012a & 2012b; Shaikh et al., 2013a & 2013b). Together,
these interacting pressures highlight the vulnerability of soil systems to chemical degradation and
underscore the need for integrated assessment of contamination pathways, ecological consequences, and
75 sustainable mitigation strategies.

1.1 Soil ecosystem services and contamination pathways

Soil is an irreplaceable natural resource that provides a broad spectrum of ecosystem services essential
for environmental stability and human well-being (Figure 1). It functions as a genetic reservoir, a
80 habitat for plants and soil organisms, and a medium supporting complex biological community.
Through these functions, soil sustains biodiversity while supplying nutrients and energy for terrestrial

ecosystems and agricultural production. In addition, soils contribute to food security, water and air quality, climate regulation, and carbon sequestration (FAO, 2022). Ecosystem services are broadly defined as the conditions and processes through which biotic and abiotic ecosystem components sustain human life and societal development (Daily et al., 1997).

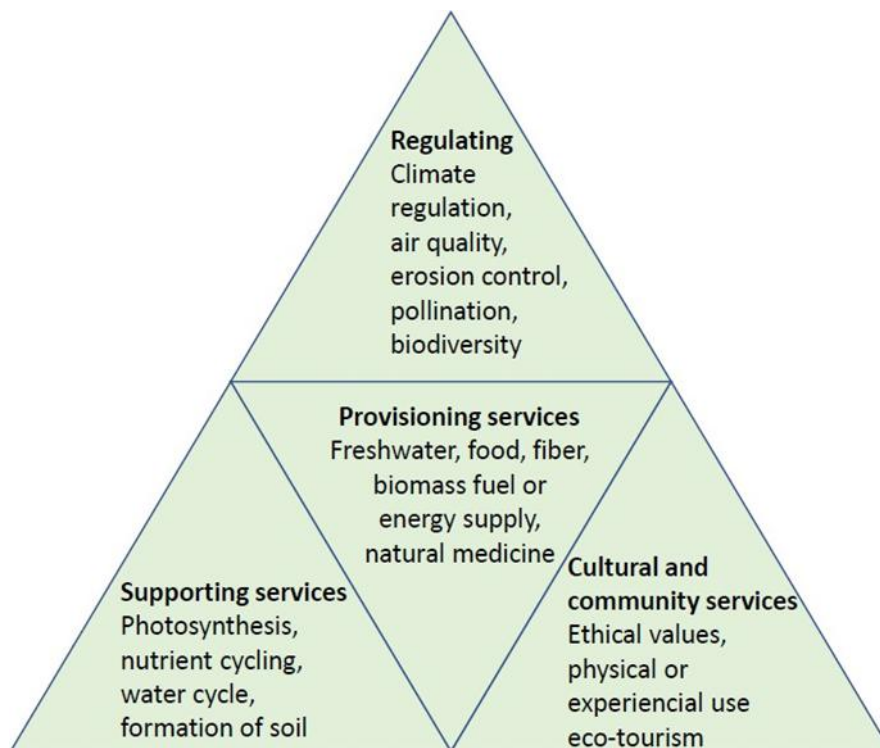


Figure 1. Ecosystem services of soil.

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According to the Common International Classification of Ecosystem Services (CICES), soils provide three broad categories of ecosystem services: (i) regulation and support services, (ii) provisioning services, and (iii) cultural and community services (Fisher & Turner, 2008; Smith et al., 2015; Haines-Young & Potschin, 2018). Regulation and support services include nutrient cycling, soil formation, contaminant buffering, and climate stabilization; provisioning services include food, fibre, and raw materials; while cultural services provide aesthetic, educational, and social benefits. However,

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increasing food demand, population growth, and agricultural intensification continue to accelerate soil degradation and fertility decline globally (FAO & ITPS, 2015; FAO, 2018a).

Globally, soils support approximately 95% of food production (FAO, 2022). Soil pores retain water and dissolved nutrients, thereby regulating plant growth and agricultural productivity, while soils also store carbon, maintain air quality, and mediate gas exchange within the root zone. Soil quality emerges from interactions among mineral and organic components, soil solution chemistry, gaseous exchange, and living biota, collectively governing nutrient cycling, carbon sequestration, microbial diversity, contaminant transformation, and structural stability (Nikitin, 1982; Bünemann et al., 2018). Climate-induced changes in nutrient cycling and physico-chemical soil properties increasingly impair soil's capacity to buffer, transform, and retain contaminants (Köhler & Triebkorn, 2013; Biswas et al., 2018). Environmental stressors – including pollutants, erosion, land-use change, and climate change – can disrupt microbial activity, weaken enzymatic functions, and impair soil fertility, ultimately diminishing ecosystem services. Together, these interactions shape soil functionality and ecosystem-service outcomes.

One critical ecological role of soil is its ability to decompose, immobilize, and transform contaminants, thereby acting as a natural filter for water entering aquifers and surface waters (Nikitin, 1982). When contaminant loads exceed soil buffering capacity, these processes decline, compromising ecosystem functioning. For instance, Black Cotton Soil (Regur soil) of India's Deccan Plateau, derived from weathered basalt, contains montmorillonite, kaolinite, iron oxides, calcium carbonate, and humus. It is nutrient-rich, and its composition supports crops such as cotton, groundnut, sugarcane, sorghum, chilies, and wheat. However, its high clay content makes it prone to shrink–swell behaviour and erosion, illustrating how intrinsic soil properties mediate vulnerability to environmental and anthropogenic disturbances. The contrast between slow geological soil formation and rapid human-driven disturbances underscores the importance of timely assessment of soil chemical and structural alterations (Figure 2). Compromised soil buffering and filtering capacities can lead to water pollution, eutrophication, and phytotoxicity, further undermining agricultural productivity and ecosystem stability (Shaikh et al., 2012; Shaikh et al., 2013a & 2013b). This underscores the importance of linking soil processes with ecosystem-service outcomes within an integrated framework.

125 Soil contamination also interacts with water and air systems, enabling pollutant transport through interconnected environmental pathways (Jones, 2005). Heavy metals, pesticides, plastics, and other persistent pollutants migrate through erosion, runoff, atmospheric deposition, and hydrological transport, allowing contamination to spread across ecosystems (Alloway, 1995; Jones, 2005; Perk, 2006; Yeheyo et al., 2024). Persistent pollutants, including microplastics, have even been detected in
130 remote regions such as Antarctica, highlighting the transboundary nature of soil degradation (Liu et al., 2023).

Globally, nearly two billion hectares of land have already experienced degradation caused by erosion and chemical contamination (Jie et al., 2002). In combination with climate change, these pressures increasingly threaten ecosystem functioning, food security, biodiversity, and human health (Parmesan,
135 2006). Soil nevertheless remains a largely non-renewable resource essential for agriculture, biodiversity conservation, forestry, and civil engineering, with approximately half of the world’s houses constructed from soil-based materials (Dai et al., 2022). These interacting pressures underscore the importance of integrated assessment of contamination pathways, soil-process disruption, and ecosystem-service outcomes.

140 According to the Food and Agriculture Organization of the United Nations, approximately 135 billion tonnes of soil have been depleted from farmlands since the industrial revolution (FAO et al., 2020). Soils are now under substantial global pressure (FAO, UNEP, & WHO, 2021), and declining soil quality has become a critical concern (Fausak et al., 2024). In response, the FAO emphasizes that sustainable soil management, pollution prevention, and restoration are essential for safeguarding
145 ecosystem services and food security, while advancing a resilient “new green revolution” to address land degradation affecting billions worldwide (FAO, 2015; FAO, 2018c; FAO, 2024; FAO, 2025). This challenge is further underscored by the United Nations Convention to Combat Desertification, which reports that land degradation impacts nearly 40% of the global land surface, with serious consequences for biodiversity, climate regulation, and livelihoods (UNCCD, 2024).

150 According to FAO reports and guidelines, sustainable soil and agricultural management are essential for maintaining ecosystem services, food security, environmental sustainability, and climate resilience. The FAO “Save and Grow” framework emphasizes the sustainable intensification of smallholder crop

production (FAO, 2010), while the Revised World Soil Charter and the Voluntary Guidelines for Sustainable Soil Management advocate responsible soil stewardship and long-term soil health preservation (FAO, 2015; FAO, 2017). The Status of the World's Soil Resources reports identified soil degradation, pollution, erosion, and nutrient imbalance as major global threats affecting agricultural productivity and ecosystem stability (FAO & ITPS, 2015; FAO, 2018a). FAO further highlighted soil pollution as a hidden but critical global issue requiring coordinated remediation and policy interventions through the Global Symposium on Soil Pollution and related outcome documents (FAO, 2018b; FAO, 2018c; FAO, UNEP, and WHO, 2021). International frameworks such as the International Code of Conduct on Pesticide Management and the Sustainable Use and Management of Fertilizers stress minimizing environmental contamination while improving agricultural efficiency (FAO and WHO, 2014; FAO, 2019). Recent FAO assessments also indicate that approximately 1.7 billion people experience reduced crop yields due to land degradation, underscoring the urgent need for sustainable land and water resource management (FAO, 2025). Furthermore, FAO reports on soils for nutrition and pollinator protection emphasize the interconnected roles of healthy soils, biodiversity conservation, sustainable pesticide regulation, and human well-being in achieving global sustainability goals (FAO, 2022a, 2022b). Thus, international sustainability frameworks increasingly recognize the importance of sustainable soil management and restoration. The United Nations Convention to Combat Desertification (UNCCD) emphasizes that combating land degradation through sustainable soil management is essential for enhancing ecosystem resilience and climate adaptation (UNCCD, 2024). Similarly, UNESCO sustainability initiatives, including the Decade of Education for Sustainable Development and the Greening Education Partnership, highlight the importance of integrating scientific knowledge, policy development, education, and societal engagement to promote resilient socio-ecological systems (UNESCO, 2005; UN, 2019; UNESCO, 2022) (Figure 3). The International Union for Conservation of Nature further emphasizes that scaling up ecosystem-based land restoration and sustainable soil management is essential for effective remediation and long-term soil health (IUCN, 2024a, 2024b). Restorative mitigation of contaminated soils is therefore increasingly shaped by research-driven innovation, global climate-finance commitments, and sustainability governance aligned with the Sustainable Development Goals (UNFCCC, 2024a; UNFCCC, 2024b).

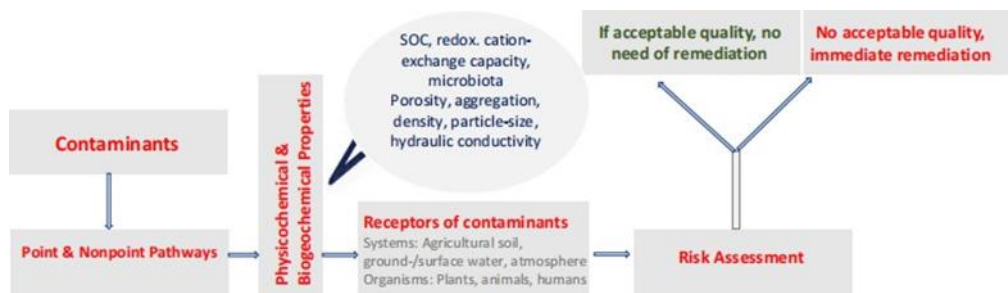


Figure 2. Conceptualization of soil contamination, deterioration of soil quality parameters, and the need for risk assessment. Point sources refer to identifiable, localized inputs (e.g., industrial discharge, spills), whereas non-point sources refer to diffuse inputs across landscapes (e.g., runoff, atmospheric deposition).

1.2 Conceptual framing and research gap

While numerous studies have examined soil contamination, pesticide impacts, heavy metals, and remediation approaches independently, relatively few have integrated contamination pathways, soil functional dynamics, ecosystem-service degradation, and sustainability governance within a unified analytical framework. Existing studies also frequently treat remediation primarily as a technical process, with limited integration of socio-ecological systems, research enterprise, and Sustainable Development Goal (SDG) linkages.

This study therefore synthesizes current knowledge on agricultural soil contamination and develops an integrated conceptual framework linking soil contaminants, soil processes, ecosystem-service impacts, and restorative mitigation strategies, with particular emphasis on agrochemicals. Although agrochemicals contribute substantially to agricultural productivity, they also function as pervasive pollutants that accelerate soil degradation and ecosystem disruption. Building on current understanding of soil quality, ecosystem-service frameworks, microbial indicators of contamination (Gómez-Sagasti et al., 2012), and climate influences on contaminant fate and mobility (Köhler & Triebkorn, 2013; Biswas et al., 2018), the study examines contamination pathways, ecological consequences, and mitigation strategies encompassing physico-chemical, biological, and integrated approaches.

205 At a mechanistic level, the framework examines contaminant–soil interactions governing sorption, mobility, microbial inhibition, elemental cycling, and contaminant persistence, thereby linking contaminant behaviour directly to soil-process disruption and ecosystem-service degradation. These remediation approaches are evaluated in terms of effectiveness, scalability, functionality, and long-term sustainability.

210 Consistent with this conceptual framework, the study integrates scientific, mechanistic, socio-ecological, and governance perspectives while aligning soil restoration with global sustainability frameworks, particularly the SDGs. It further examines how climate change, land-use pressures, and unsustainable agricultural practices intensify soil degradation risks and influence restoration outcomes. As illustrated in Figure 4, the linkages among contamination pathways, soil processes, ecosystem-

215 service impacts, and mitigation strategies provide the analytical basis for evaluating sustainable restoration pathways. Collectively, this integrated perspective advances a systems-based understanding of soil contamination and restoration while highlighting the need for coordinated approaches that integrate scientific evidence, agricultural management, policy development, and sustainability governance to protect soil health and sustain agroecosystems.

220 While numerous studies have examined soil contamination and remediation in isolation, there remains a lack of integrative frameworks that explicitly connect contamination processes with soil functional dynamics, ecosystem-service recovery, and their alignment with the Sustainable Development Goals (SDGs) (Biswas et al., 2018; FAO, UNEP, & WHO, 2021; Fausak et al., 2024). This study advances a systems-based conceptual framework that links contaminant-induced disruptions in soil processes to

225 cascading effects on ecosystem services and, ultimately, to socio-environmental sustainability targets. By explicitly positioning remediation strategies within this continuum, the paper moves beyond descriptive synthesis toward a more holistic understanding of how soil restoration contributes to sustainable development pathways.

This study develops an integrated systems-based synthesis linking contaminant sources, soil

230 degradation processes, and ecosystem service disruption within a unified socio-ecological framework. Unlike conventional narrative overviews, the analysis explicitly connects physico-chemical and biological mechanisms with governance structures, sustainability transitions, and SDG-relevant

outcomes. By consolidating previously fragmented discussions into a single analytical structure, the study provides a clearer conceptual pathway for understanding how soil contamination propagates across scales and how integrated remediation strategies can restore ecosystem functionality.



Figure 3. Socio-Ecological System (SOCI, 2024).

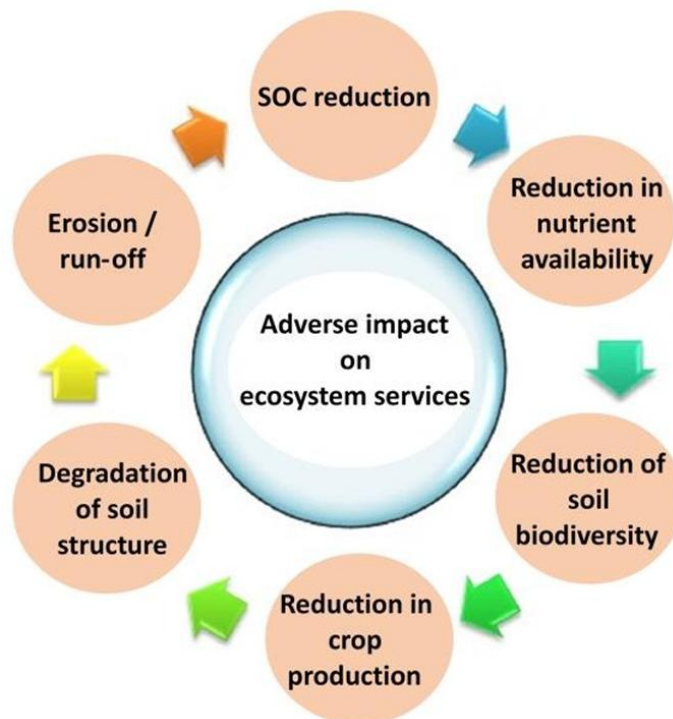


Figure 4. Degradation processes in polluted soil and their relevance to key ecosystem services.

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 245 lack of integrative frameworks that explicitly connect contamination processes with soil functional
 dynamics, ecosystem service recovery, and their alignment with the Sustainable Development Goals
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 environmental sustainability targets. By explicitly positioning remediation strategies within this
 250 continuum, the paper moves beyond descriptive synthesis toward a more holistic understanding of how
 soil restoration contributes to sustainable development pathways.

1.3 Research aims and scope

Building on the conceptual framework outlined above, this study examines the interconnections among
 255 soil contamination, ecosystem services, and sustainable development through the following objectives:

- (i) to analyse the mechanisms through which agrochemical contaminants alter soil physico-chemical properties, microbial functions, and overall soil quality;
- (ii) to evaluate the implications of pesticide- and heavy metal-induced degradation for nutrient cycling, microbial activity, soil fertility, ecosystem resilience, and associated environmental and human-health risks;
- (iii) to assess restorative mitigation strategies, including physico-chemical, biological, and integrated approaches, in terms of effectiveness, scalability, and long-term sustainability;
- (iv) to examine the role of research enterprise, sustainability governance, and policy frameworks in advancing soil restoration aligned with the Sustainable Development Goals; and
- (v) to develop a coherent systems-based framework linking contamination pathways, soil processes, ecosystem-service outcomes, mitigation strategies, and SDG relevance.

The study further emphasizes the role of research enterprise in advancing sustainable soil management through the integration of scientific innovation, policy development, education, and practice. Collectively, this scope provides a clear analytical foundation for integrating mechanistic, ecological, technological, and governance perspectives within a unified framework (Biswas et al., 2018; FAO, 2018b; Rockström et al., 2009), while positioning soil restoration not only as a technical remediation challenge but also as a broader socio-ecological and sustainability process requiring coordinated scientific innovation, sustainable agricultural management, and evidence-based governance. Building on this analytical foundation, the following section outlines the methodological approach used to operationalize this framework and synthesize the evidence base.

2 Materials and Methods

2.1 Methodological approach

This study employed a structured literature-based conceptual synthesis to examine soil contamination, degradation processes, ecosystem-service disruption, and restorative mitigation strategies within broader sustainability and governance frameworks. The investigation integrated:

- (i) established scientific knowledge and widely accepted evidence;
- (ii) contemporary review and research literature;

(iii) policy- and practice-oriented analyses; and

285 (iv) critical appraisal of existing scientific contributions.

The methodological approach aimed to characterize the evolving research enterprise surrounding soil contamination, sustainable soil management, and restorative mitigation while identifying major scientific trends, knowledge gaps, methodological limitations, and emerging remediation perspectives. Particular emphasis was placed on integrating mechanistic understanding of contaminant–soil
290 interactions with broader socio-ecological, environmental-governance, and sustainability considerations. Rather than relying solely on descriptive reporting (Moher et al., 2009; Page et al., 2021), the study synthesized evidence through thematic and conceptual analysis to evaluate interrelationships among contamination pathways, soil degradation, ecosystem-service loss, remediation strategies, and Sustainable Development Goal (SDG) relevance. This approach enabled critical
295 assessment of both the strengths and limitations of existing research while informing the development of an integrated analytical framework for sustainable soil restoration and ecosystem resilience.

2.2 Literature search and data synthesis

The study was initially based on a structured review of scientific literature published primarily during
300 recent decades, focusing on soil contamination, remediation technologies, ecosystem services, sustainability governance, and restorative mitigation strategies. Literature sources included SciFinder, Scopus, Web of Science, ScienceDirect, Google Scholar, and related scientific databases. Peer-reviewed articles, technical reports, institutional publications, and authoritative international documents were systematically screened and synthesized within the context of sustainable soil management, environmental governance, and ecosystem restoration. The review process emphasized current scientific
305 understanding, technological developments, remediation approaches, contaminant impacts, and policy-oriented perspectives associated with sustainable agriculture, pollution prevention, ecosystem services, and SDG implementation. Particular attention was given to pesticide contamination, heavy metals, soil degradation processes, contaminant mobility, microbial responses, and restorative mitigation strategies.
310 To improve methodological transparency, key elements of the PRISMA framework were incorporated (Moher et al., 2009, 2019; Page, 2021; Tarla et al., 2020). Searches were conducted using keywords

including “soil degradation,” “soil contamination,” “pesticide contamination,” “ecosystem services,” “soil restoration,” “bioremediation,” and “soil remediation technologies.” Studies were included if they:

- (i). addressed soil contamination or degradation associated with pesticides, heavy metals, or related
315 contaminants;
- (ii) examined impacts on soil properties, microbial functions, ecosystem services, or environmental
quality; or
- (iii) evaluated remediation, restoration, or mitigation technologies relevant to sustainable soil
management.

320 Studies lacking scientific relevance, empirical basis, methodological clarity, or direct linkage to soil
systems were excluded. Screening involved title and abstract evaluation followed by full-text
assessment. Extracted information focused on contaminant types, degradation mechanisms, soil-process
impacts, remediation strategies, sustainability implications, and ecosystem-service outcomes. Although
a formal systematic-review protocol and quantitative quality assessment were not applied, the synthesis
325 followed a transparent and structured methodology consistent with multidisciplinary scientific reporting
standards (Moher et al., 2009; Moher et al., 2019). Contributions were critically evaluated according to
scientific relevance, conceptual integration, technological applicability, sustainability significance, and
practical implications for sustainable agriculture and soil restoration. The PRISMA 2020 framework
was used to illustrate the identification, screening, eligibility assessment, and inclusion of studies within
330 the synthesis process (Figure 5). Accordingly, the present work constitutes a structured literature search
and conceptual synthesis rather than a formal systematic review.

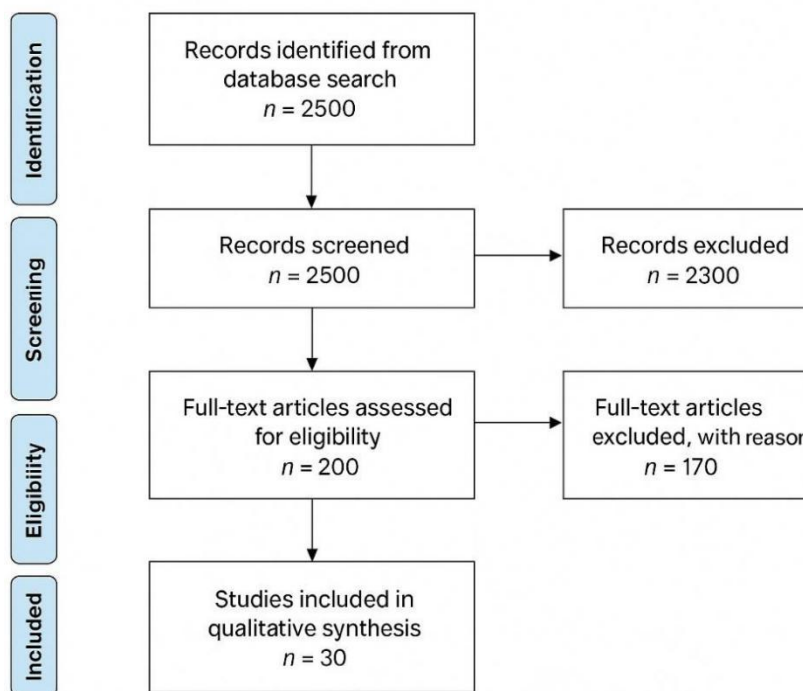


Figure 5. The PRISMA flow diagram.

3 Results and Thematic Synthesis

The thematic synthesis examined soil contamination, degradation processes, ecosystem-service disruption, remediation strategies, and sustainability governance within an integrated socio-ecological framework. The analysis combined scientific, technological, and policy-oriented perspectives to clarify relationships among contaminant pathways, soil functionality, ecosystem resilience, and sustainable development. The study critically evaluated developments in bioremediation and alternative mitigation strategies reported in the literature, integrating scientific understanding with policy-oriented perspectives to elucidate linkages among soil degradation, ecosystem services, and sustainable development.

3.1 Sustainable socio-ecological systems, soil restoration, and the SDGs

Global soil systems are under increasing pressure from land degradation, contamination, unsustainable agricultural intensification, and climate-related stressors. Approximately 135 billion tonnes of soil have

been depleted from farmlands since the industrial revolution (FAO et al., 2020), while land degradation
350 currently affects nearly 40% of the global land surface (UNCCD, 2024). This decline, in turn,
constitutes a significant barrier to achieving multiple SDGs (UN, 2015; FAO, 2024; UNCCD, 2024). In
other words, soils are now under substantial global pressure (FAO, UNEP, & WHO, 2021), and
declining soil quality has become a critical concern (Fausak et al., 2024). These pressures compromise
ecosystem services, agricultural productivity, biodiversity, climate regulation, and human well-being.
355 International organizations increasingly recognize sustainable soil management, pollution prevention,
and restoration as essential for protecting ecosystem services, food security, and advancing the
Sustainable Development Goals (FAO, 2015; FAO, 2018c; FAO, 2024; FAO, 2025). Soil degradation
directly affects SDGs related to poverty alleviation, food security, health, water resources, climate
action, terrestrial ecosystems, and sustainable communities (Jie et al., 2002). Consequently, restorative
360 mitigation strategies are increasingly framed within broader socio-ecological transitions emphasizing
resilient and sustainable land systems.

3.1.1 Sustainability governance and international environmental frameworks

Global sustainability discourse has progressively integrated environmental protection, sustainable
365 development, and soil restoration within broader governance frameworks. The World Commission on
Environment and Development introduced sustainability as a term, which the author defined as a
concept accounting for system dynamics and balances between inputs and outputs (Shaikh, 2020).
Although the term sustainable development appeared earlier in a 1969 document endorsed under the
International Union for Conservation of Nature, the Brundtland Commission formalized its definition as
370 development that meets present needs without compromising future generations (Brundtland
Commission, 1987). Subsequent international frameworks, including the United Nations Conference on
Environment and Development (UNCED, 1992) and Agenda 2030 with the Sustainable Development
Goals (SDGs), further strengthened linkages between environmental sustainability, socio-economic
development, and ecosystem protection (UN, 2015). Within this evolving governance context, soil
375 pollution has emerged as a major global environmental concern due to its impacts on soil functioning,
food security, biodiversity, and human health. International initiatives such as the FAO Global Soil

Partnership, the Intergovernmental Technical Panel on Soils, and the Global Symposium on Soil Pollution have emphasized the need for coordinated monitoring, pollution prevention, and remediation strategies (FAO & ITPS, 2015; FAO, 2018a; FAO, UNEP, & WHO, 2021). The Global Status of Soil
380 Pollution report, adopted within the framework of the UN Decade on Ecosystem Restoration (2021–2030), further highlighted key challenges, including fragmented datasets, methodological inconsistencies, limited compatibility among assessment methods, and restricted accessibility of contaminant assessment technologies (FAO, 2018b). High analytical costs and continued reliance on laboratory-based analyses remain significant barriers to large-scale soil assessment efforts. These
385 findings informed the GSOP18 outcome document “Be the solution to soil pollution” and contributed to the United Nations Environment Assembly resolution on soil pollution (FAO, 2018). Subsequent FAO initiatives, including efforts to strengthen pesticide regulations and pollinator protection, have further reinforced preventive soil-management approaches.

Multilateral environmental agreements provide an essential regulatory framework for managing
390 hazardous chemicals and pollutants relevant to soil systems. The Basel Convention regulates hazardous waste movement and disposal, including provisions under the Basel Protocol on Liability and Compensation and the Ban Amendment (UNEP, 1989; Basel Convention, 2011, 2019). Complementary agreements, including the Rotterdam Convention on hazardous chemicals and pesticides and the Stockholm Convention on Persistent Organic Pollutants, further support chemical regulation, pollution
395 prevention, and environmentally sound management practices (Rotterdam Convention, 2010, 2020a, 2020b, 2020c, 2021; Stockholm Convention, 2021; UNDP, 2024). Collectively, these frameworks strengthen accountability mechanisms and promote coordinated international responses to chemical risks affecting soil systems (UNEP, 2011a). Additional governance instruments, including FAO sustainability initiatives, pesticide and fertilizer codes of conduct, and soil-quality standards developed
400 through ISO Technical Committee 190, further contribute to sustainable soil management and global soil governance (FAO, 2015; FAO & WHO, 2014; FAO, 2017; FAO, 2019; ISO, 2024). Despite these coordinated efforts, progress toward sustainable chemical management remains limited, and prevailing development pathways continue to reflect unsustainable practices within the broader framework of the 17 interconnected SDGs (UN, 2015). Figure 6 depicts tools for implementing sustainable management

of soil, whereas the figure 7 shows a set of 17 interconnected Sustainable Development Goals (UN, 2015).

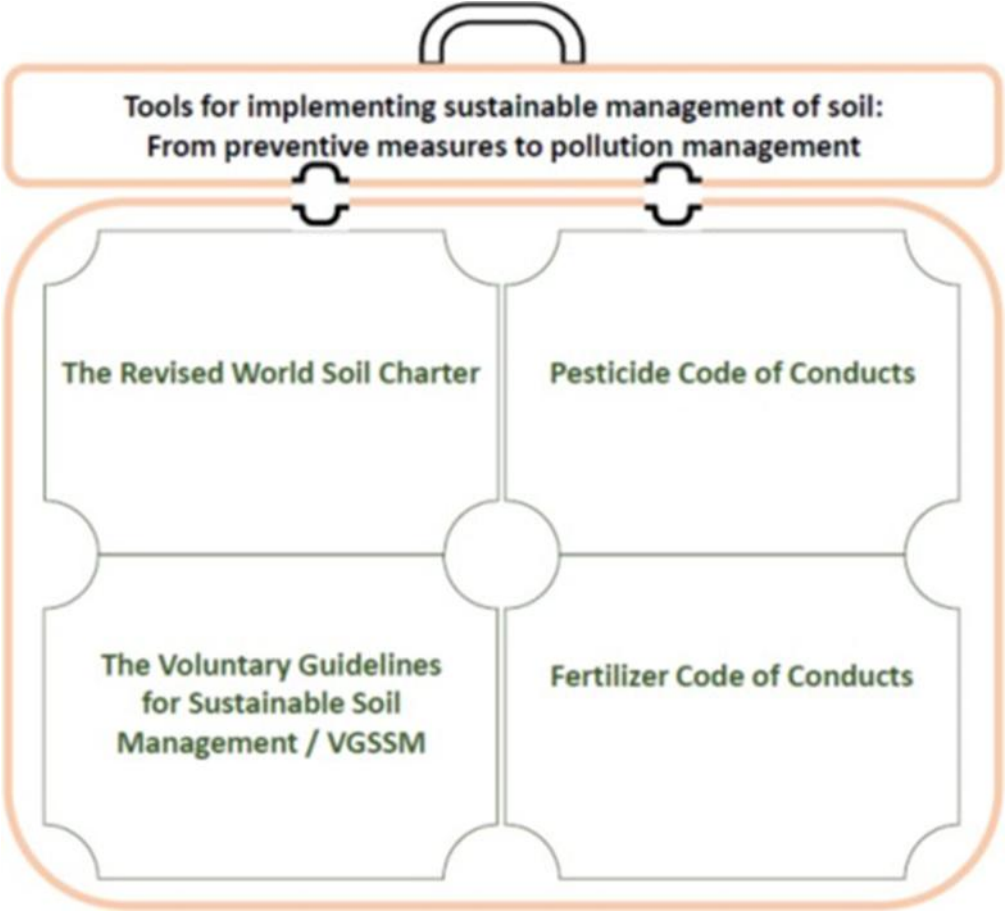


Figure 6. Managing soil sustainably [The revised World Soil Charter (FAO, 2015); Pesticide Code of Conducts (FAO & WHO, 2014); VGSSM (FAO, 2017); Fertilizer Code of Conducts (FAO, 2019)].

3.1.2 Soil contamination and systemic degradation processes

Soil contamination is a major driver of land degradation and ecosystem-service deterioration, particularly within intensively managed agricultural systems. Anthropogenic contaminants alter soil physico-chemical and biological properties, impair nutrient cycling, reduce microbial activity, and

compromise ecosystem functioning. Pesticides, heavy metals, industrial pollutants, plastics, pharmaceuticals, and emerging contaminants contribute substantially to these degradation processes. Contaminant behaviour is governed by interactions among soil properties, climatic conditions, and land-

420 management practices. Soil pH, texture, organic matter, and redox conditions influence contaminant mobility and bioavailability, while climatic processes such as erosion, runoff, volatilization, leaching, and atmospheric transport facilitate pollutant movement across landscapes (Rockström et al., 2009). Mechanized agricultural practices further contribute to physical degradation, including soil sealing and compaction. Contaminants negatively affect soil organic matter and microorganisms and may disrupt

425 soil structure, increasing erosion susceptibility (Korkina & Vorobeichik, 2018). Co-contamination involving microplastics, crude oil residues, pharmaceuticals, and antimicrobial compounds further complicates degradation pathways and remediation efforts by altering soil porosity, bulk density, and pollutant mobility (Adamu et al., 2024; Klamerus-Iwan et al., 2015; de Souza Machado et al., 2018). Although no single metric exists for soil lifespan, projected declines highlight the urgency of protecting

430 soils formed over millennia (Evans et al., 2020). Anthropogenic drivers of soil degradation include intensive agriculture, mining, industrialization, urbanization, excessive agrochemical application, irrigation-induced salinization, acidification, soil sealing, and fossil fuel combustion (Peña, 2022; Gautam et al., 2023). Heavy metals accumulate through industrial emissions, mining, atmospheric deposition, wastewater irrigation, and long-term agrochemical use, whereas pesticide persistence

435 depends on chemical composition, environmental conditions, and application intensity.

Soil contaminants originate from both natural and anthropogenic sources and may exist as water-soluble, lipid-soluble, airborne, or residual compounds associated with plant decay and industrial activities. Contaminants transfer among air, water, soil, and plants through partitioning, dry deposition, and wet deposition processes (Malakar et al., 2019; Cornu et al., 2001; Lamastra et al., 2018; Orosun et

440 al., 2023; EEA, 2024a, 2024b; Goldmund, 2004; Shaikh et al., 2012). Natural events may also contribute to long-range contaminant transport; for example, radionuclides released during the 2015 forest fire within the Chernobyl exclusion zone dispersed across parts of Eastern and Central Europe (Evangelidou et al., 2014, 2016).

Global contamination patterns reflect regional economic activities and land-use systems. Industrial
445 pollution predominates in North America and Western Europe, mining-related contamination is
common in sub-Saharan Africa, urban pollution affects Northern Africa and the Near East, and
intensive agriculture contributes substantially to pesticide accumulation in Asia, Eastern Europe, and
Latin America (FAO, UNEP, & WHO, 2021). These contaminants pose significant environmental and
public-health risks through carcinogenicity, neurotoxicity, teratogenicity, endocrine disruption,
450 oxidative stress pathways, and stress-protein induction (Landrigan et al., 2018; Stohs & Bagchi, 1995).
Soil pollution therefore represents a direct risk to human health and sustainable development
(Abrahams, 2002; Oliver, 2008; Landrigan et al., 2018; Shaikh et al., 2025). The World Health
Organization identified arsenic, cadmium, lead, mercury, dioxins, fluoride, benzene, asbestos,
hazardous pesticides, and air pollution among major public-health concerns, with most directly
455 associated with soil contamination pathways (WHO, 2010).

The Green Revolution substantially increased agricultural productivity and food security through high-
yield crop varieties, synthetic fertilizers, and pesticides (Swaminathan, 2009; Ritchie, 2017;
Vaidyanathan et al., 2023). Contributions from Norman Borlaug and M. S. Swaminathan were
particularly influential in advancing global food security. However, intensified agrochemical use also
460 accelerated environmental contamination, pesticide resistance, soil acidification, biodiversity decline,
reduced carbon sequestration, and broader ecosystem deterioration (Cachada et al., 2018; Duarte-
Guardia et al., 2019; Brühl et al., 2024). By the 1990s, these environmental consequences prompted
increasing emphasis on sustainable productivity, restoration of soil fertility, environmentally compatible
farming practices, and preventive pollution management (FAO, 2010, 2025; Sanchez, 1997). With the
465 global population projected to reach 9.6 billion by 2050 (Tripathi et al., 2019), the environmental
implications of agrochemical use have become increasingly evident.

Research addressing potentially toxic elements, agrochemical-induced fertility loss, human-health risk
assessment, remediation technologies, and sustainable agricultural practices has become increasingly
integrated (Alloway, 1995; Adriano et al., 1999; Piñeiro et al., 2020; Saikanth et al., 2023; Shaikh,
470 2020, 2025). Increasing attention has focused on contaminant identification, source analysis,
geostatistical approaches, metabolomics, physico-chemical remediation technologies, and bio-

/phytoremediation strategies. Environmentally sustainable agriculture emphasizes restoration of soil fertility, pollution prevention, ecosystem resilience, enhancement of biotic and abiotic soil resources, and environmentally benign chemical processes (Shaikh, 2014a & 2014b). At broader scales, contaminated sites continue to represent major environmental challenges. The USEPA estimated approximately 294,000 contaminated sites in 2004 (USEPA, 2004), while China reported contamination in approximately 16.1% of soils (MEP China, 2014). Similar concerns have prompted national remediation and rehabilitation initiatives in several countries, including India (CPCB India, 2015). International assessments emphasize the need for stronger societal and political commitment, preventive management, research investment, and integrated remediation strategies to address escalating soil degradation and contamination pressures (FAO, UNEP, & WHO, 2021; Fantke et al., 2012). Farmers and broader societal stakeholders, supported by legislation and incentives, are increasingly encouraged to adopt sustainable land-management, restoration, and mitigation strategies compatible with natural ecosystems (Piñeiro et al., 2020; Saikanth et al., 2023; Shaikh, 2020, 2025). Collectively, these interacting degradation processes demonstrate that soil contamination cannot be understood as an isolated chemical problem but rather as a systemic socio-ecological challenge involving interconnected impacts on biodiversity, ecosystem services, agricultural productivity, climate resilience, and environmental sustainability. This integrated perspective emphasizes that interacting stressors propagate across biological, ecological, and socio-economic domains, reinforcing the need for multi-scale and interdisciplinary intervention strategies.



Figure 7. A set of 17 interconnected Sustainable Development Goals (UN, 2015).

These governance frameworks actively shape how contamination risks are defined, monitored, and mitigated. Their integration into soil system analysis is therefore essential for understanding how scientific, regulatory, and socio-economic dimensions interact within broader sustainability transitions.

3.1.3 Contamination as a causal agent of soil degradation and deterioration

Soil contamination is recognized as a major causal agent of degradation, particularly in intensively managed agricultural systems. Anthropogenic contaminants alter soil physico-chemical and biological properties, impair soil functions, and reduce the capacity of soils to provide ecosystem services. Among these contaminants, pesticides and heavy metals are of particular concern due to persistence, toxicity, and widespread use. Chemical contamination interferes with soil processes by modifying structure, reducing organic matter, and impairing nutrient cycling. Pesticides persist depending on chemical properties, application rates, and environmental conditions, affecting microbial biomass, enzymatic activity, and microbial diversity. Heavy metals accumulate through industrial activities, mining, atmospheric deposition, wastewater irrigation, and long-term agrochemical use. Contaminant mobility and bioavailability are governed by soil properties (pH, texture, organic matter, redox conditions) and climatic factors (leaching, runoff, erosion, volatilization), potentially extending degradation effects across landscapes. These processes impair ecosystem services, including food production, water regulation, carbon sequestration, and habitat provision.

3.1.4 Soil degradation: Global extent and systemic nature of soil degradation

Land degradation and soil-quality deterioration are primarily driven by mining, industrial operations, and urbanization-related pollution. At the launch of the Sustainable Soils Alliance in 2017, the United Kingdom's environment secretary warned that only 30–40 years remained before farmland soil fertility could be severely diminished (SOCI, 2024). Although no single metric exists for soil lifespan, projected declines highlight the urgency of protecting soils formed over millennia (Evans et al., 2020). Additional drivers include unsustainable irrigation, erosion, fertilizer and pesticide overuse, acidification, salinization, compaction, and fossil fuel combustion (Peña, 2022; Gautam et al., 2023). Soil pollution represents a chemical deterioration process, yet it is intertwined with broader environmental stressors including climate change, land-use change, biodiversity loss, and hydrological dynamics (Rockström et al., 2009).

Human activities may cause physical degradation, soil sealing, and compaction by machinery. Contaminants negatively affect soil organic matter and microorganisms and may disrupt soil structure, increasing erosion (Korkina & Vorobeichik, 2018). Co-contamination, e.g., microplastics and crude oil, further complicates remediation efforts by altering soil porosity, bulk density, and pollutant mobility (Adamu et al., 2024; Klamerus-Iwan et al., 2015; de Souza et al., 2018). At broader scales, contaminated sites pose serious challenges. The USEPA estimated ~294,000 sites in 2004 (USEPA, 2004), ~16.1% of soils were contaminated in China (MEP China, 2014), and India established national guidance under the programme for rehabilitation of polluted areas (CPCB India, 2015). FAO–UNEP assessments emphasize the need for societal and political commitment to reduce toxic substance reliance and increase investment in research, prevention, and remediation (FAO, UNEP, & WHO, 2021; Fantke et al., 2012). Farmers and societal stakeholders, supported through incentives and legislation, must adopt improved land-management, restoration, and mitigation strategies using modern, cost-effective agricultural practices compatible with natural ecosystems. Research on sustainable agricultural practices has gained momentum in response to these challenges (Piñeiro et al., 2020; Saikanth et al., 2023; Shaikh, 2020, 2025).

540 **3.2 Policy, green economy, and sustainable communities**

Environmental sustainability, pollution prevention, and green economic development have become central priorities within global policy frameworks (UNEP, 2011; UNEA, 2018). Within this transition, sustainable soil management is increasingly linked to environmental governance, ecoefficiency, circular economy principles, sustainable agricultural innovation, and entrepreneurial approaches to sustainability transitions (UN, 2015, 2017; UNEP, 2011, 2017; Schaltegger et al., 2018). Implementing environmental sustainability in agriculture therefore requires systematic evaluation of environmental, social, and economic outcomes consistent with the Triple Bottom Line framework for industry (WBCSD, 2024). The concept of ecoefficiency introduced by the World Business Council for Sustainable Development emphasized minimizing hazardous materials while improving environmental and economic performance (Schmidheiny & WBCSD, 1992). Related approaches such as life cycle assessment, long-term risk assessment, and total-cost analysis are increasingly applied to evaluate sustainable agricultural systems and remediation strategies (Kirk et al., 2007; Paun et al., 2016; Huang et al., 2022). Impact categories addressed through life-cycle assessment include resource sustainability, ecosystem health, and human health. Green chemistry principles further support sustainable remediation by promoting environmentally benign chemical processes, reducing pollutant generation, and encouraging sustainable chemical innovation (Anastas & Warner, 1998; Shaikh, 2013a & 2013b, 2014a & 2014b; Shaikh et al., 2018). Similarly, doughnut economics provides a broader socio-economic framework integrating ecological boundaries with social sustainability objectives and planetary limits (Raworth, 2017). Collectively, these approaches reinforce the importance of integrating scientific innovation, environmental governance, sustainable business practices, green chemistry, and ecosystem restoration within long-term soil-management strategies. Figures 8 and 9 synthesise complex multi-dimensional interactions; therefore, simplified visual hierarchies and reduced informational density have been implemented to improve clarity and readability.

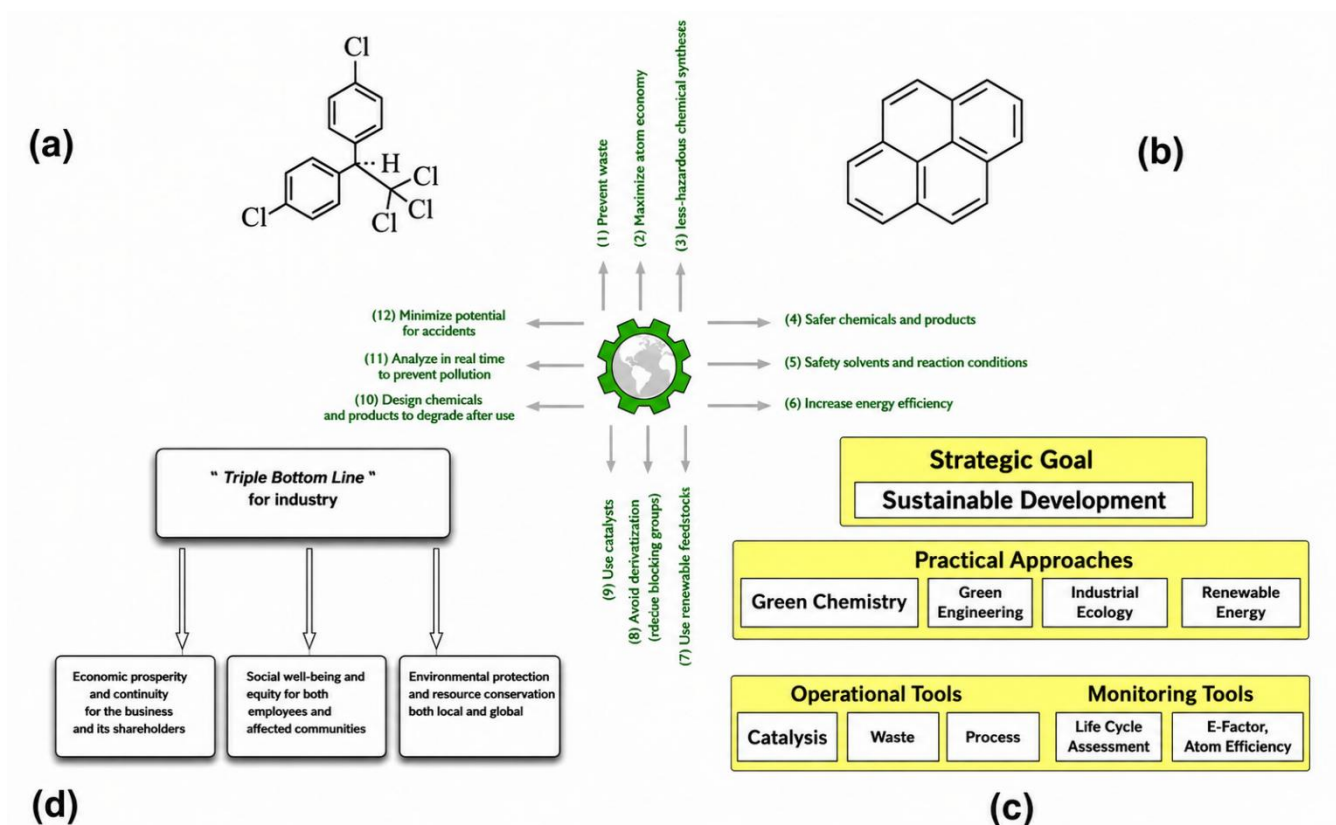


Figure 8. Green chemistry and its twelve principles (Anastas & Warner, 1998; Shaikh, 2013, 2014). Panels (a) and (b) show the chemical structures of dichlorodiphenyltrichloroethane (DDT) and pyrene, respectively. Panel (c) illustrates sustainable development from a chemistry-focused perspective (Shaikh, 2014a & 2014b; Shaikh et al., 2018), while panel (d) depicts the *triple bottom line* framework for industries (Schmidheiny & WBCSD, 1992).

3.3 Remediation technologies, restorative mitigation, and ecosystem recovery

The increasing complexity of soil contamination and degradation has accelerated the development of diverse remediation and restorative mitigation strategies aimed at protecting ecosystem services, environmental quality, agricultural productivity, and human health (Shaikh et al. 2025). Remediation approaches now extend beyond contaminant removal alone and increasingly emphasize restoration of soil functionality, microbial activity, nutrient cycling, ecological resilience, and long-term sustainability within socio-ecological systems. Conventional remediation technologies include physical and chemical

approaches such as excavation, soil washing, thermal treatment, vitrification, immobilization, stabilization, electrokinetic remediation, and chemical oxidation–reduction processes (Alloway, 1995; Adriano et al., 1999; Wuana & Okieimen, 2011). Although many of these technologies can effectively reduce contaminant concentrations, they are frequently associated with high operational costs, disturbance of soil structure, secondary pollution risks, intensive energy requirements, and limited restoration of biological soil functions. Consequently, increasing attention has shifted toward sustainable, biologically oriented, and ecologically compatible remediation strategies.

Bioremediation has emerged as one of the most promising restorative mitigation approaches because of its comparatively low cost, environmental compatibility, and capacity to support ecosystem recovery. Bioremediation utilizes microorganisms, fungi, plants, enzymes, and natural biological processes to transform, degrade, immobilize, or detoxify contaminants within soil environments (Vidali, 2001; Glick, 2003; Megharaj et al., 2011). Microbial remediation processes are strongly influenced by soil physicochemical conditions including pH, redox potential, temperature, moisture, organic matter, oxygen availability, and nutrient status, all of which regulate microbial metabolism and contaminant bioavailability.

Among biological approaches, phytoremediation has gained substantial scientific attention because of its ability to simultaneously remediate contaminated soils and improve ecosystem functions. Phytoremediation strategies include phytoextraction, phytostabilization, phytodegradation, phytovolatilization, and rhizofiltration (Salt et al., 1998; Pilon-Smits, 2005). Certain hyperaccumulator plant species can absorb and concentrate heavy metals from contaminated soils, whereas rhizospheric interactions between plant roots and microorganisms may stimulate degradation of pesticides and organic pollutants. In addition to contaminant removal, phytoremediation may contribute to carbon sequestration, erosion control, habitat restoration, and improvement of soil structure. Mycoremediation and algae-assisted remediation approaches have also attracted increasing research interest. Fungi possess extracellular enzymatic systems capable of degrading persistent organic pollutants, hydrocarbons, dyes, and xenobiotic compounds (Harms et al., 2011). Similarly, algae-based remediation systems may facilitate nutrient uptake, pollutant sequestration, and wastewater-associated soil restoration processes. Nanotechnology-assisted remediation has further expanded emerging remediation

possibilities through the application of nanoparticles, nano-adsorbents, and engineered materials for enhanced contaminant immobilization and degradation (Karn et al., 2009). However, ecological safety, nanoparticle persistence, and long-term environmental risks remain important concerns requiring additional investigation.

610 Recent advances increasingly emphasize integrated remediation frameworks combining physical, chemical, and biological processes to improve remediation efficiency and ecosystem recovery. Biochar amendments, compost application, constructed wetlands, microbial consortia, and nature-based solutions are increasingly investigated as multifunctional approaches capable of improving soil fertility while reducing contaminant mobility and ecological toxicity (Lehmann & Joseph, 2015; Keesstra et al., 615 2018). Sustainable remediation therefore increasingly prioritizes restoration of ecological integrity rather than solely achieving contaminant concentration thresholds. Microbial iron cycling has also emerged as an important mechanism within restorative remediation systems. Dissimilatory iron-reducing bacteria can facilitate transformation and detoxification of chlorinated compounds through coupled redox processes under anaerobic conditions. Zhong et al. (2024) demonstrated that 620 dissimilatory iron-reducing bacteria may significantly contribute to remediation of chlorinated contaminants by enhancing reductive dechlorination pathways and influencing iron-mediated biogeochemical cycling. These processes further illustrate the growing importance of microbially mediated remediation strategies within sustainable soil-restoration frameworks.

Despite major technological progress, remediation effectiveness remains constrained by contaminant 625 heterogeneity, co-contamination, site-specific variability, limited scalability, economic barriers, and uncertainties regarding long-term ecological outcomes. Many remediation studies continue to prioritize short-term contaminant reduction without adequately addressing restoration of ecosystem services, biodiversity, soil resilience, and socio-economic sustainability. Consequently, increasing emphasis is being placed on adaptive, site-specific, and sustainability-oriented remediation frameworks integrating 630 ecological restoration, risk assessment, environmental governance, stakeholder participation, and long-term monitoring. Within the broader sustainability context, restorative mitigation strategies increasingly support multiple SDGs including SDG 2 (Zero Hunger), SDG 3 (Good Health and Well-being), SDG 6 (Clean Water and Sanitation), SDG 12 (Responsible Consumption and Production), SDG 13 (Climate

Action), and SDG 15 (Life on Land) (UN, 2015). Restoration of contaminated soils therefore represents not only a technological challenge but also a critical socio-ecological priority for sustaining ecosystem services, environmental resilience, food security, and human well-being under accelerating global environmental change.

4 Discussion

This discussion integrates cross-cutting scientific, technical, governance, and sustainability themes emerging from the thematic synthesis. Rather than reiterating individual findings, the discussion synthesizes major insights on degradation processes, remediation pathways, and their implications for soil ecosystem services, sustainable land management, and SDG-aligned outcomes. Particular emphasis is placed on the interconnections among contamination pathways, remediation processes, ecosystem-service restoration, and sustainability governance within a systems-based framework. The discussion further identifies key synergies and trade-offs among remediation strategies and situates soil restoration within broader environmental and policy contexts. It also highlights priority research needs:

1. Improved mechanistic understanding of multi-contaminant interactions,
2. Long-term impacts of contaminants on soil–plant–microbe systems,
3. Field-scale validation of integrated remediation approaches, and
4. Effective translation of scientific evidence into actionable policy at farm, national, and international levels.

Collectively, the synthesis demonstrates that remediation effectiveness depends not only on contaminant removal efficiency, but also on restoration of soil functionality, ecological integrity, and long-term sustainability. These findings reinforce the importance of integrated and multi-scale approaches that connect remediation science, ecosystem-service recovery, agricultural management, and governance systems, while emphasizing how advances in remediation science can inform governance frameworks and support SDG-aligned outcomes.

4.1 Remediation strategies for pesticides and heavy metals

A wide range of remediation technologies has been developed to address pesticide-contaminated soils, broadly classified into physico-chemical, phytoremediation, and biological approaches (Correia & Rasteiro, 2025). While these approaches differ in mechanisms and operational requirements, they collectively contribute to reducing contaminant loads, restoring soil functionality, and improving
665 ecosystem-service recovery.

Physico-chemical methods – including soil washing, thermal desorption, chemical oxidation, and solidification – are widely applied because of their ability to rapidly reduce contaminant concentrations, particularly for POPs such as organochlorines and organophosphates (Shit et al., 2023; Aparicio et al., 2022). Soil washing mobilizes contaminants using aqueous solutions or surfactants to enable removal
670 and recovery, while thermal desorption employs elevated temperatures to volatilize and extract organic pollutants. Chemical oxidation techniques (e.g. Fenton's reagent or ozone treatment) degrade recalcitrant compounds into less toxic intermediates, whereas solidification and stabilization immobilize pollutants within a matrix, thereby limiting leaching and off-site transport (Usman et al., 2022).

Phytoremediation exploits plants to uptake, stabilize, or degrade pesticides. Hyperaccumulators
675 sequester toxic compounds, while rhizosphere-enhanced degradation relies on root exudates stimulating microbial activity (Ali et al., 2013; Li, 2022). Biological remediation emphasizes microbial degradation through bioaugmentation or biostimulation (Cycoń et al., 2017; Singh & Walker, 2006; Chia et al., 2024). Omics tools enhance efficiency by revealing degradative pathways and optimizing enzyme activity (Shah et al., 2024).

680 Integrating physico-chemical, phytoremediation, and microbial approaches supports soil fertility, ecosystem functioning, and sustainable agricultural practices (Aparicio et al., 2022; Ali et al., 2013). However, the synthesis also highlights important trade-offs. Physico-chemical approaches are often rapid and efficient but may generate secondary environmental impacts or alter soil structure, whereas biological approaches are generally more environmentally compatible but slower and constrained by
685 ecological and climatic conditions. Consequently, integrated or hybrid remediation approaches are increasingly recognized as more effective for achieving long-term restoration of soil functionality and ecosystem services.

4.1.1 Heavy metals: Sources, impacts, and remediation approaches

690 Heavy metals (Pb, Cd, As, Hg, Cr, Cu, Zn) originate from mining, smelting, industrial emissions, urban runoff, and agrochemical inputs, particularly phosphate fertilizers (Alloway, 1995; Wang et al., 2007). These contaminants persist in soils, accumulate within food chains, and negatively affect soil biological activity, nutrient cycling, and ecosystem functioning. Their mobility and toxicity are strongly influenced by pH, redox potential, organic matter content, and climatic conditions.

695 Remediation strategies include immobilization, phytoextraction, soil washing, electrokinetic remediation, and combined biological–chemical approaches; selection depends on metal speciation, soil properties, and site-specific constraints (Shaikh et al., 2025; Shaikh et al., 2013). Heavy-metal contamination warrants explicit treatment and is addressed in detail in one of our related studies (Shaikh et al. 2025); accordingly, a concise subsection is included here to contextualize sources, impacts, and

700 remediation options. While Table 1 contains several heavy-metal examples with recent citations, all four case studies presented herein focus primarily on pesticide contamination. Readers are referred to earlier work (Shaikh et al., 2013) for model heavy-metal-remediation case studies, including phytotoxicity and extraction projects. In the present study, the objective is to demonstrate the close alignment between advances in agricultural research and the evolving global environmental discourse,

705 emphasizing the need for integrated and holistic approaches to sustainable development, ecosystem-service restoration, and sustainable land management.

4.1.2 Pesticides: Crop protection agents with environmental repercussions

Pesticides, derived from Latin *pestis* (plague) and *caedere* (to kill), protect crops from insects, fungi,

710 and weeds. Early first-generation pesticides (sulphur, arsenic, nicotine) were replaced post-WWII by second-generation organochlorines, organophosphates, and phenoxy acids (Handford et al., 2015). Pesticides are inherently xenobiotic and frequently persist as residues in soils, exerting detrimental effects on the structure, diversity, and functioning of rhizosphere microbiomes (Magdoff & Van, 2021). Unsystematic application leads to accumulation, disrupting beneficial microbial communities and

715 impairing detoxification processes at cellular and molecular levels (Jeyaseelan et al., 2024). Many pesticides are water-insoluble and poorly biodegradable, and excessive use inhibits nitrogen fixation by

altering plant–microbe interactions, including impacts on rhizosphere Bacteroidetes, Proteobacteria, and other copiotrophic taxa (Ling et al., 2022).

Persistent compounds include DDT, HCH, lindane, aldrin, chlordane, dieldrin, endrin, and endosulfan, while PAHs are released unintentionally via fossil fuel combustion (Syafrudin et al., 2021). In parallel, polycyclic aromatic hydrocarbons (PAHs), listed under the Stockholm Convention, are unintentionally released through fossil fuel combustion, industrial activities, and biomass burning. Depending on type, concentration, and environmental conditions, herbicides disrupt beneficial microbial interactions, inhibit mycorrhizal fungi, reduce enzyme activities, and impede nitrogen mineralization (Aravind et al., 2023; Ikioukenigha et al., 2024; Sarker et al., 2023, 2024a & 2024b).

The synthesis further indicates that pesticide contamination is not solely a chemical problem, but a systems-level challenge affecting soil functionality, biodiversity, ecosystem services, food systems, and climate resilience. Contaminant persistence, transport, and degradation are strongly influenced by climatic variability, land-management practices, and soil physico-chemical properties, highlighting the need for integrated remediation and prevention strategies. Although pesticides are often portrayed as barriers to sustainable agri-food systems (Aktar et al., 2009), their use remains integral to crop productivity and pest control. Over the past decade, global pesticide use has increased by approximately 20%, with a 153% rise reported in low-income countries (Shattuck et al., 2023). Preventing pesticide contamination therefore requires science-based soil management tailored to local climatic and site conditions, including integrated pest management, organic amendments, crop rotation, enhanced plant–microbe interactions, improved germplasm, and biotechnological innovations capable of catalyzing pesticide degradation (Rebello et al., 2021).

4.1.3 Physico-chemical and microbial studies in remediation

Physico-chemical and microbiological investigations underpin remediation (Shaikh et al., 2012). Trace elements are immobilized to reduce bioavailability (Adriano et al., 1999) and prevent translocation (Semple et al., 2004; Klaassen et al., 2013). Microorganisms transform hexavalent chromium to less toxic trivalent forms and facilitate reductive dechlorination for chlorinated organics (Sumikura & Shiiba, 2016; Thatoi et al., 2014; Elgh-Dalgren et al., 2009a & 2009b; Garcia et al., 2013). In such

745 cases, soils are wetted and amended to exclude oxygen, thereby stimulating anaerobic microbial processes; similar approaches are applied to treat explosives such as RDX and HMX. Chlorinated organic compounds undergo reductive dechlorination through the addition of suitable electron donors. Several studies (Elgh-Dalgren et al., 2009a & 2009b; Garcia et al., 2013) have shown that biodegradation efficiency can be enhanced by combining phytoremediation with microbial remediation
750 strategies.

A wide range of remediation and mitigation strategies has been developed to address soil contamination, depending on the type of pollutant, site conditions, and desired restoration outcomes. To provide a clearer conceptual and practical understanding of these approaches, Figure 9 illustrates the overall pathways and mechanisms involved in soil remediation, while Table 1 presents a structured
755 synthesis of major contaminants and their corresponding treatment methods. These visual elements contextualize remediation strategies within the broader framework of soil processes, ecosystem-service recovery, and sustainability governance, particularly in relation to SDG 2 (Zero Hunger), SDG 6 (Clean Water and Sanitation), SDG 12 (Responsible Consumption and Production), SDG 13 (Climate Action), and SDG 15 (Life on Land), by way of nutrient cycling, soil fertility, and climate regulation.

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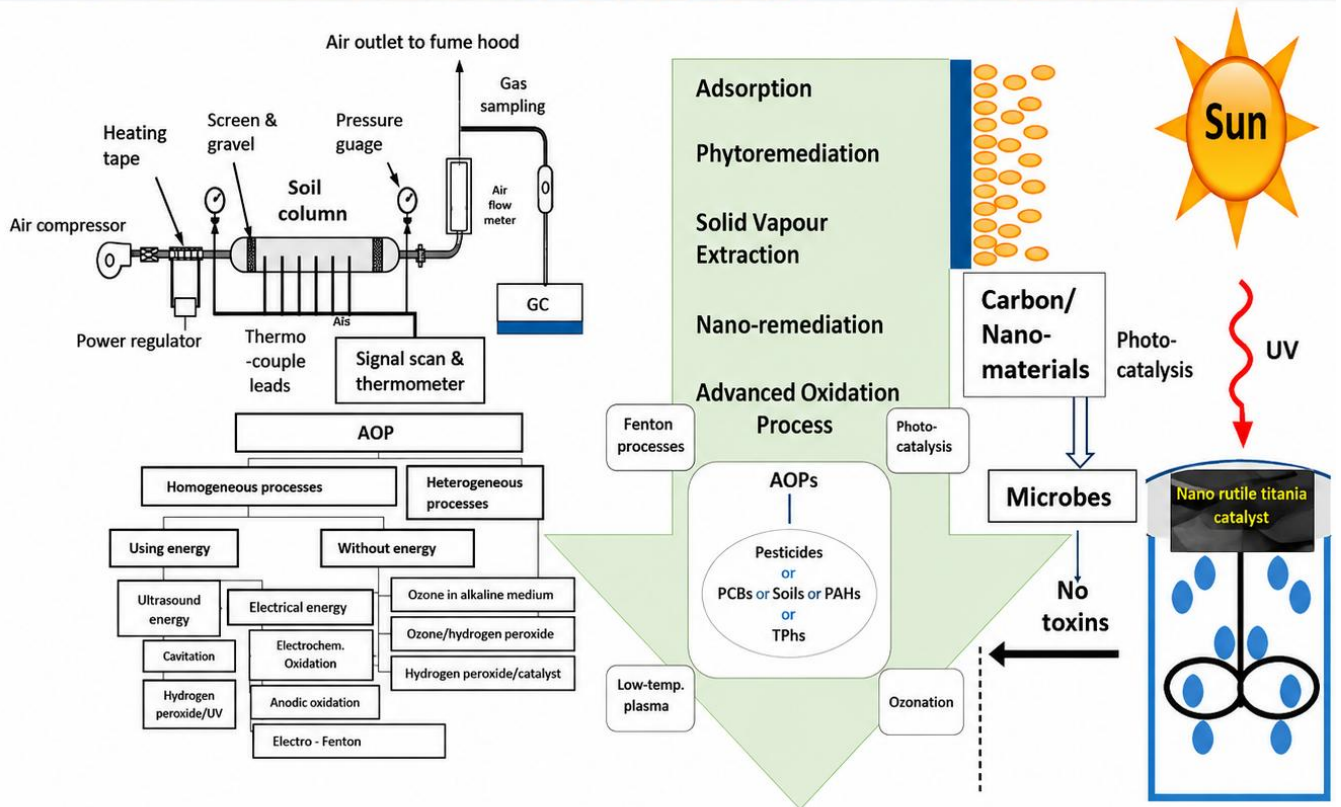


Figure 9. Soil remediation (Disclaimer: Although drawn by the authors, part of this figure – specifically the Soil Vapour Extraction component – is adapted from Shah et al. (1995) and credited accordingly; the remaining portion is based on Evuti et al. (2022), who cited the former.).

765 *This is important for illustrating the integration of physico-chemical, biological, and thermal remediation pathways and their role in restoring soil functions and ecosystem services within the SDG framework.*

For clarity, remediation strategies can be broadly categorized into three main groups: (i) physico-chemical methods, which involve direct removal, stabilization, or transformation of contaminants through engineering or chemical interventions; (ii) biological methods, including phytoremediation and microbial processes that utilize living organisms to degrade or immobilize pollutants; and (iii) thermal and advanced treatment methods, which rely on high-energy processes to eliminate contaminants. This classification provides a structured basis for comparing remediation approaches in terms of their mechanisms, effectiveness, and implications for soil functionality.

Table 1. Soil contaminants and methods of treatment: Pollutant destruction and remedial actions to restore degraded soil.

Soil contaminants	Treatment or method of destruction and removal or remediation
Heavy metals (Pb and Cd) or trace metalloid having pH and redox condition dependent mobility; toxic effects on plants and humans	Chemical & phytoremediation Chlorination and thermal treatment, Remedial technologies like solidification, stabilisation, liming, etc. (Sante, 2020, Hu et al., 2024, CLU-IN, 2024)
Heavy metals (e.g., Cu, Zn, Pb, Cd), metalloids, and other inorganic contaminants with high mobility in soil under varying pH and redox conditions; these contaminants pose risks to human health, wildlife, and plant growth	Methods like immobilization/stabilization (using lime or phosphate), phytoextraction, soil washing, electrokinetic methods, and combined bioremediation strategies. (Sun et al., 2024)
Radionuclides	Mainly stabilization and excavation

Serious consequences upon human exposure to radionuclides	Remediation by electro-kinesis (Ammar et al., 2024)
Highly soluble, mobile and phytotoxic inorganic salts	Chemical Leaching; application of $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$
PAHs Phenanthrene, Pyrene	AOP, Nanoremediation, Bioremediation, etc.
	Photocatalysis UV treatment using rutile nanosized TiO_2
	Chemical Magnetite-activated persulfate oxidation
PFHxA, PFOA, and PFOS	Thermal Temperature 900–1100 °C
Dieldrin, endrin, DDT and lindan	Bioremediation Iron reducing bacteria for the soil remediation with Chlorinated organic compounds (Zhong et al., 2024)
DDT contaminated sediments	Mixed methods / phytoremediation: Bacteria and white-rot fungi enhanced DDT degradation, biological approach, use of cattle manure compost, spent mushroom waste degrade DDT dredging, capping, natural attenuation. sediment washing, and
Petroleum hydrocarbons Complex mixture of compounds; significant solubility/toxicity	Land farming; thermal desorption, biodegradation

780 As shown in Table 1, different categories of contaminants require distinct remediation approaches, ranging from physical and chemical treatments to biological and nature-based solutions. This diversity reflects the complexity of soil systems and highlights the need for integrated and site-specific management strategies. Importantly, these remediation pathways are closely linked to the restoration of key soil functions, including nutrient cycling, water regulation, carbon sequestration, and biodiversity
785 support. By enabling the recovery of these functions, soil remediation directly contributes to ecosystem-service enhancement and supports multiple SDGs related to environmental sustainability, food security, and climate resilience. Figure 9 further emphasizes these interconnections by illustrating how remediation interventions influence soil processes and ecosystem outcomes.

Despite the wide range of available remediation strategies, their effectiveness varies significantly
790 depending on site-specific conditions, contaminant characteristics, and temporal scales. Physico-chemical methods, while often rapid and efficient in reducing contaminant concentrations, may lead to secondary environmental impacts such as soil structure degradation or chemical residues. In contrast, biological approaches such as phytoremediation and microbial remediation are generally more sustainable and environmentally compatible but are often slower and limited by ecological constraints.
795 This highlights an inherent trade-off between remediation efficiency and ecological sustainability, suggesting that no single method is universally optimal. Instead, integrated or hybrid approaches that combine multiple techniques are increasingly recognized as more effective in achieving long-term soil restoration, ecosystem-service recovery, and sustainable land management.

Bioremediation employs microbes, algae, and plants (Saxena & Bharagava, 2020; Kuppusamy et al.,
800 2015) with key degraders like *Pseudomonas putida*, *Bacillus cereus*, *Phanerochaete chrysosporium*, and *Trametes versicolor*. Integrated omics approaches optimize degradation pathways (Rodríguez Eugenio et al., 2018; Gangola et al., 2023; Kumar et al., 2024).

Bioremediation represents an effective, economical, and environmentally benign approach, employing microbes, algae, and plants to remove or minimize soil contaminants (Saxena & Bharagava, 2020;
805 Kuppusamy et al., 2015). Key degraders include *Pseudomonas putida*, *Bacillus cereus*, *Phanerochaete chrysosporium* (white-rot fungus), and *Trametes versicolor*, all documented for efficient degradation of DDT, PAHs, and organochlorines. Increasing investments are anticipated in pest and insect control

technologies using microbial agents, plant-incorporated protectants, and biochemically derived pesticides originating from nature (Duarte et al., 2018), rather than continued reliance on conventional chemical inputs.

Omics tools comprise high-throughput molecular approaches that systematically analyze biological systems across multiple molecular levels. Although no single Omics technique provides comprehensive coverage of all biological processes, integrated approaches encompassing bioinformatics, genomics, transcriptomics, proteomics, and metabolomics collectively yield detailed insights into genes, enzymes, and metabolic pathways involved in pesticide degradation. In this sense, Omics tools provide molecular-level understanding essential for optimizing bioremediation strategies (Rodríguez Eugenio et al., 2018; Gangola et al., 2023; Kumar et al., 2024). Pesticide remediation outcomes are further influenced by climatic conditions, redox status, catalytic processes, and hydrolysis reactions (Sarker et al., 2023).

Reducing pesticide use remains challenging due to agriculture's long-standing dependence on chemical inputs, despite European Union goals to phase them out (Jacquet et al., 2022). Official records indicate that 370 million kilograms of pesticides were sold in the EU in 2018 (Eurostat, 2020). Under the European Green Deal strategy, soil plays a central role in achieving the ambitious target of a climate-neutral EU by 2050 (EC, 2017a, 2017b, 2020a, & 2020b; FAO, 2022a & 2022b). Irresponsible practices can result in pesticide residues persisting within the food chain (Damalas & Eleftherohorinos, 2011). While the EU has banned approximately 850 active ingredients (Landrigan et al., 2018; Pappas & Foos, 2023), China, the United States, and Brazil remain the largest users, collectively accounting for nearly 70% of global pesticide consumption (Zhang et al., 2022; Tang et al., 2022).

Sustainable practices therefore require crop-protection agents that do not pose risks to off-target vegetation, alongside continued research addressing gaps in residue monitoring, safe disposal, ecological impacts, and long-term ecosystem-service recovery (Sarker et al., 2024a & 2024b). Multidimensional chemical and biological degradation strategies, including synthetic biology approaches, are receiving increasing attention (Ruomeng et al., 2023). Jacquet et al. (2022) identified five key innovation fronts essential for transitioning toward pesticide-free agriculture (Figure 10).

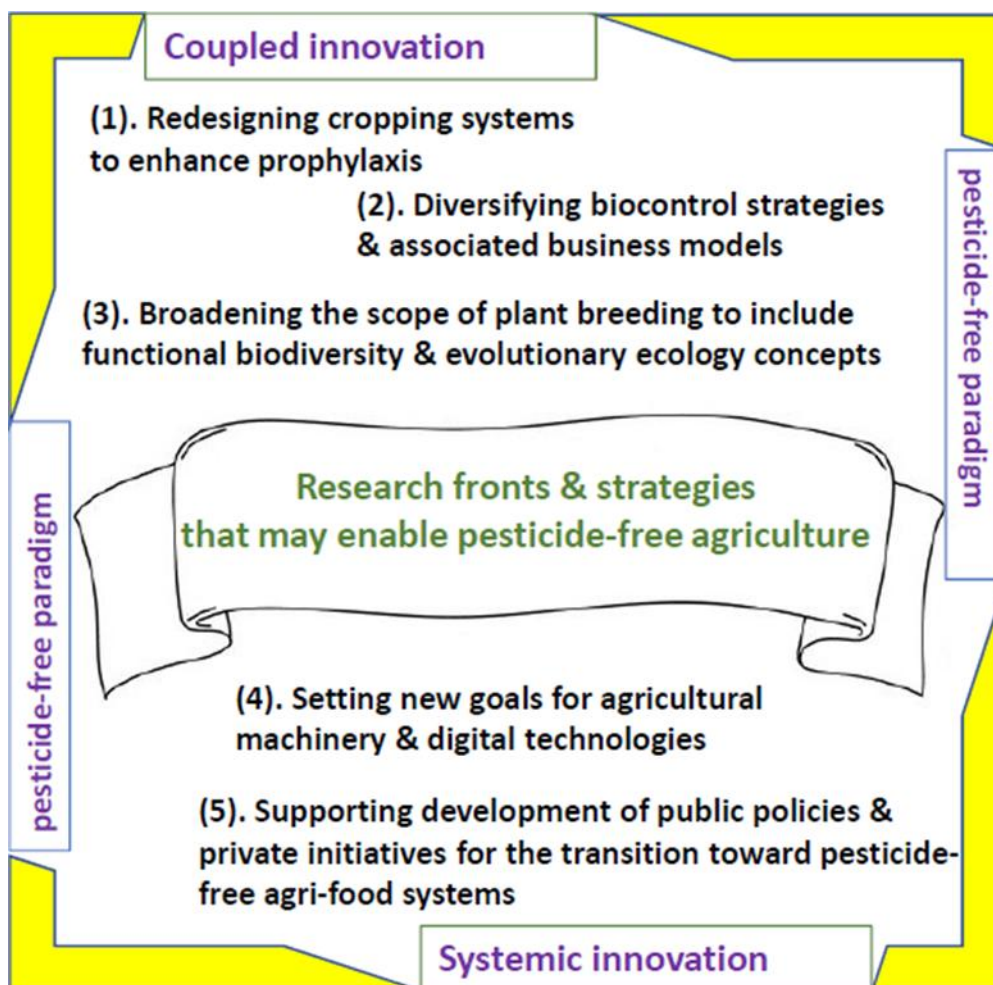


Figure 10. Five research fronts for pesticide-free paradigm: Systematic and coupled innovation (Jacquet et al., 2022).

840 4.2 Role of research enterprise and innovation pathways

Beyond technological interventions, the research enterprise plays a central role in advancing soil restoration by generating evidence-based knowledge, driving innovation, and informing policy and practice. Contemporary scientific approaches – including genomics, metabolomics, and integrated Omics frameworks – have significantly enhanced understanding of microbial degradation pathways and

845 contaminant transformation processes, thereby improving the efficiency and adaptability of bioremediation strategies. Emerging innovations in synthetic biology, enzyme engineering, and

biologically derived crop-protection strategies are contributing to a gradual transition toward reduced reliance on conventional agrochemicals. At the same time, policy-driven initiatives – such as those aligned with the European Green Deal and global sustainability frameworks – emphasize the need for environmentally benign alternatives and integrated soil-management systems.

Importantly, the translation of scientific advances into field-level applications remains a key challenge, requiring coordinated efforts across research institutions, policy frameworks, and agricultural stakeholders to ensure that innovation is scientifically robust, practically applicable, and socio-economically viable. These insights position soil restoration within a systems framework, where interactions among contaminants, soil processes, and governance structures determine degradation trajectories and mitigation outcomes. Within this framework, research enterprises contribute not only to technological development, but also to the integration of scientific evidence into sustainability governance, agricultural management, and environmental decision-making processes. This further highlights the importance of interdisciplinary and cross-sectoral collaboration for strengthening the long-term effectiveness and scalability of remediation strategies.

4.3 Case studies

As mentioned earlier, recent soil washing projects underscore cost-effective, regulation-compliant remediation (Wilson & Conway, 2024), with CLU-IN (2024) case studies validating performance, costs, and monitoring in real settings. Despite outlined strategies, real-world effectiveness remains the key challenge, making empirical case studies vital for linking technology, governance, and stakeholder action to measurable outcomes. Advances are strengthened by Omics-based insights (Rodríguez Eugenio et al., 2018; Gangola et al., 2023; Kumar et al., 2024) and biotechnological tools that enhance bioremediation and pest control, positioning research to support the shift toward pesticide-free, sustainable agriculture. This subsection presents a collection of notable, well-documented examples illustrating site monitoring and remediation applications across different countries, highlighting results, lessons learned, and benchmarks that inform technology performance, cost-effectiveness, and future directions in sustainable agricultural practices.

875 **Case Study 1. The Vemmenhög project, Sweden**

Indiscriminate use of pesticides in agriculture contaminated water bodies of Vemmenhög in Sweden during the mid-1980s. Accordingly, the Vemmenhög Project was launched in 1990 after monitoring studies on aquatic environments within the Vemmenhög agricultural catchment revealed pesticide contamination (Kreuger, 1998; Kreuger & Brink, 1988). This project, based on research, started
880 investigating sources of pesticides, pathways, and occurrence thereof in water streams within the catchment area, and continued over almost the entire decade of the 1990s. Monitoring work was conducted in co-operation with the local farmers. Farmers were made aware of the benefits and environmental repercussions of pesticides. This project encouraged transfer of scientific knowledge to farmers and inspired them to adopt improved agricultural practices; as a result, the average pesticide
885 concentrations dropped by more than 90%. The Vemmenhög catchment area saw a drastic reduction in transport of pesticides to surface waters (EEA, 2014, 2024). This project is a good example of a research enterprise influencing practitioners (farmers) by generating evidence of impact for informing decision-making in agricultural sustainability. It further demonstrates how stakeholder engagement, long-term monitoring, and science-based communication can contribute to measurable environmental
890 improvements and support sustainable land-management practices.

Case Study 2. Remediation of DDT and HCH contaminated soil, Huaxin Cement, Hubei, People's Republic of China

Firstly, a pre-processing unit was constructed for grinding and drying of the polluted soil.
895 Dichlorodiphenyltrichloroethane (DDT) and Hexachlorocyclohexane (HCH) were made to partially volatilize by passing hot gases (300 °C to 350 °C) through that unit, and then they were combusted in the pre-calciner. Contaminated soils with DDT concentrations of 243 mg/kg to 429 mg/kg and HCH concentrations of 37.9 mg/kg to 60.6 mg/kg were subjected to thermal oxidation and stored in a silo, and the remnant DDT and HCH were made to combust in the pre-calciner (1000 °C). Such soil was then
900 made to convert to cement clinker by passing through the rotary kiln as an alternative raw material and as an additive to other usual raw materials. According to Li et al. (2015), 400 000 tonnes of contaminated soil was successfully co-utilized in this plant within just two years. This case study

demonstrates how industrial-scale thermal remediation approaches can contribute to effective treatment of persistent organic pollutants while simultaneously supporting resource recovery and circular-economy-oriented practices.

Case study 3. Use of spent mushroom compost for remediation of PCB polluted soil, Italy

The Caffaro company had a chemical manufacturing unit in Brescia, Italy, since 1906. The company manufactured polychlorinated biphenyls (PCBs) during the period 1938–1984. PCBs are listed under Annex A as persistent organic pollutants. This polluted site in Brescia, Italy, is no longer in use, but Teseco undertook an important project and demonstrated effective remediation of the soil by using spent mushroom substrate. A biopile pilot plant treated ten tonnes of polluted soil, and the decontamination capacity was verified; following the public health intervention, a substantial decline in PCB serum levels was observed (Magoni et al., 2016). This example highlights the potential of biologically based remediation approaches for reducing pollutant loads while supporting environmentally sustainable restoration practices.

Case study 4. Chloroform and tetrachloromethane polluted soil remediation, Italy

The vadose and saturated soil layers in Northern Italy had been polluted due to leakage of tetrachloromethane (CCl₄), chloroform (CHCl₃), hexavalent chromium, and perchloroethene (PCE) and trichloroethene (TCE) from an underground storage at a chemical manufacturing site. CHCl₃ and CCl₄ were found at high concentrations in the saturated zone during the initial risk assessment and conceptual site model, while CHCl₃ was present at high concentrations in the vadose zone. As remediation strategies, a hydraulic containment barrier using a pump-and-treat technique and soil vapour extraction (for chloroform) were implemented for the saturated zone and the vadose zone, respectively. After one year of operation in 2017, the in-situ remediation project successfully decreased contaminant concentrations in the polluted soil zones (Donato et al., 2016). This case further illustrates the importance of integrated remediation approaches that combine engineering interventions with site-specific risk assessment and monitoring strategies.

930 Collectively, these case studies demonstrate that effective remediation outcomes depend not only on technological efficiency, but also on long-term monitoring, stakeholder participation, regulatory compliance, and the integration of scientific knowledge into environmental management practices. They further reinforce the importance of linking remediation strategies with broader sustainability objectives, including restoration of ecosystem services, reduction of environmental risks, and support for
935 sustainable agricultural systems.

4.4 Synthesis and implications for sustainable development

Revaluing resource use and production patterns to ensure that they are safe and environmentally benign is central to addressing soil pollution and restoring soil ecosystem services. This requires the adoption
940 of circular economy principles and entrepreneurial sustainable development, together with the systematic inclusion of risk assessment prior to pest management and waste treatment, and the integration of environmental sustainability into agricultural practices through sustained research enterprise. In this context, implementation of operational and policy tools – including Life Cycle Assessment, the Triple Bottom Line, and the Doughnut Model – alongside international commitments
945 such as the Basel Convention, the Voluntary Guidelines for Sustainable Soil Management (VGSSM), and the International Code of Conduct for the Sustainable Use and Management of Fertilizers (Fertilizer Code), is essential for effective prevention, mitigation, and restoration of soil pollution.

International frameworks and United Nations initiatives collectively emphasize that soil pollution, land degradation, desertification, biodiversity loss, hazardous waste accumulation, and climate change are
950 interconnected global environmental challenges that threaten ecosystem services, agricultural sustainability, human well-being, and long-term sustainable development (UNCED, 1992; UN, 2015, 2017). The 2030 Agenda for Sustainable Development highlights the importance of integrated and transformative approaches for restoring degraded ecosystems, promoting sustainable agriculture, strengthening climate resilience, ensuring responsible consumption and production, and protecting
955 ecosystem integrity through the achievement of the Sustainable Development Goals (SDGs), particularly SDGs 2, 6, 12, 13, and 15 (UN, 2015, 2017). In this context, the United Nations Decade on Ecosystem Restoration (2021–2030), the UNCCD framework, and the recent UNCCD COP16

discussions further emphasize the urgent necessity of restoring degraded land, improving soil health, enhancing drought resilience, and strengthening ecosystem recovery through coordinated scientific, policy, and community-based interventions (UN, 2019; UNCCD, 2024a, 2024b). Complementary international environmental governance frameworks – including the Basel, Rotterdam, and Stockholm Conventions, UNEP Resolution 3/6 on managing soil pollution to achieve sustainable development, and the UNEA implementation plan “Towards a Pollution-Free Planet” – underscore the importance of environmentally sound management of hazardous chemicals and wastes, prevention of transboundary pollution, reduction of persistent organic pollutants, liability and accountability mechanisms, circular economy approaches, and sustainable resource management (UNEP, 1989, 2011a, 2017; UNEA, 2018; UNDP, 2024). UNEP’s green economy framework further highlights the importance of environmentally sustainable development pathways, resource efficiency, and poverty eradication through environmentally benign production and consumption systems (UNEP, 2011). Contemporary climate-policy initiatives under the UNFCCC and associated EU climate frameworks additionally reinforce the importance of climate finance, low-carbon transitions, ecosystem resilience, and integrated sustainability governance for protecting livelihoods and strengthening climate adaptation pathways (UNFCCC, 2024a, 2024b; EC, 2017a, 2017b, 2020a, 2020b). UNESCO initiatives on education for sustainable development and the Greening Education Partnership further emphasize the importance of environmental education, scientific literacy, interdisciplinary research, and capacity building in supporting long-term sustainability transitions (UNESCO, 2005, 2022). In parallel, remediation-focused studies and technological frameworks demonstrate the growing importance of innovative and integrated remediation approaches, including advanced oxidation and Fenton-based technologies, while also highlighting limitations, ecological compatibility, risk assessment, and long-term sustainability considerations associated with remediation systems (USEPA, 2004; Usman et al., 2022). Collectively, these international policy frameworks, sustainability initiatives, and scientific contributions reinforce the necessity of integrated physico-chemical, biological, and governance-based approaches to soil remediation, ecosystem restoration, and sustainable agricultural management, supported by broader socio-ecological considerations, in order to achieve resilient socio-ecological systems and long-term environmental sustainability (UNEP, 2017; UNEA, 2018; FAO, 2015; UN, 2015).

This thematic synthesis demonstrates how contaminants such as pesticides and heavy metals enter and disrupt soil systems, impairing physico-chemical properties, microbial functions, and nutrient cycling, while climate dynamics further modulate contaminant behaviour. These disruptions cascade to reduce key ecosystem services, including carbon sequestration, soil fertility, water regulation, and biodiversity support. Restorative strategies integrating physico-chemical, biological, ecological, and socio-technical interventions are critical for restoring soil functionality and can simultaneously advance multiple Sustainable Development Goals, notably food security (SDG 2), clean water (SDG 6), responsible consumption and production (SDG 12), and climate and ecosystem resilience (SDGs 13 and 15).

Consistent with Xiong et al. (2024), this study highlights the value of multi-scale approaches that integrate site-level remediation with landscape-scale planning to restore soil ecosystem services, support research-driven innovation, and strengthen sustainability governance. The synthesis underscores that soil restoration is not solely a technical challenge, but a systemic process requiring alignment among scientific knowledge, agricultural practice, and policy frameworks. In this context, research enterprises play a critical role in generating evidence, informing decision-making, and enabling the translation of remediation strategies into measurable sustainability outcomes across socio-ecological systems.

The findings further demonstrate that remediation efficiency, ecological compatibility, and long-term sustainability are closely interconnected and often involve important trade-offs. Physico-chemical approaches may provide rapid reductions in contaminant concentrations, whereas biological and ecological strategies frequently offer greater environmental compatibility and long-term ecosystem recovery potential. Consequently, integrated and hybrid remediation strategies are increasingly important for balancing restoration efficiency with ecosystem integrity and sustainable land-management objectives. Collectively, these findings reinforce that restoring soil functionality requires integrated physico-chemical, biological, ecological, and socio-technical interventions, supported by circular economy principles, systematic risk assessment, and alignment with international policy frameworks. Such integrated and multi-scale approaches are essential for translating remediation outcomes into measurable and policy-relevant improvements in ecosystem services and sustainability indicators across multiple spatial and governance scales.

1015 **5 Future Scope**

5.1 Organic amendments and biopesticides

Organic soil amendments and biopesticides, supported by monitoring and modeling, remain central to future research. Investigations include phytotoxicity assessments, eutrophication impacts, and optimization of bioremediation strategies across agro-environmental conditions. Biologically derived
1020 pest-control agents provide environmentally benign alternatives to conventional chemicals. Future work should also strengthen understanding of how organic amendments influence soil microbial diversity, contaminant bioavailability, and long-term ecosystem-service recovery under varying climatic and land-management conditions. Greater emphasis is also needed on integrating biological pest-control systems with sustainable agricultural management practices to reduce dependency on conventional
1025 agrochemicals while maintaining productivity and environmental integrity.

5.2 Soil resilience and microbial diversity

Future research emphasizes soil resilience, microbial diversity, and nutrient cycling for ecosystem functioning. Strengthening biological integrity supports productivity, buffers environmental stressors,
1030 and maintains ecosystem services, including carbon sequestration, nutrient turnover, and soil stability. Additional long-term investigations are required to understand how contaminant mixtures, climate variability, and agricultural intensification influence soil–plant–microbe interactions and ecosystem resilience across different spatial and temporal scales. Improved mechanistic understanding of microbial adaptation, functional redundancy, and ecological recovery processes will be essential for strengthening
1035 long-term soil functionality and resilience under changing environmental conditions.

5.3 Development of efficient remediation technologies

Emerging remediation technologies – including nano-remediation – show promise for scalable, safe, and cost-effective application. Field validation is required for performance, environmental safety, and
1040 long-term effectiveness. Integrating technological innovations with ecological strategies enhances restoration outcomes. Future research should therefore prioritize comparative assessments of integrated

remediation systems under real field conditions to evaluate long-term sustainability, ecosystem-service recovery, and socio-economic feasibility. Recent studies further demonstrate the potential of biologically mediated remediation approaches, including the application of dissimilatory iron-reducing bacteria for degradation of chlorinated compounds, highlighting the importance of microbial processes, ecological compatibility, and integrated biological strategies for sustainable soil and groundwater restoration (Zhong et al., 2024). Particular attention should be directed toward hybrid remediation systems that combine physico-chemical, biological, and ecological approaches to improve contaminant removal efficiency while minimizing unintended environmental impacts and supporting restoration of soil functionality.

5.4 Green chemistry and sustainable practices

Green chemistry innovations and environmentally sustainable chemical interventions are fundamental for pollution-free soils and sustainable agriculture (Anastas & Warner, 1998; Shaikh et al., 2012a & 2012b, Shaikh et al., 2012, 2013a, 2013b, 2014a, 2014b, 2018, 2020, & 2025). Chemistry plays a central role in designing environmentally benign processes and products, supporting the transition toward sustainable agricultural systems. It also plays a pivotal role in life cycle assessment, resource efficiency, and pollution prevention, with cross-sectional contributions across natural and industrial systems essential for sustainable development.

Implementing sustainable soil and ecosystem service management requires continued basic-to-applied research in green chemistry (Anastas & Warner, 1998) to: (i) identify contaminants, (ii) conduct risk assessments, (iii) analyze soil contamination levels, (iv) develop mitigation strategies, and (v) implement improved measures in real farm-field settings. Innovation in green chemistry and engineering, integrated with environmental sustainability principles, is instrumental in transitioning toward pollution-free soils and restoring ecosystem services.

In the context of chemical crop protection agents, sustainability can be achieved through operational tools, monitoring frameworks, and chemistry-based interventions. In the Anthropocene, the design of benign industrial ecology through chemistry is intrinsically linked to environmental sustainability. These research efforts contribute to global scientific discourse, inform evidence-based policy-making,

1070 and catalyze local-level actions that translate knowledge into practical solutions. Future developments should also focus on reducing hazardous inputs at source, improving biodegradability of agricultural chemicals, and strengthening integration between green chemistry, circular economy approaches, and sustainable soil-management systems. Advancing environmentally benign industrial ecology through chemistry-based innovation will therefore remain essential for linking agricultural productivity, 1075 pollution prevention, ecosystem-service restoration, and long-term sustainability goals.

5.5 Future governance and SDG linkages

Advancing effective mitigation of soil contamination necessitates coordinated efforts among the research community, national policy arenas, and intergovernmental organizations. Future work should 1080 strengthen evidence-based governance mechanisms that directly support Sustainable Development Goal-linked outcomes, including restored soil fertility (SDG 2), reduced contaminant leaching and improved water quality (SDG 6), sustainable pesticide management and responsible production systems (SDG 12), and enhanced climate resilience and ecosystem integrity (SDGs 13 and 15).

Strengthening these linkages ensures the convergence of scientific innovation, agricultural policy, and 1085 international sustainability agendas, thereby promoting long-term soil health and resilient food systems. Future governance frameworks should further support standardized monitoring systems, interdisciplinary collaboration, and integration of scientific evidence into regulatory and agricultural decision-making processes across local, national, and international scales. Greater policy emphasis is also required on translating remediation science into operational sustainability frameworks capable of 1090 linking soil restoration outcomes with ecosystem-service indicators, climate resilience targets, and long-term agricultural sustainability objectives.

6 Conclusions

This study synthesizes and critically evaluates existing literature to show that agricultural soil 1095 contamination – driven primarily by pesticides and heavy metals – continues to intensify and leads to the degradation of soil physico-chemical properties, microbial communities, and ecosystem services. The synthesis demonstrates that pesticide residues disrupt nutrient cycling, nitrogen fixation, and

microbial diversity, while contaminant mobility is strongly influenced by soil properties and climate-related processes such as leaching, runoff, and volatilization. The analysis indicates that soil degradation is driven by complex interactions among contaminants, climate dynamics, land-use change, and socio-economic pressures, resulting in cascading effects on soil functions and ecosystem services. Across the reviewed literature and case studies, soil degradation is consistently linked to declines in key ecosystem services, including soil fertility, water regulation, carbon sequestration, and biodiversity support. By explicitly linking contamination pathways to soil-process disruption, ecosystem-service loss, and mitigation strategies, this study advances a systems-level understanding of soil degradation. The analysis further demonstrates that remediation approaches – physico-chemical, biological, and integrated – can reduce contaminant loads, but their effectiveness varies depending on site-specific conditions and requires validation at field scale. Evidence from case studies, including the Vemmenhög project, confirms that combining scientific research with stakeholder engagement can significantly reduce contamination levels and improve environmental outcomes. Scientific innovation – ranging from Omics-based approaches to green chemistry and integrated remediation technologies – provides important pathways for reducing contamination and restoring soil functionality, but effective implementation depends on alignment across research, policy, and practice. Building on the synthesis, these findings indicate that effective soil restoration requires coordinated action across policy, practice, and research. From a policy perspective, the results highlight the need for stronger regulatory frameworks, standardized monitoring systems, and alignment with Sustainable Development Goals related to food security, water quality, and ecosystem protection. For agricultural practice, the evidence supports the adoption of integrated soil management strategies, including reduced pesticide reliance, improved nutrient management, and the use of biologically based and green chemistry-driven interventions. From a research standpoint, the study underscores the importance of linking mechanistic understanding of contaminant behaviour with scalable, field-level remediation approaches and highlights the role of the research enterprise in shaping sustainable soil management. Overall, soil restoration is not solely a technical challenge but a multi-level process requiring coordinated action among researchers, policymakers, agricultural practitioners, and institutions, supported by the integration of scientific innovation, agricultural management, and governance systems.

The study also identifies several critical gaps in the existing literature. There is limited mechanistic understanding of multi-contaminant interactions under changing climatic conditions, as well as insufficient long-term, field-scale evaluations of remediation technologies. In addition, significant gaps remain in linking remediation outcomes to measurable improvements in ecosystem services and sustainability indicators. Future research should therefore focus on: (i) integrated studies of contaminant mixtures and their impacts on soil–plant–microbe systems; (ii) field validation and comparative assessment of combined remediation strategies; and (iii) development of standardized frameworks that connect soil restoration outcomes with policy-relevant sustainability metrics. Addressing these gaps is essential for translating scientific advances into effective, large-scale solutions for sustainable soil management and ensuring long-term soil resilience.

This study provides an integrative synthesis of soil contamination, remediation strategies, and their implications for ecosystem services and sustainable development. By linking soil processes with remediation pathways and SDG outcomes, the analysis demonstrates that soil restoration is not merely a technical challenge but a complex socio-ecological process. A key insight emerging from this synthesis is that effective soil remediation requires balancing efficiency, ecological integrity, and long-term sustainability. This underscores the importance of adopting integrated, system-based approaches rather than relying on isolated technical solutions.

Taken together, this integrative perspective reinforces the role of sustainable land management, scientific innovation, circular economy principles, and governance systems in maintaining soil functionality and resilience under accelerating global environmental change. The study further emphasizes that restoration of soil ecosystem services requires coordinated and evidence-based action capable of linking scientific advances with practical implementation and sustainability governance across multiple spatial and institutional scales. Ultimately, the findings demonstrate that restoring soil functionality and resilience depends on integrated physico-chemical, biological, ecological, and socio-technical interventions that simultaneously address contaminant reduction, ecosystem-service recovery, agricultural sustainability, and long-term environmental governance.

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