https://doi.org/10.5194/egusphere-2025-271
Preprint. Discussion started: 17 July 2025
© Author(s) 2025. CC BY 4.0 License.

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

Isak Rajjak Shaikh,*[,1-4] Parveen Rajjak Shaikh[3-5]
[1] Swedish University of Agricultural Sciences, P.O. Box 7070, Uppsala, SE-750 07, Sweden
[2] School of Chemical Sciences, Swami Ramanand Teerth Marathwada University, Nanded 431 606, Maharashtra, India
[3] Razaaq University Consortium, Paulsgatan 8 D, 214 46 Malmö, Sweden
[4] Razak Institution of Skills, Education & Research (RISER) India
[5] School of Earth Sciences, Swami Ramanand Teerth Marathwada University, Nanded 431 606, Maharashtra, India

Correspondence to: Isak R. Shaikh (isak@razaaq.se)

Abstract. Soil is a vital component of the ecosystem, as it provides nutrients needed for the growth of plants and supports all terrestrial life on the planet. The global agricultural sector underwent enormous change after the World Wars, thanks to some important developments in technology transfer that saw increased crop production during the Green Revolution of the 1960s; the initiatives included the use of high yielding variety seeds and also the application of synthetic agrochemicals as nutrient inputs and crop protection agents. This was meant secure food grains for growing human population. Despite all the achievements, the initiatives taken during the Green Revolution are meeting with some harsh criticism now. Soil is under constant pressure due to irresponsible land use and resource exploitation, erosion, escalating climate change, and also the indiscriminate usage of synthetic pesticides and fertilizers. Synthetic pesticides are contaminating soil, and the contaminants are making serious alterations to the content and most importantly to the chemical quality, properties and functions of soil, requiring an immediate risk assessment owing to the hazard and scientific uncertainty surrounding it. Soil pollution is one of the most serious concerns of our time, which not only limits the sustainability of community livelihood but also compromises ecosystem services, causing depletion in its fertility and risks to the environmental and human health. So, the environmentalists, economists, and social scientists have begun advocating more organic amendments to farming and restoration of ecosystems services of soil. Researchers explore physico-chemical and biological methods to mitigate the soil contamination. Research enterprise, local policy making, and globalized discourses on environment at the highest decision-making authority of intergovernmental organizations are being directed towards sustainable future of socio-ecological system.

1 INTRODUCTION

Cultivating crops for food while moving away from a hunter-gatherer lifestyle is considered a driving force behind the growth of human civilization on the planet (Dirt, 2008). Although this shift happened gradually and independently as early as 11000 BCE in the Fertile Crescent and the rest of the world, there is no denying to the fact that fertile soil and freshwater bodies had known to have attracted and developed human settlements. Soil consists of (i) the solid phase containing minerals and organics i.e. soil organic matter (SOM) and or soil organic carbon (SOC), (ii) the solution phase with minerals dissolved in

https://doi.org/10.5194/egusphere-2025-271
Preprint. Discussion started: 17 July 2025
© Author(s) 2025. CC BY 4.0 License.

water, (iii) the atmospheric gases such as nitrogen (80%), oxygen and carbon dioxide (making majority of remaining 20%), and (iv) the living phase biomass. Bacteria, archaea and fungi consist of majority of the soil biomass. It is therefore that the soil quality, unlike other environmental compartments like air and water, will depends upon multiple factors, not just the presence of pollutants in each of these phases and impact thereof on the quality of soil, but a host of interactions among the phases (Bünemann *et al.*, 2018). Contaminants may affect soil microorganisms negatively, decrease their enzymatic activities, alter the soil communities, and diminish the biomass (Smejkalova, *et al.*, 2003; Wang *et al.*, 2007; Kenarova *et al.*, 2014; Xiong, 2015). Gómez-Sagasti *et al.* (2012) jotted following as the parameters needed for bioindicators to clearly pinpoint the impacts of soil pollution; (i) the microbiota or biomass, (ii) microbial activity (both respiration and enzymatic activity), and (iii) soil microbial diversity. In addition to that, the climate change alters ecosystem functioning and brings about more direct and adverse effects on the nutrient availability, nutrient use efficiency, nutrient and elemental cycling (Köhler & Triebskorn, 2013), and the overall physicochemical properties and functions of soil responsible for regulating and controlling contaminants' fate (Biswas *et al.*, 2018).

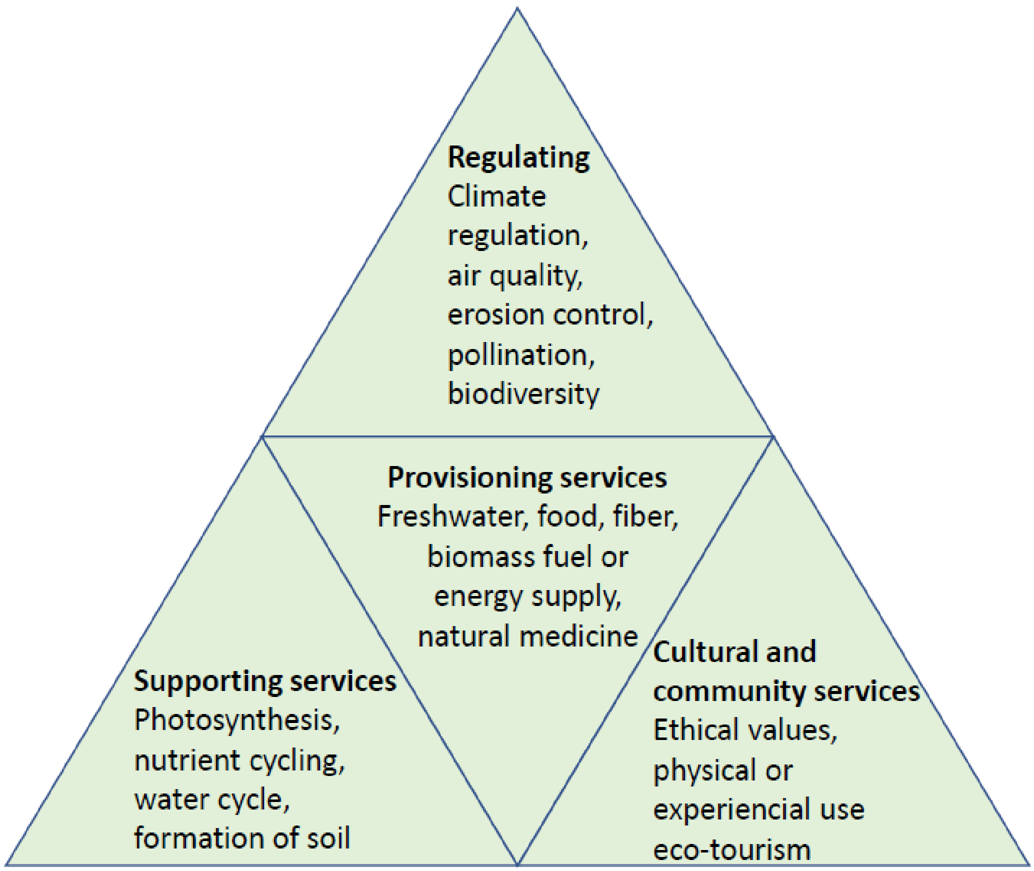

Figure 1 Ecosystem services of soil

https://doi.org/10.5194/egusphere-2025-271
Preprint. Discussion started: 17 July 2025
© Author(s) 2025. CC BY 4.0 License.

1.1 Soil and its ecosystem services

Soil is the important natural resource. It provides and regulates a plethora of ecosystem services (Figure 1). Soil functions as a gene reserve, a habitat for plants and other living organisms, including a large variety of biota in the locality, and also caters for their nutrients or food. Soil make provisions for various services to the environment and the human well-being, including food security, clean air and water, ecological protection, temperature regulation, and carbon sequestration, etc. Ecosystem services are defined as the conditions and processes provided by both biotic and abiotic ecosystem components to sustain and maintain human well-being (Daily, 1997). As per the Common International Classification of Ecosystem Services (CICES), there are three major services provided by soils: (i) regulation and support, (ii) provision, and (iii) cultural and community services (Fisher & Kerry 2008; Smith *et al.*, 2015; Potschin-Young *et al.*, 2017; Haines-Young & Potschin, 2018). But the growing population is causing soil degradation, and depletion in its fertility and functions by putting soil under constant pressure for resource exploitation and services (FAO and ITPS, 2015).

Today soil provides 95% of all food for mankind (FAO, 2022). Soil supplies almost all the essential elements (N, P, K, Ca, Mg, S, Fe, Zn, Mn, Cu, B, Mo, and Cl) required for the growth of plants, except for atmosphere-derived carbon, hydrogen, oxygen. For seeds to germinate and plants to start using nutrients efficiently, sunlight, water, and heat should be adequate, and apart from that the cultural practices and pest control practices have also major roles to play in crop productivity.

Soil absorbs water within pores, and dissolves nutrients, stores, and supplies them for the plant growth. Soil is crucial in mitigating climate change because it, like the oceans, accumulates carbon (cf. SOC), maintains air quality by reducing the total concentration of carbon dioxide (CO_2), and releases oxygen to the roots. Climate change changes soil nutrient cycling and availability owing to alteration in ecosystem functioning (Köhler & Triebskorn, 2013), and the overall physicochemical properties and functions of soil responsible for regulating and controlling contaminants' fate (Biswas *et al.*, 2018). Soil transforms and decomposes materials in the environment and traps contaminants through soil particles and sends filtered or relatively purified water to the aquifers or rivers (Nikitin, 1982) but contaminants that deteriorate soil quality causes imbalances in nutrient cycling, biological activity and functional diversity only to alter the agricultural environment. A soil's properties such as its colour, texture, density, structure, chemistry, aggregate stability, porosity, consistency, and temperature are determined by the soil's composition i.e. the combination of particles of minerals, SOC, air, water, and microorganisms. For example, the Black Cotton Soil found mostly in the Deccan Plateau of India is the result of weathering of fissure volcanic rock (basalt), and contains montmorinolite and kaolinite (minerals), iron oxide and calcium carbonate (chemical compounds) and humus (organic matter). The soil is considered most suitable for the cotton crop; it also offers a fertile and flexible canvas for other crops like groundnut, sugarcane, jowar, chilies, citrus fruits, banana, and wheat. Characterized by high content of clay, the Black Cotton Soil, also known as Regur soil, suffers from repeated shrinking and swelling, which by the way is also considered by many as a good self-plowing quality. This soil is rich in nutrients, but its fine texture makes it prone to erosion. So, one can just imagine how there is too big a difference between natural (i.e. unexpected natural calamities, weather change, weathering or surface geological changes) and man-made alterations made to the content or

https://doi.org/10.5194/egusphere-2025-271
Preprint. Discussion started: 17 July 2025
© Author(s) 2025. CC BY 4.0 License.

composition and most importantly the chemical properties of soil; the latter type of alteration can happen quite quick, and owing to the hazard and scientific uncertainty surrounding it, it can require an immediate assessment (Figure 2). Water pollution, eutrophication, and phytoxicity are one of those negative impacts that arise from disruption in or overexploitation of the natural functions of soil, such as buffering, filtering, and transforming capacities.

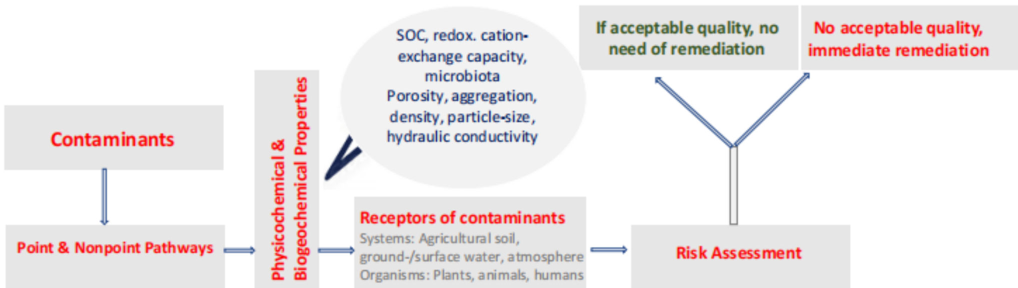

Figure 2 conceptualizes soil contamination, deterioration of soil quality parameters, and need for risk assessment

1.2 Transboundary nature of soil pollution

Soil should not be treated like a sink; it is not advisable for humans to release harmful substances into the soil environment as many pollutants tend to accumulate, and when their cconcentrations goes above a defined background value, this can lead to phytotoxicity, and cause negative health impacts on humans, domesticated animals and wildlife, and the ecosystem as a whole. Soil pollution can extend to other environmental media such as water and air (Jones, 2005). This is true, for example, in case of heavy metal contamination of soil (Alloway, 1995; Yeheyo, et al, 2024). Anything above a permissible level is regarded as "contaminated," and it might not take much time to get such localized contamination diffused or spread elsewhere (Perk, 2006).

Soil pollution can be categorised into point-source pollution (well-delimited area) and diffuse (covering large area). Research shows that soil pollution is transboundary in nature (Liu, et al, 2023), nearby natural areas' pollution reflects that of in urban greenspaces, and contaminants can traverse beyond continents, as they also found soil contaminants as far as in Antartica.

Anything that can cause the deterioration of soil properties can degrade the quality and function of soil; this is true for all types of soils. The loss of soil functions adversely affects socioecological and terrestrial life support system. Studies shows that nearly 2 billion hectares of soil have already been degraded in the world, owing to physical degradation or erosion and chemical deterioration (Jie, et al, 2002). And the present situation points to alarming climate change emergencies plausible in near future with more negative impacts for the ecological balance, life-supporting systems, and human life (Parmesan, 2006).

https://doi.org/10.5194/egusphere-2025-271
Preprint. Discussion started: 17 July 2025
© Author(s) 2025. CC BY 4.0 License.

Although challenged by food demand and material needs of the population, soil is truly an irreplaceable resource that provides numerous ecosystem services for sustaining life and the quality of life on the planet. Thus, the soil functions range from agricultural food production to environmental interaction, and biodiversity conservation and forestry to urbanisation and or even civil engineering applications, as approximately 50% of the houses on the planet are constructed from soil causing land degradation (Dai, et al, 2022). So, the phrase "think globally, act locally" is being used in various contexts of the care for people and the planet, such as agricultural soil, the ecosystems and sustainability of socio-ecological system along with its social dimensions like cultures, institutions, various actors, and economies, including deliverables like livelihoods and sustainable communities. After all, this thin layer of material covering the Earth is a valuable natural resource that needs to be cared, conserved if we want to secure our sustenance, sustainability, and also a sustainable future for our socio-ecological systems. There is also a need to promote teaching and learning for sustainable society (Figure 3), and that's the reason why UNESCO (2005) had declared the Decade of Education for Sustainable Development from 2005 to 2014. The UNESCO later launched a global initiative the *Greening Education Partnership* with institutions and individuals like us to take a whole-of-system approach to get every learner climate ready, and to support countries in dealing with climate emergencies by mobilizing the critical role of education.

https://doi.org/10.5194/egusphere-2025-271
Preprint. Discussion started: 17 July 2025
© Author(s) 2025. CC BY 4.0 License.

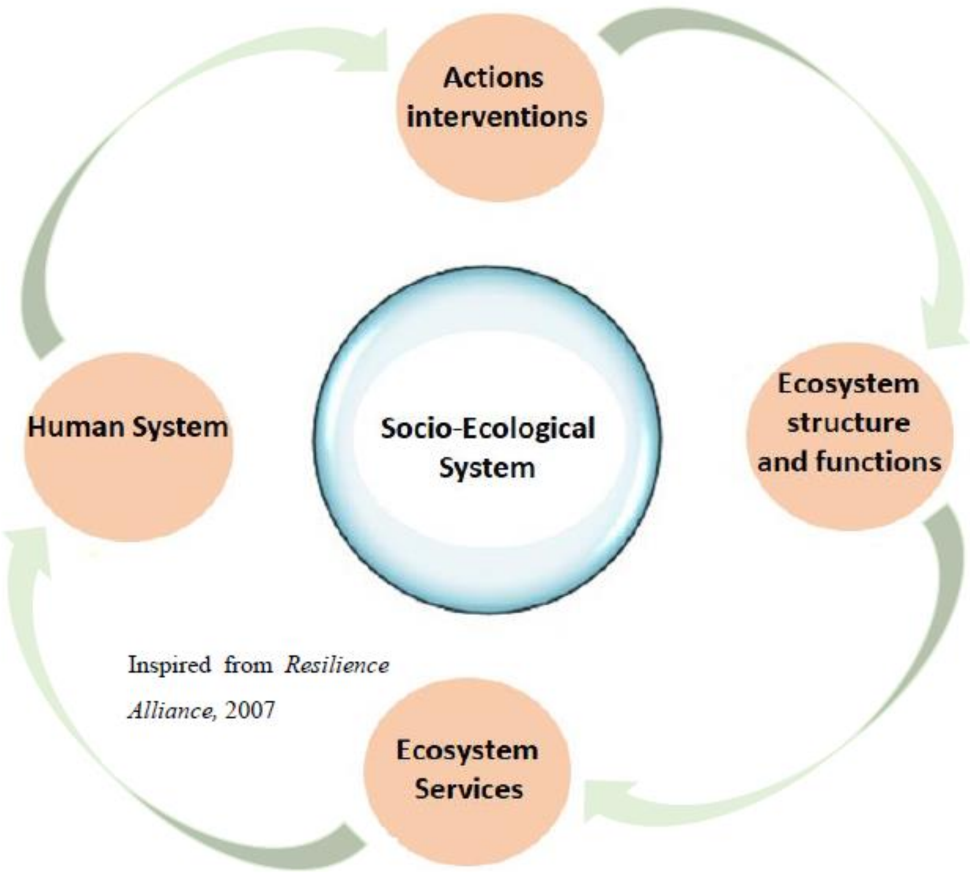

Figure 3 Socio-ecological System | Inspired from *Resilience Alliance*, 2007

https://doi.org/10.5194/egusphere-2025-271
Preprint. Discussion started: 17 July 2025
© Author(s) 2025. CC BY 4.0 License.

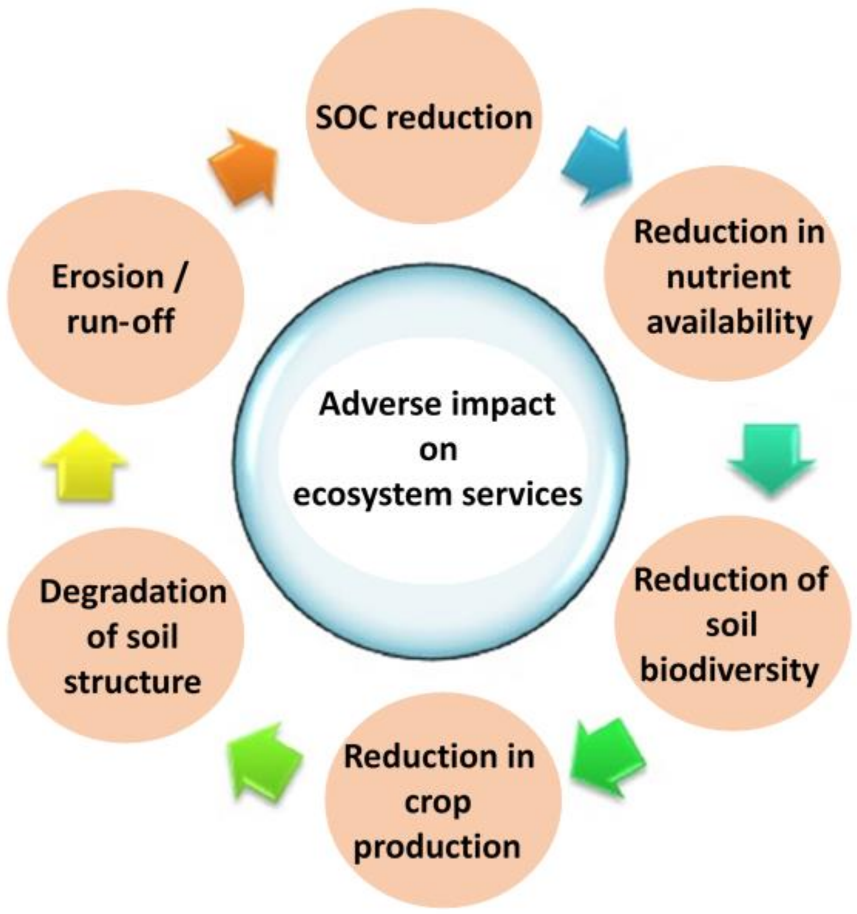

Figure 4 Degradation processes in polluted soil and their relevance to key ecosystem services.

Objectives: This manuscript aims to conceptualize and critically evaluate the current state of knowledge on degradation of soil quality and soil pollution (Figure 4) with a special focus on pesticide contamination, impact, mechanism and implications thereof on ecosystem services, with the possibility of large-scale applications, with high standards of scalability and sustainability. The idea is to conceptualize the anthropogenic contamination of agricultural soil leading to the degradation or deterioration of its properties and functions i.e. the implications for ecosystem services, and highlight the importance of research into restorative mitigation strategies, key trends, potential applications in real farm field setting, and most importantly, with a special focus on nexus approaches in environmental sustainability for policy making towards resilient socio-ecological system in a more globalized agricultural sector for achieving sustainable development goals (SDGs).

2 MATERIALS AND METHOD

The review has been prepared for submission to this interdisciplinary research journal, as it is a key resource for dissemination of knowledge for the environmental and soil science communities. We examine the effects of agricultural soil contamination on ecosystem services and the global sustainable development.

2.1 Method of investigation

Various components from relevant research were identified by conducting a comprehensive searching of current literature; this encompasses any possible combination of the following: (i) common public knowledge or what is already known, (ii) state-of-the-art literature survey, (iii) addressal of issues from a practice and policy development point of views, and (iv) critical appraisal of existing research. The whole study aimed at identifying the nature and extent of research enterprise providing impact, evidence and real-world applications, while combining the strengths of critical review and conceptual and thematic analyses. This draft addresses the knowledge gaps or heterogeneity of recommendations for future research by characterizing both literature and correlation between aspects missing in literature and limitations of their methodologies and practices.

2.2 Data collection

This started as a secondary research i.e. the literature review. We went on to assemble articles and reports published from academia and kind of presented this scattered literature in state-of-the-art manner and tried to present them in the context of the research problem in question. The current state of our knowledge, trends in further studies and advancements in application thereof, and finally the potential impact mechanisms, and research gaps of sustainable agriculture were identified. A special focus was laid on policy making directed towards meeting the SDGs. The idea was not to attempt formal quality assessment of others contribution, but to evaluate the contribution, the current knowledge technologies, and most importantly, conceptual synthesis not just as narrative approach to understanding soil and its ecosystem services, contaminants and remediation, and following on from that the importance from research and real farm field application point of views. It’s not about pointing to pitfalls, but showing how promising scientific endeavors are and how political debates, knowledge-based policy making, and agricultural practices are tackling soil degradation and pollution with mitigation and

https://doi.org/10.5194/egusphere-2025-271
Preprint. Discussion started: 17 July 2025
© Author(s) 2025. CC BY 4.0 License.

replenishment for its quality restoration. Thus, the methods employed for included search, appraisal, synthesis, and analysis, not mere description, while trying to maintain scientific reporting to subject specific protocol even within multidisciplinary analysis. We also considered PRISMA protocol as the name itself suggests preferred reporting items on chemical, biological degradation or remediation processes for pesticides while systematic reviewing the topic. (Moher, et al 2009 & 2019; Page, 2020, Tarla et al., 2020). Our review writing purports to stand as a succinct account that summarizes some of knowledge advancements in the field, including origin, challenges, key trends, scope and shows the vitality of the environmental sustainability in agriculture. While reviewing, we cannot help but jot our ideas to conceptualize contamination and deterioration of soil quality, implications for ecosystem services and restorative mitigation strategies for achieving sustainable development goals (SDGs).

3 RESULTS

This report addresses the issues with regards to soil contamination, degradation, remediation, and globalized discourse on ecosystem, and also critically evaluates the developments in bioremediation and other alternative mitigation strategies noted in the literature.

3.1 Towards Sustainable Socio-Ecological Systems: Land and Soil Quality Restoration for Sustainable Development Goals

According to FAO et al. (2020), about 135 billion tonnes of soil has been depleted from farmlands since the industrial revolution. Soil is under great pressure globally (FAO & UNEP, 2021) and the quality of soil itself has become a cause of serious concern (Zhang, Y. et al 2023) Land degradation and deterioration in agricultural fertility comes with far-reaching impacts and affects about 40% of the surface globally with dire consequences for biodiversity, climate and livelihood (UNCCD website, 2024). Rapid degradation in quality of soil is an alarming reality, and it is widespread so much so that it mocks the global sustainable development (Jie, 2002).

3.1.1 Globalized discourse on environment at the intergovernmental organizations

The efforts made at intergovernmental organizations is noteworthy. The World Commission on Environment and Development WCED used the term sustainability for the first time in 1987. Sustainability has emerged as an across-the-board, actually the most comprehensive, concept of all. Sustainability refers to the immutability of systems and processes that gives an account of the dynamics and the balance between the input and output (Shaikh, 2020)

Sustainable development, as a term, is said to have appeared first in a 1969 official document signed by African nations under the auspices of the International Union for Conservation of nature (IUCN). In 1987, while pressing the need to study and identify the human impacts on the environment, the term sustainable development was revisited again in a report entitled, “Our Common Future,” wherein the United Nations (UN) commission led by Gro Harlem Brundtland defined sustainable development as “the development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (Brundtland Commission, 1987). The UN Conference on Environment and

https://doi.org/10.5194/egusphere-2025-271
Preprint. Discussion started: 17 July 2025
© Author(s) 2025. CC BY 4.0 License.

Development (UNCED, 1992) highlighted the pressing need to come up with a more sustainable way of life by reducing environmental emissions and using resources carefully. The global goals for sustainable development were adopted by world leaders in 2015. On 01 January 2016, the goals replaced the eight millennium goals that the UN and the world's countries had been working on since 2000. Agenda 2030 was adopted to lay out an ingenious approach to socio-economic development going hand in hand with the environmental conservation (UN, 2015). FAO's Global Soil Partnership GSP, its Intergovernmental Technical Panel on Soils ITPS identified soil pollution as a serious problem, and started collecting data at all levels viz. national, regional and the global (FAO and ITPS, 2015). And since then, there is an increased globalized discourse on soil, environment and human health (FAO et al., 2021). The Global Status of Soil Pollution report was presented by FAO's GSP, its ITPS supported by UNEP, and this report is the result of an inclusive process with scientists from all regions of the world to bring the science behind soil pollution, and pledge to prevent, address, and remediate soil pollution within the recently declared UN Decade on Ecosystem Restoration (2021-2030). Actually, the UN Decade on Ecosystems Restoration was adopted in March 2019.

Soil pollution is a topic of concern, the significance of the problem two/fold as soil pollution adversely affects soil functioning in the environment and threatens human health and food security. This is evident from the globalized discourse and collaborative efforts of these intergovernmental organizations and agencies. They highlight the urgency in introducing national, regional, and international regulations for prevention of pollution in agricultural soil and remediate, as and when required. The conclusions drawn from the Global Symposium on Soil Pollution (GSOP18, FAO Rome, Italy) unveiled a very heterogeneous and fragmented data from different regions, data was fairly often missing in many other such instances. And participants of the GSOP18 called attention to the lack of compatible and comprehensive methods, and also the costly hassle of pollutant analysis in laboratories. The outcome document of the GSOP18 entitled, "Be the solution to soil pollution," reflected the conclusions and recommendations, which further made provisions for substantiating the UNEA3 resolution (FAO, 2018). In March of 2019, the UN Decade on Ecosystems Restoration was adopted. And off late, FAO (2022) organized a virtual two-day Global seminar on strengthening regulations to protect pollinators from pesticides in the month of February that year.

Figure 5 shows some key tools for the sustainably managing soil, including the preventive measures and management of polluted soils. These documents and dedicated efforts of the FAO & GSP are directed towards valuing and conserving the soil for the coming generations.

https://doi.org/10.5194/egusphere-2025-271
Preprint. Discussion started: 17 July 2025
© Author(s) 2025. CC BY 4.0 License.

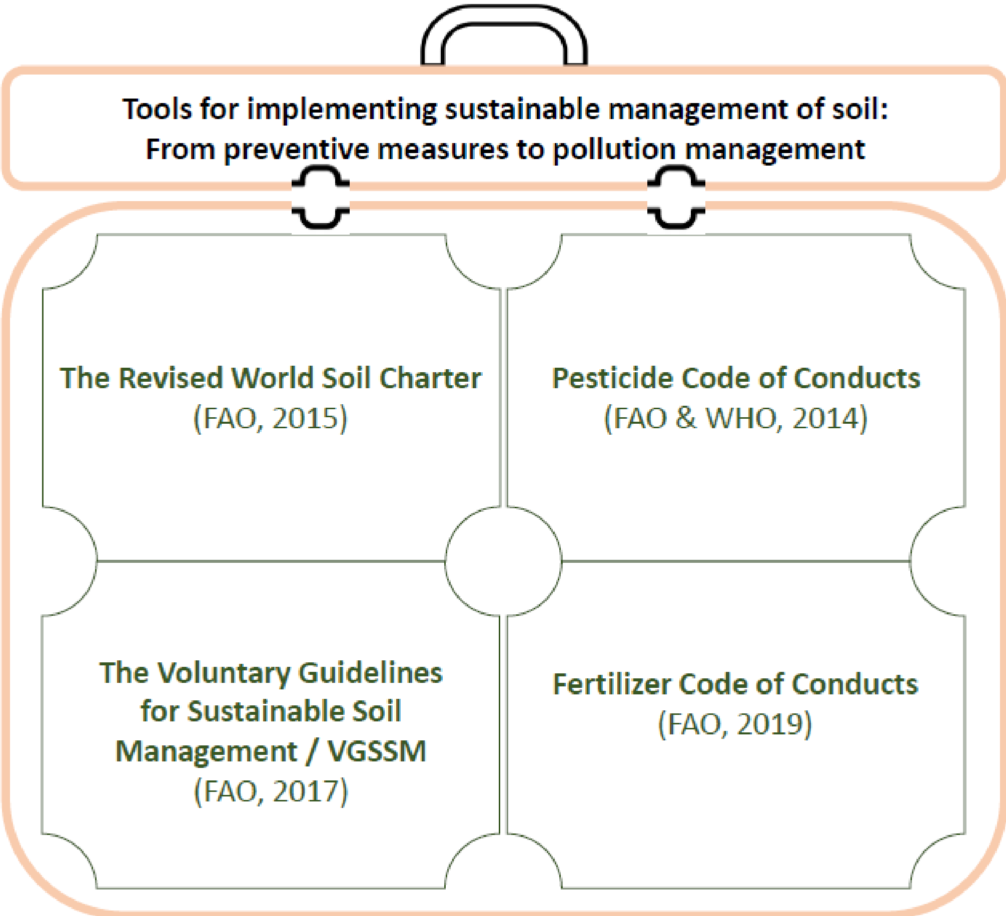

Figure 5 Managing soil sustainably

A standard methods" catalogue for collecting and analyzing contaminants is available with the ISO Technical Committee 190 (Soil Quality). It also offers toolkit for the design and implementation of soil sampling of contaminated sites (ISO, 2024).

The 'Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal' was adopted in 1989, and entered into force in 1992. The Basel Convention work towards reducing the generation and movement of hazardous wastes, except for the wastes deemed to be safe in environmental management practices, and that such waste management practices protect human health and *the environment from any adverse impact* which may arise from such wastes (UNEP, 1989; Basel Convention, 2011). The Basel Protocol on Liability and Compensation establishes financial responsibility for incidents during transboundary movement until its final disposal or spillages, if any. The Basel Protocol also aims to put a check on illegal dumping or accidental spillage, and to put in place a comprehensive framework liability and financial compensation for damage (Basel Convention, 2011).

In 1994, the Basel Convention Ban Amendment was proposed, it was aimed at strengthening the prohibition on export of hazardous waste to the Least Developed Countries LDCs that have low level of economic and human development. Thanks to a country-led initiative from Switzerland and Indonesia (Basel Convention, 2019a, 2019b), 98 countries ratified this amendment as of December 2019.

In 1998, the Rotterdam Convention on Prior Informed Consent for Hazardous Chemicals and Pesticides in International Trade was adopted and entered into force in 2004. The Rotterdam Convention obliges 164 countries exchange information on chemical characteristics and also by better export import regulations at national level (Rotterdam Convention, 2010), and thereby the convention works towards promoting shared responsibility and cooperative efforts between or among or Parties in international trade of specific hazardous chemicals, including pesticides and industrial chemicals.

In May 2001, the Stockholm Convention on Persistent Organic Pollutants (POPs) was adopted. The Stockholm Convention entered into force in 2004. The Stockholm Convention is ratified by the record 184 Parties, and tops the list among all the multilateral environmental agreements or international treaties addressing hazardous waste and chemicals management, (Stockholm Convention, 2021, UNDP website, 2024). The Convention aims at prohibiting and reducing POPs release, and works towards restricting POPs in various products, owing to their particularly serious health and environmental properties.

The Stockholm Convention categorized chemicals in three annexes. Annex A covers list of chemicals whose production and use must be prohibited by the Parties to the Convention. As of now, there are total 14 pesticides in this list, and the import and export of such pesticides and or chemicals must be legally prohibited by the parties. Annex B lists those two chemicals that signatories are legally constrained to restrict the production as well as the usage. Annex C lists seven chemicals whose unintentional release should be reduced.

But, despite all these international efforts over all these years, it feels like we are not doing enough, and are still on the path of un-sustainable development even though the UN with a set of 17 interconnected SDGs (Figure 6) defined global priorities and aspirations for the year 2030 aiming at a better and sustainable future for all. (UNGA, 2015).

The United Nations Climate Change Conference (COP29) in Baku, Azerbaijan, like its predecessors, focused on furthering the UNFCCC (The UN Framework Convention on Climate Change) and the Paris Agreement. COP29 concluded on 24 November 2024 with an agreement to reduce greenhouse gas emissions drastically, and protect lives and livelihoods from negative impacts further worsening amid climate change. Climate change mitigation topics of limiting the global warming and adapting to the impacts thereof were revisited. In addition to that, COP29 called on developed countries to take a lead in

https://doi.org/10.5194/egusphere-2025-271
Preprint. Discussion started: 17 July 2025
© Author(s) 2025. CC BY 4.0 License.

mobilizing every year $300 billion for developing countries, and thereby involving all in scaling finance up for developing countries to $1.3 trillion per year by 2035.

Figure 6 A set of 17 interconnected SDGs (UNGA, 2015).

UN Secretary-General Antonio Guterres asked for climate justice earnestly to build a prosperous and sustainable future for everyone, and appraised this agreement as a base for building more ambitious mitigation outcome and finance while facing the great climate challenge. (UNFCC, 2024; EC, EU, 2024).

COP16 of the United Nations Convention to Combat Desertification (UNCCD) in Riyadh addressed the urgent global crises of land degradation, drought and desertification. In the 2024 position paper for COP16, the International Union for Conservation of Nature (IUCN) recommended, among other things, increased action for the restoration of agricultural lands for climate and biodiversity benefits (IUCN, 2024).

3.1.2 Contamination as a causal agent of soil degradation and deterioration

Land degradation and quality deterioration or contamination of soil is mostly caused by mining, industries, and urbanisation or urban pollution. For example, the UKs environment secretary warned at the launch of the Sustainable Soils Alliance in 2017 that only 30 to 40 years are left for their countrys soil fertility to completely diminish from the farmlands (SOCI, website 2024). Although there is no single metric to estimate the lifespan of a soil, eventual decline in farmland’s fertility is cause of concern that highlights the importance of need for protection and restoration of the soils that have formed under thousands of years (Evans, D. L. et al 2020).

Irresponsible farming practices like irrigation and erosion - the removal of soil particles by wind and quick water run-offs degrade the agricultural land and negatively impact the soil fertility. And other factors including the use of fertilizers or pesticides while farming, acidification, salt contamination and compaction, and the the fossil fuel burning (Peña, 2022; Gautam, et al., 2023) degrade the quality and or deplete the fertility of soil. While broadening our perspective on land use, we tend to show a prevalent sense of entitlement but lack accountability; we need to narrow down our focus to land degradation and soil pollution. Soil pollution is nothing but a chemical deterioration and degradation. Soil is under constant threat from climate change, hydrogeological cycle, natural landscape change or land use change, loss in biodiversity, and chemical pollution. (Rockström *et al.*, 2009). Human activities for infrastructure development and land use can cause physical degradation of soil, change in physical status and or sealing of soil, for example, compaction by agricultural machinery. Soil contaminants can impact soil organic matter and beneficial soil microorganisms negatively, and change the soil structure increasing soil erosion (Korkina & Vorobeichik, 2018).

Contamination of soil is an environmental problem; co-contamination is even worse due to its complexity. Inorganic and organic contaminants require different mitigation strategies, as they behave differently. Microplastics behave different than heavy metals and organic pollutants. As rightly pointed by Liu et al. (2019), microplastics are contaminants which can further adsorb other contaminants, and also present soil microorganisms with a microhabitat. Soils physical structure can be degraded by contaminants like microplastics, nanomaterials or crude oils. Soil bulk density is increased by crude oils and lowered by microplastics. Hydrophobic contaminants, if accommodated in the soil pore space, block air and water permeability (Klamerus-Iwan *et al.*, 2015; de Souza *et al.*, 2018). In addition to that, soil contaminants reach distant areas by characteristic mode of motion of soil particles in air (saltation movement) and by aerial transport of contaminated soil particles due to wind and erosion. And if one can only recall, in 2004, the US Environmental Protection Agency estimated 294,000 sites requiring clean-up (USEPA, 2004). Chinese Ministry of Environmental Protection (MEP China, 2014) reported that an estimated 16.1% of soil was contaminated in China. In India, a guidance document (CPCB India, 2015) for the assessment and mitigation of contaminants was published by the national program for rehabilitation of polluted sites under the auspices of Ministry of Environment, Forest and Climate Change. The guidance documents methodologies mainly covered process for selection and implementation of preferred remediation options, and the technical guidelines and standards that can be applied.

According to the FAO UNEP report cited earlier, soil is under great pressure globally, and there can be irreparable consequences for ecosystem and human health due to soil contaminants (FAO & UNEP, 2021); Fantke, P. et al., 2012). The report also says, “Greater political, business, and social commitment is needed to seek alternatives to the use of

https://doi.org/10.5194/egusphere-2025-271
Preprint. Discussion started: 17 July 2025
© Author(s) 2025. CC BY 4.0 License.

highly toxic contaminants and to increase investment in (pollution) research, prevention and remediation." (FAO & UNEP, 2021). This shall have a special focus on SDGs including zero hunger, no poverty, livelihood, and concerning SDGs concerning land (soil), air, clean water and sanitation, climate change, biodiversity and ecosystems, etc. Farmers and other societal stakeholders through incentives and legislative frameworks need to adopt to better land management, restoration and mitigation strategies with the help of modern and better knowledge technologies i.e. cost effective agricultural practices more friendly with natural and environmental ecosystems; such practices are essential to delivering sustainable communities. And in response to this growing threat to humanity, research into sustainable agricultural practices has already gained significant momentum

(Piñeiro, et al., 2020; Saikanth, et al, 2023; Shaikh, 2020)

3.2.3 Policy, Business and Sustainable Communities

Environmental policy making and knowledge-based green economy are the most sought after deliverables (UN3P, 2011), and entrepreneurial sustainable development (UN, 2017; Schaltegger, 2018), as we understand it, can be the driving force behind this paradigm shift. Implementation of environmental sustainability in the agriculture sector requires us to perform not only the usual economic analysis but also the quantification of its benefits, this includes the justification for economic prosperity, as in any other industry while keeping in view social wellbeing and equity as well as the environmental protection and resource conservation, as in the Triple Bottom Line for industry (WBCSD, 2024).

The term "ecoefficiency" was coined by the World Business Council for Sustainable Development (WBCSD) in its 1992 publication "Changing Course," (Schmidheiny, WBCSD, 1992); it denoted the sustainable development's business value and pinpointed corporate enterprises' responsibility and culpability for using unsafe materials in their processes or products (Fiskel, & Fiskel, 2001; Rogers, & Roberta, 2001), which by the way needs tools viz. Life Cycle Analysis (LCA), Long term Risk Assessment, and Total Cost Assessment for evaluating the benefits of implementing environmental sustainability in agriculture. One can find the list of impact categories (resources, ecosystem health and human health) addressed in a LCA and learn more from Wiley's renowned reference work *Chemical Technology and the Environment*; an important information can also be found on green chemistry (Figure 7 including its insets a-d) in one of earlier papers. (Kirk-Othmer Chemical Technology & the Environment, 2007; Shaikh, et al., 2018)

The doughnut model of economics is especially handy in public policy making. It is line with the framework for sustainable development; the doughnut model converges core needs of all on the economic activities (the concept of social boundaries) that reside within the planetary means (the concept of planetary boundaries), or flourish in harmony with the planet (Raworth, 2017). In our opinion, it is therefore, a special research front tackling land degradation that impacts agro ecological system productivity and resource sustainability is high on demand; knowledge transfer initiatives towards mitigation and adaptation to climate change while making provisions for ecosystem services of soil should be our topmost priorities with a more planet- and people-centred inclusive growth model over only (what) profits.

https://doi.org/10.5194/egusphere-2025-271
Preprint. Discussion started: 17 July 2025
© Author(s) 2025. CC BY 4.0 License.

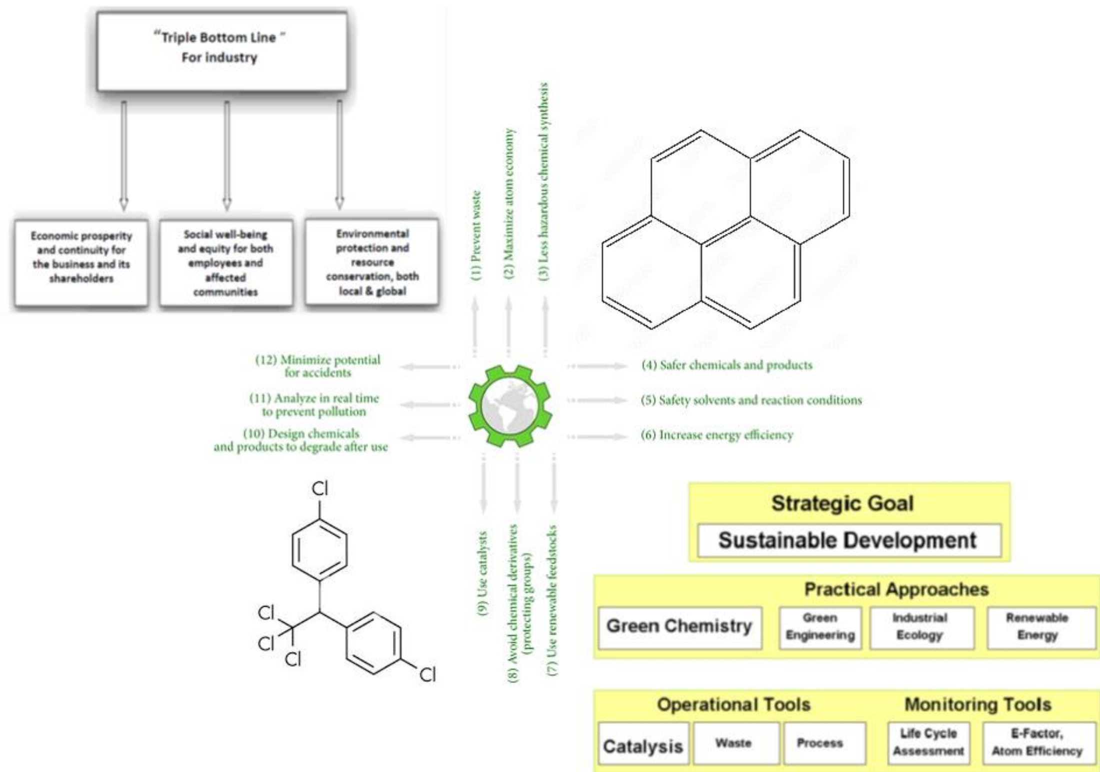

Figure 7 Green chemistry and its 12 principles (Shaikh, 2013, 2014; Anastas, & Waner, 1998). Figure insets: Figure 7 a & 7 b shows the chemical structures of DDT & Pyrene respectively; Figure 7 c Sustainable development from chemistry point of view; Figure 7 d The triple bottom line for industry (WBCSD. 1992).

3.3 Soil Contaminants Origin, causes and status

Anything that poses risks to human health by way of exceeding its naturally-occurring level is considered as a contaminant in soil. But there is no single reason or source of soil pollution; it actually varies by region. Industrial pollution is the culprit in North America and western Europe, whereas in sub-Saharan Africa it is mining. Urban pollution or poor waste disposal is responsible for soil pollution in the northern Africa and near east. Irresponsible farming is the biggest reason behind the soil pollution in Asia, eastern Europe and Latin America (8 FAO UNEP, 2021).

Soil is already a complex mixture of inorganic components, organic matter or materials, water and various microbial life forms, and soil contamination may result naturally from the transfer by rain or from windborne dust. In 2015, when a forest fire broke out in the 30-kilometre exclusion zone or the Chernobyl nuclear power plant zone of alienation, radiocaesium or Cesium -137 radionuclides were transported long distance affecting not only the Russian Federation but also Eastern and

Central Europe, Latvia, Lithuania, Finland, and southeastern Europe or the Balkan Penninsula region (Evangeliou *et al.*, 2016). Water or lipid soluble contaminants of soil, soil contaminants in air, and residual soil contaminants from plant decay, etc. can all be transferred between or among different components like air, water and soil or even plants through partitioning, by dry deposition, wet deposition, etc. Deposition from the atmosphere is one thing, but contaminant sources like direct spraying or mixing of contaminants to soil, including the use of synthetic fertilizers and plant protection agents, sewage sludge application on agricultural lands and pasture, contaminated irrigation waters, etc. are actually internal to soil (Malakar, et al 2019; Iticescu, et al., 2021; Lamastra, et al 2018: Orosun, et al., 2023; EEA, 2024; Goldemund, 2004; Shaikh, et al., 2012).

Let's be honest; even the agrochemical contaminants directly applied to the agricultural soil was not of concern for many people for many years, until serious health effects started propping up. Toxicity of organic and inorganic contaminants have four main mechanisms carcinogenic, neurotoxic, teratogenic, and endocrine disruption. Such contaminants are also found to produce stress proteins by inducing cellular oxidative stress (Landrigan *et al.*, 2018; Stohs & Bagchi, 1995). There is a definite risk to human health due to soil pollution. The role soil plays on human health (Abrahams, 2002; Oliver, 2008) is crucial in achieving SDG number 3: healthy lives and well-being for all.

WHO (2010) has identified and listed Arsenic, Cadmium, Lead, Mercury, Dioxin, Flouride, Benzene, Asbestos, hazardous pesticides and air pollution as ten contaminants of public health concern, and 9 out of 10 are soil contaminants with confirmed adverse impacts on human health.

3.3.1 Soil pollution: Impact and its implications on environment

As noted earlier, anything that poses risks to human health by way of exceeding its naturally-occurring level is considered pollutant, and we know by now that direct spraying of contaminants to the crops and or the agricultural soil is of a greater concern. It is high time we weigh the scientific judgement over commercial considerations and promote better farming and effective waste management (Shaikh, et al., 2012). Pollution prevention is always better than costly and cumbersome cleanups after pollution, and this cannot be far from truth as the long-lasting pollutants in soil cannot be easily quantified. Reasons that require immediate attention among other things are the emergence of pesticide resistance among insect-pests, and the high cost of pesticides not delivering desired results, instead having ecological and environmental repercussions. And research into investigating increased concentrations of potentially toxic elements in soil, crop protection chemical agents causing loss of soil fertility and thereby forcing soil remediation, and the human health risk assessment of various soil contaminants including agrochemicals are rapidly becoming complementary now. And so an increasing number of scholars have therefore started focusing on different types of land use and the identification of the of the effects thereof on pollutant concentrations and in different functional areas; this includes identifying contaminants, sources of contaminants, sampling for soil contamination analysis, further experimenting, and even applying geostatistical methods and studying

https://doi.org/10.5194/egusphere-2025-271
Preprint. Discussion started: 17 July 2025
© Author(s) 2025. CC BY 4.0 License.

pollution processes and their impact, mechanisms, assessment and remediation by way of physico-chemical technologies, phyto-/bioremediation, metabolomics, etc.

Soil fertility can be conserved by implementing environmental sustainability in farming i.e. by minimizing biological, chemical and physical degradation of soil; this shall include (i) enhancing biotic and abiotic resources, (ii) minimizing the disruption of these biotic and abiotic resources, and (iii) minimizing the disruption of and also minimizing the mining of soil nutrient pool, etc. In cases such as these, there is no excuse for the ignorance, but we do need to undertake the chemical and toxicological profiling of such chemical products and their effects, and embark upon environmental sustainability to make natural as well synthetic chemical processes benign (Shaikh, 2014). If we give careful attention and resolve several problems that arise from the present-day agricultural practice, we can reap socio-economic benefits and healthy food from soil.

3.3.2 The green revolution

The technology transfer initiatives taken during the Green Revolution really revolutionized the crop production and secured self-sufficiency in food grains for many nations, but it all came with significant environmental cost.

Agricultural Sector: From Crop Production to Pollution

Over the period 1961 to 2020, the global agricultural sector underwent enormous change, in terms of resource use and the improvements in and optimization of crop production (Vaidyanathan, et al., 2023; Swaminathan, 2009; Ritchie, 2017). The works of American scientist Norman Borlaug and Indian scientist M. S. Swaminathan were exemplary in food security owing to the growth in global population and demand in feeding these people. Some important measures were taken during the 1960s and 1970s; these drastic changes included the use of high yielding seeds, their variety, especially for wheat and rice, and most importantly the application of synthetic fertilizers and insecticides ensuring increased production of food grains and pest-control respectively (Fuglie, et al, 2024). But despite all the achievements of the Green Revolution, the initiatives taken during the Green Revolution met with some harsh criticism by 1990s and the environmentalists, economists, and social scientists began advocating careful adoption of the technology transfer and or new Green Revolution (FAO, 2010 retrieved 2024) aiming at but replenishing soil fertility (Sanchez, et al. 1997) and increased crop agricultural productivity or functional food availability for good health as the global population with its current rate is expected to reach 9.6 billion by 2050 (Tripathi, et al. 2019). So, no matter how much useful agrochemicals are in controlling the weeds or insects, their use comes at a significant environmental repercussion. Nowadays, when the word agrochemical or just chemical is uttered in public, all seem to assume that chemistry applications disregard the environment, and in the public eye, the word chemical is becoming synonymous to contaminant now. But the chemical age has contributed to the well-being of mankind by contributing to pharmaceutical, petrochemical and agrochemical industries; there is no denial to the fact that the global population could meet the overall food demand because of these chemical crop protection agents. Pollution due to agrochemical industries is considered un-avoidable, and a widespread phenomenon now. Almost every component of the environment has been contaminated by pesticides (Brühl, et al. 2024), and such contamination present significant

© Author(s) 2025. CC BY 4.0 License.

risks to off-target vegetation including the beneficial soil microbes, insects, animals, birds, fish, and the environment. And it's not always easy to fully evaluate or comprehend the short-term and long-term risks to the human health. Acidification of agricultural soil is caused by indiscriminate use of inorganic (nitrogen) fertilizers (Cachada et al., 2018), and carbon sequestration is adversely impacted due to land use changes (Duarte-Guardiaet et al., 2019). Moreover, contaminants like plastics, pharmaceuticals and anti-microbials leading to drug-resistant bacteria are emerging, meaning soil contaminants are expected to increase further. There are health consequences of exposure to trace elements, but other inorganic contaminants although less of a concern should be studied for their toxicity, too. So be it fertilizer or pesticide, a little can do good to the production of grains, but a lot can deteriorate the quality or fertility of soil and damage human health.

4 DISCUSSIONS

The results point to observations and findings, and highlight the process and technical or scientific contributions to knowledge or technical research on soil degradation and remediation. There is a strong correlation between progress in research enterprise and the global discourse on environment for progressing with holistic approach towards sustainable development.

4.1 Pesticide – Crop protection agent with environmental repercussions

Pesticide, derived from the Latin words pestis (plague) and caedere (kill), is a chemical or biological agent used to protect plants from insects or fungi and weeds. Sulphur, arsenic, and nicotine were among the "first-generation" pesticides sprayed on crops, but owing to their ineffectiveness and toxicity were gradually replaced with the "second-generation" synthetic pesticides after the World War II; the examples of affordable insecticides among other things were organochlorines like dichloro-diphenyl-trichloroethane (DDT), dieldrin, and organophosphates and phenoxy acids (Handford, et al., 2015).

As said earlier, pesticides are inherently xenobiotic in nature, and pesticides remain as exorbitant deposition in soils causing harmful effects on the composition, abundance and proliferation of rhizosphere microbiome (Magdoff & Van, 2021). Unmethodical or haphazard usage of synthetic pesticides cause their exorbitant depositions, and consequent accumulation in soil adversely affecting the abundance, diversity, composition, and functions of beneficial Rhizosphere microorganisms. In other words, pesticide kills pests and insects, but it also has ecological repercussions. (Jeyaseelan, et al. 2024).
Pesticide contaminated soil disrupts the detoxifying role microbiomes play; pesticides can harmfully affect or kill symbionts by destructing ultra-structures, morphology, cellular permeability, and even the protein profiles of the microbes.

Generally speaking, pesticides are not soluble in water and are non-biodegradable. When applied in excess, pesticides form exorbitant deposits, and consequent accumulate in soil inhibiting the nitrogen fixation process by altering molecular level interaction between plants and soil microbiome, e.g. rhizosphere Bacteroidetes, Proteo-bacteria, and other Copiotrophs (Ling, et al 2022); excessive usage of pesticides has adverse effects on further biotransformation of beneficial

https://doi.org/10.5194/egusphere-2025-271
Preprint. Discussion started: 17 July 2025
© Author(s) 2025. CC BY 4.0 License.

microorganisms in soil and biochemical reactions, viz. mineralization of organic matter, nitrification, de-nitrification, ammonification, etc. And substantially less water-soluble DDT (dichlorodiphenyltrichloroethane), HCH (hexa-chlorocyclohexane), aldrin, chlordane, dieldrin, endrin, endosulfan, heptachlor, lindane can chemically bound to the soil particles (Syafrudin et al., 2021).

PAHs, already listed in the Stockholm Convention, are continuously and unintentionally emitted globally as by-products of fossil fuel use or refineries, smoke-stack industries, and also the biomass burning.

Depending on the type or class, concentration, and the environmental factors, herbicides can disrupt benign microbial interactions, herbicides can e.g. inhibit Mycorrhizal fungi, reduce enzyme activities, and taper the mineralization of nitrogen (Ikioukenigha, et al., 2024; Sarker, et al., 2024).

Although perceived obstacular in securing agri-food sustainably (Aktar, et al., 2009), the application of chemical pesticides in the farm fields is still considered indispensable for optimized and increased crop-production in meeting the needs of growing population and in controlling pests and various communicable diseases in most parts of the planet. And over the last decade, an increase of 20% in volume was observed in pesticide use globally, and a whopping 153% increase was witnessed by the coutries with low-income economies. (Shattuck, et al 2023).

So, the best way to start preventing pesticide contamination in soil for farmers is to prefer safer and possibly non-chemical weed control and insect killing alternatives. What we need is an in-depth science based understanding of the soil quality, knowledge of local weather conditions, and the locality along with suitable recommendations on organic inputs, integrated pest control strategies, enhancing beneficial plant-microbe interactions, harvest or post-harvest strategies, breeding, crop rotation with legumes, and or the use of improved germplasm, etc. And soil health can be restored by Genetically modified organisms (GMOs) capable of catalyzing pesticide degradation process and thereby neutralizing or removing the xenobiotic effects of pesticides in soil.(Rebello, et al 2021).

4.2 Remediation Importance of physicochemical and microbial studies for environmental sustainability

Physicochemical and microbiological studies of soil are essential to remediation Shaikh et al 2012. Trace elements are immobilized to reduce their bioavailability (Adriano, et al., 1999), to prohibit a chemical/substance from crossing an organism's cellular membrane (Semple et al., 2004, Klaassen et al., 2013)

Microorganisms cannot degrade trace elements, but convert them to less hazardous forms i.e. possessing less hazardous physical and chemical properties. Highly mobile and toxic chromium in its hexavalent state can be reduced to its less mobile and less toxic trivalent state by anaerobic microorganisms. (Sumikura and Shiiba, 2016; Thatoi *et al.*, 2014). Soils are generally wetted and also added with organic and inorganic amendments to exclude oxygen and thereby stimulate the anaerobic microorganisms. Explosives RDX and HMX can also be effectively treated anaerobically. And in case of contaminants such as chlorinated organic compounds, reductive dechlorination of these compounds are carried out by adding electron donors to the

https://doi.org/10.5194/egusphere-2025-271
Preprint. Discussion started: 17 July 2025
© Author(s) 2025. CC BY 4.0 License.

contaminated soil. Researchers (Dalgren, *et al.*, 2009; Garcia, et al. 2013) suggested that biodegradation can be enhanced by combining phytoremediation and microbial remediation strategies. And, there are many more chemical and thermal treatments available for complete destruction of soil contaminants, and or their degradation to less toxic species (Figure 8 & Table 1).

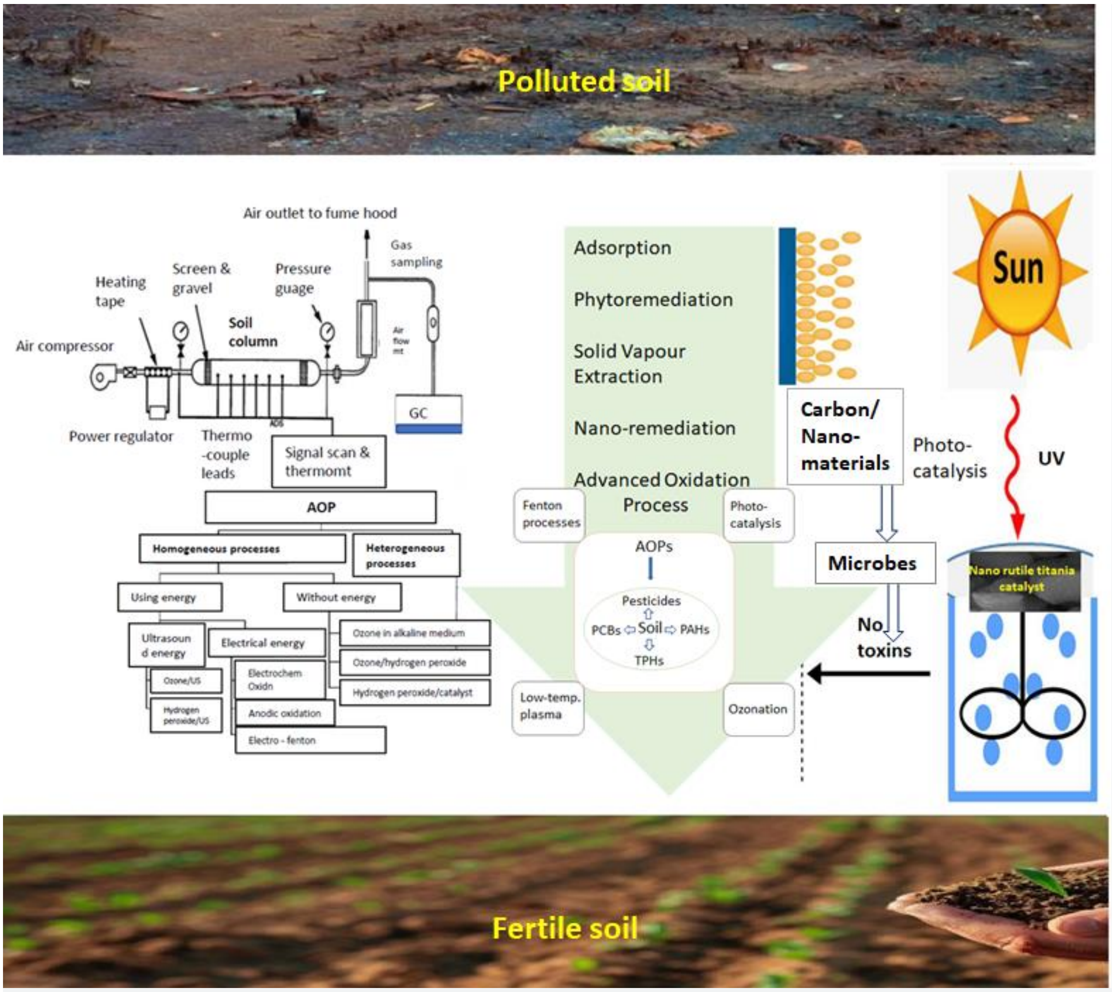

Figure 8 Soil remediation [Disclaimer: Part of this figure, although drawn by the authors include Soil Vapour Extraction from Shah et al., (1995), and credited to them, but the aforementioned part of drawing was found by accessing Evuti, M. et al. (2022) published in book: Research Anthology on Emerging Techniques in Environmental Remediation (pp.236-261). DOI:10.4018/978-1-6684-3714-8.ch012 I, but accessed on Researchgate https://www.researchgate.net/publication/357491320_Application_of_Soil_Washing_Treatment_Method_for_the_Remediation_of_Petroleum_Polluted_Soil].

https://doi.org/10.5194/egusphere-2025-271
Preprint. Discussion started: 17 July 2025
© Author(s) 2025. CC BY 4.0 License.

Table 1. Soil contaminants and methods of treatment. Pollutant destruction and or 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 solification, stabiliation, liming, etc. (Sante, M.Di. 2020, Hu, Y. et al., 2024, CLU/IN, 2024)
Radionuclides Serious consequences upon human exposure to radionuclides	Mainly stabilization and excavation Remediation by electro-kinesis (Ammar, A. et al., 2025)
Highly soluble, mobile and phytotoxic inorganic salts	**Chemical** Leaching; application of $CaSO_4 2H_2O$
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 ^{o}C
Dieldrin, endrin, DDT and lindan	**Bioremediation** Iron reducing bacteria for the soil remediation with Chlorinated organic compounds (Zhong, H. et al., 20224)
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

https://doi.org/10.5194/egusphere-2025-271
Preprint. Discussion started: 17 July 2025
© Author(s) 2025. CC BY 4.0 License.

Bioremediation is an effective, economical, and environmentally benign biological therapy for soil ecosystem, wherein microbes, algae, and plants are put to good use for removing and or minimizing severity of soil contaminants present in the ecosystem (Saxena & Bharagava, 2020; Kuppusamy et al., 2020). Increased investments are expected in pests and insect control technologies by employing such microbial, plant-incorporated protectants, and biochemical pesticides originating from Nature. (Duarte, et al., 2018) rather than taking time out and reduce our exposure.

Omics tools: Although no single omics method can provide enough data, omics methods such as bioinformatics, genomics, metabolomics, proteomics, and transcriptomics can produce data relating to the genes and proteins involved in pesticide degradation pathway (Rodríguez et al., 2020; Gangola et al., 2022; Raj, et al., 2023, Kumar, et al. 2024).

Biotechnological advances can improve pest control by using gene editing, gene transformation, marker-assisted selection, omics, RNA interference, etc.

Pesticide remediation is a complex issue specific to pesticide- and climate-factors and redox, catalysis, and hydrolysis are key reported pesticide remediation strategies. (Sarker, 2023)

Irresponsible agricultural practices can lead to pesticide residues persisting in the food chain (Damalas & Eleftherohorinos, 2011). The European Union has already banned around 850 pesticide-active ingredients (Landrigan et al., 2018; Pappas & Foos, 2023). Countries like China, USA, and Brazil still top the list of the world's top three pesticide users based on the frequency of application, and that amounts to over 70% of all the global pesticide use. (Zhang, et al 2022, Tang et al., 2022). Sustainable or good agricultural practice requires use of crop protection agents posing no threat to off-target vegetation. And identifying and filling-up of holes in our knowledge on diversified life cycle studies starting from pesticide residue monitoring, pesticide-specific safety recommendations, transport and secured disposal, and potential risks to benign biota and transformed metabolites, if any are vital (Sarker, et al., 2024).

Multi-dimensional chemical and biological degradation methods and especially the prospects of synthetic biology in degrading pesticide residues are of great interest (Ruomeng, et al 2023). Substantial reduction in use of pesticide has become a complex issue because most of the agriculture-based food sector relies heavily on pesticide use, despite phasing pesticide out from the farm field applications has become a common goal for the EU nations. (Jacquet, et al., 2022). As per the official records, 370 million kilograms of pesticides had been sold in the EU in 2018. (Eurostat 2020/a). And as the European Green Deal strategy goes, soil plays a crucial role in achieving the ambitious target of a climate neutral EU by year 2050. (EC, 2020; EC, 2017; FAO, 2022). The research enterprise e.g. Jacquet, F. et al. (2022) highlights the need to adapt to a pesticide-free agriculture or navigating paradigm shift, and outlines five conjointly undertaken strategies which shall have a deep impact on pesticide use (Figure 9). Here, by *research enterprise* we mean research projects conducted by academicians aimed at generating evidence of impact for informing decision-making in agricultural sustainability.

https://doi.org/10.5194/egusphere-2025-271
Preprint. Discussion started: 17 July 2025
© Author(s) 2025. CC BY 4.0 License.

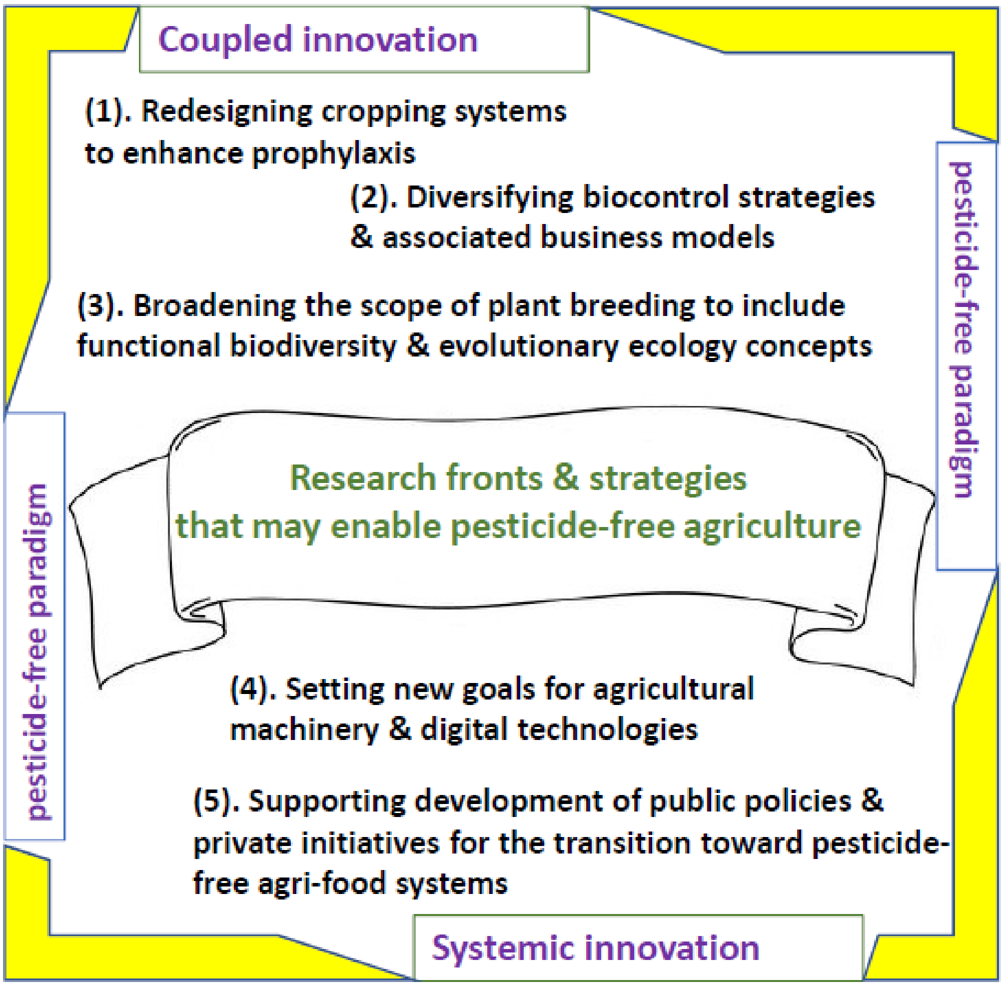

Figure 9 Five research fronts for pesticide-free-paradigm: Five Systematic and coupled innovation (Jacquet, et al. 2022)

545 Off late, cost-effective, efficient and advanced technology driven soil washing projects are being taken up to respect stringent environmental regulations. (Wilson, and Conway, 2024). Many remediation case studies were conducted in the past (CLU-IN, 2024). We present herein a collection of case studies of site monitoting and or remediation applications, these studies were undertaken in different countries with different motives, but what is interesting to notice is the the results and lessons learned from applications in soil remediation of polluted sites, and even in real farm field setting. Most of them help us establish benchmark data on technology advancement, cost effectiveness, and the overall performance leading us to believe in futurustic sustainable agricultural practices.

https://doi.org/10.5194/egusphere-2025-271
Preprint. Discussion started: 17 July 2025
© Author(s) 2025. CC BY 4.0 License.

4.3 CASE STUDIES

Case Study 1 *The Vemmenhög Project, Sweden*

Indiscriminate use of pesticides in agriculture contaminated water bodies of Vemmenhög in Sweden during the mid-1980's. And so the Vemmenhög Project was launched in 1990 after monitoring studies on aquatic environments within the Vemmenhög agricultural catchment revealed pesticide contamination (Kreuger & Brink, 1988). This project based on research started investigating sources of pesticides, pathways and occurrence thereof in water streams within the catchment area, and continued over almost the entire decade of 1990. A 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 change to better agricultural practices, and as a result the average pesticide concentrations dropped by more than 90%. The Vemmenhög catchment area saw a drastic reduction in transport of pesticides to surface waters. (EEA, EU, 2024) This project is a good example of *research enterprise* influencing practitioners (farmers) by generating evidence of impact for informing decision-making in agricultural sustainability.

Case Study 2. *Remediation of dichloro-diphenyl-trichloroethane (DDT) and hexachlorocyclohexane (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. DDT and HCH were made to partially volatilize by passing hot gases (300 ºC to 350 ºC) through that unit, and then they were combusted in the pre-calciner. Contaminated soils with DDT concentrations 243 mg/kg to 429 mg/kg and HCH concentrations 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 (1 000 ºC). Such soil is then 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.

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

The Caffaro company had a chemical manufacturing unit or site in Brescia, Italy since 1906. The company manufactured polychlorinated biphenyls (PCB) during the period of 1938 1984. PCB is listed under Annex A as a persistent organic pollutant. This polluted site in Brescia, Italy is no longer is use, but Teseco undertook an important project and demonstrated effective remediation of the soil there by using spent mushroom substrate. Biopile piolot plant treated ten tonnes of polluted soil, and the decontamination capacity was verified, and after the public health intervention, a substantial decline of PCBs serum levels was observed (Magoni, et al. 2016).

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

The vadose and saturated soil layers in northern Italy had been polluted due to the leakage of tetrachloromethane (CCl_4), chloroform (CCl_3), hexavalent chromium, and perchloroethene (PCE) and trichloroethene (TCE) from an underground storage at a chemical manufacturing site there. $CHCl_3$ and CCl_4 were found in high concentrations in the saturated zone during an initial risk assessment and conceptual site model, while $CHCl_3$ was in high concentrations in the vadose zone. As remediation strategies, hydraulic containment barrier using pump and treat technique and soil vapour extraction (for chloroform) was carried out in for the saturated zone and the vadose zone respectively. After a year into its operation in 2017, the in-situ remediation project successfully decreased the concentrations of contaminants in the polluted soil zones.

We should revalue resource use, production pattern and make it safe and environmental friendly; we should adopt to circular economy, entrepreneurial sustainable development, and above all, we should include risk assessment prior to the pest management, waste treatment, and inculcate environmental sustainability in agricultural practices with the help of research enterprise. In order for us to address soil pollution, what is necessary is the implementation of tools such as Life Cycle Assessment, the Triple Bottom Line, Doughnut Model and relevant policy commitments such as the Basel and most importantly the tools like the International Code of Conduct for the Sustainable Use and Management of Fertilizers (Fertilizer Code) and the Voluntary Guidelines for Sustainable Soil Management (VGSSM).

5 FUTURE SCOPE

There is always a risk in predicting the future of any research enterprise, but organic modifications to soil, application of biopesticides, periodic monitoring and model studies as that of ours in assessing phytotoxicity of trace metal concentration and other contaminants, eutrophication analysis for biota or biomass, bioremediation, etc. undoubtedly attract widespread attention. Research into enhancing soil resilience and microbe diversity for nutrient cycling, and the development of efficient degradation or contaminant removal technologies are in demand as well. It would also be good to see the researchers developing nanoremediation techniques be used for their large scale and safe applications in the real farm field setting. It will certainly be satisfying to see tremendous efforts come to fruition upon globalized discourse leading to policy making and actions at local level after having learnt from the research community. And as for the chemical crop protection agents and contamination caused by them, we can say that sustainability can achieved through various practical approaches, operational tools, and monitoring tools of chemistry. Chemistry plays pivotal role in the Life Cycle Assessment (LCA) and resource efficiency. It is therefore necessary to highlight the cross-sectional roles of chemistry and reduce pollution in natural as well as synthetic industrial chemical processes, and that could be they key aspects of sustainable development from chemical perspective (Shaikh, 2013, 2014, 2020). In other words, one cannot help but notice a strong relationship between designing benign industrial ecology with the help of chemistry in this anthropocene era. Implementing environmental sustainability for soil and its ecosystem

https://doi.org/10.5194/egusphere-2025-271
Preprint. Discussion started: 17 July 2025
© Author(s) 2025. CC BY 4.0 License.

services demands further basic to applied research on sustainable and green chemistry, (Anastas & Warner 1998) in identifying contaminants, risk assessment, and analyzing level of soil contamination, developing mitigation strategies, and improved measures and or more practical applications in real farm field setting. Innovation in green chemistry and engineering intertwined with environmental sustainability will be key to transitioning to a pollution free soil and its ecosystem services.

6 CONCLUSIONS

This report does not follow any specific methodological framework for the critical literature review, but successfully screens and synthesizes relevant literature available in the field of relevance and attempts to conceptualize what restoration of contaminated soil is, and subject the theme to two-level analyses facilitating systematic interdependence of restorative mitigation of contaminated soil for ecosystem services, and influences from research enterprise and sustainable development goals. Since there are no standards for assessing sustainability in agriculture practices, implementation of environmental sustainability, research, and encouragement for policy making through active participation of stakeholders at the highest intergovernmental level is considered crucial in transitioning to sustainable agriculture with possibility of real farm field applications. In doing so, the review tries to bring some case studies and many outstanding researches together to show the importance of good agricultural practices while illustrating the significance of soil quality, its properties, functions and or the ecosystem services.

Key findings include: There has been a marked increase in agricultural soil contamination due to agrochemicals and heavy metals. While pesticide was was encouraged during and post-green revolution as a way of providing fertilizaers and using chemicals as crop protection agents, the indiscriminate usage continues to adversely affect soil, quality and agricultural productivity. The attitude towards looking at resource use has changed, as the menace compounded with climate change has transboundary effects on soil pollution. The soil microbes are at risk causing disruptions to ecosystem services, including problems with nutrient cycling or nitrogen fixation. The soil pollution subjects to socio-ecological system at risk, and thereby mocking the global sustainable development goals.

Soil pollution or contamination with agrochemicals is a serious issue, and remedial actions need to be taken towards enhancing soil resilience while moving towards sustainable consumption and production patterns, for a well-functioning socio-ecological system. This report demonstrates extremely thorough secondary research and describes critically its characteristics to conceptual innovation and analysis that results in cross-sectional role that current science plays, in particular that of the green chemistry and environmental sustainability in conceptualizing the theme of soil restorative mitigation, and thereby reflecting upon degradation of soil quality, soil functions, and remediation of polluted soil with a special focus on pesticide contamination, impact, mechanism and implications thereof on ecosystem services, along with some exemplary case studies to show evidence of impact with high standards of scalability and sustainability. Future studies will explore further cross-sectional role of green chemistry on agro-system or agriculture.

Author Contribution

The authors Isak R. Shaikh (I.R.S. – Ph.D. in chemistry) and Dr. Parveen R. Shaikh (P.R.S. – Ph.D. in Environmental Sciences) have been collaborating for many years. Following on from the research backgrounds or experiences, as evident by their earlier publications, they collaborated here in reflecting upon the current state of knowledge in the field of soil contamination, deterioration of its quality, implications for ecosystem services, and the mitigation of contaminated soil for its restoration. I.R.S. conceived of the presented idea, shaped it from the scientific literature from the unique research enterprise and SDGs point of views, contributed with his unique insights into the subject of immense importance, and finally wrote the manuscript with some inputs from P.R.S. I.R.S. contributed to the origin, design, and implementation of this conceptual analysis and critical review. P.R.S. introduced the current viewpoint on understanding the interconnected nature of environmental components like water and soil. I.R.S. and P.R.S. were able to apply such diversity in perspectives and come up with a more holistic approach in addressing the problem under study; collaboration such as this can harness the creativity of diverse researchers in conceptualizing new thematic areas while addressing pressing challenges of our time.

Competing Interest

The authors declare no conflict of interests.

REFERENCES

Abrahams, P.W.: Soils: Their Implications to Human Health, The Science of the Total Environment, 291, 1-3, 1-32, 2002. doi:10.1016/S0048-9697(01)01102-0

Adriano, D. C., Bollag, J. M., Frankenberger, W. T. Jr., Sims, R.C. : Bioremediation of Contaminated Soils. Madison, WI: American Society of Agronomy, 1999.

Aktar, M. W., Sengupta, D, Chowdhury, A. : Impact of pesticides use in agriculture: their benefits and hazards. Interdiscip Toxicol. 2(1), 1-12, 2009. doi: 10.2478/v10102-009-0001-7. PMID: 21217838; PMCID: PMC2984095.

Alloway, B. J. : Heavy Metals in Soils, Blackie Academic and Professional, Chapman and Hall, London, 368, 1995. https://doi.org/10.1007/978-94-011-1344-1.

Ammar, A., Nouira, A., El Mouridi, Z., Boughribil, S. : Recent trends in the phytoremediation of radionuclide contamination of soil by cesium and strontium: Sources, mechanisms and methods: A comprehensive review, Chemosphere, 359, 142273, 2024. https://doi.org/10.1016/j.chemosphere.2024.142273.

Anastas, P. T. & Warner, J. C. : Green Chemistry: Theory and Practice, Oxford University Press, New York, USA, 1998.

Aravind, J., Murugesan, K., Thayanithi, S., Palanisamy, S.B. : A review of the impact of herbicides and insecticides on the microbial communities, Environmental Research, 245, 118020, 2024. https://doi.org/10.1016/j.envres.2023.118020.

Basel Convention: 2011. https://www.unep.org/resources/report/basel-convention-control-transboundary-movements-hazardous-wastes.

Basel Convention: 2019a. The Basel Convention Ban Amendment [online]. [Cited 3 January2020]. http://www.basel.int/Implementation/LegalMatters/BanAmendment/Overview/tabid/1484/Default.aspx.

Basel Convention: 2019b. Ratification of the Basel Convention Ban Amendment [online]. http://www.basel.int/Countries/StatusofRatifications/BanAmendment/tabid/1344/Default.aspx.

Biswas, B., Qi, F., Biswas, K. J., Wijayawardena, A., Khan, A. M. & Naidu, R. : The Fate of Chemical Pollutants with Soil Properties and Processes in the Climate Change Paradigm—A Review. Soil Systems, 2(3), 2018. https://doi.org/10.3390/soilsystems2030051.

Brühl, C. A., Engelhard, N., Bakanov, N. et al.: Widespread contamination of soils and vegetation with current use pesticide residues along altitudinal gradients in a European Alpine valley. Commun Earth Environ 5, 72. https://doi.org/10.1038/s43247-024-01220-1

Brundtland Commission: Our Common Future: Report of the World Commission on Environment and Development, United Nations' Commission (headed by Ms. Brundtland, the then Prime Minister of Norway) on Environment and Development, Published as Annex to General Assembly document A/42/427, Development and International Co-operation: Environment, 1987.

Bünemann, E. .K. Bongiorno, G., Bai, Z., Creamer, R. E., De Deyn, G., de Goede, R., Fleskens, L., Geissen, V., Kuyper, T.W., Mäder, P., Pulleman, M., Sukkel, W., van Groenigen, J.W. & Brussaard, L.: Soil quality – A critical review. Soil Biology and Biochemistry, 120: 105–125, 2018. https://doi.org/10.1016/j.soilbio.2018.01.030.

Cachada Anabela, Teresa Rocha-Santos, Armando C. Duarte: Soil and Pollution: An Introduction to the Main Issues, Soil Pollution, Academic Press, Pages 1-28, 2018. ISBN 9780128498736, https://doi.org/10.1016/B978-0-12-849873-6.00001-7.

(CLU-IN Website: CLU-UP, The Contaminated Site Clean-Up Information (CLU-IN Website, 2024. https://clu-in.org/download/frtr/epa542r04012.pdf

(CLU-IN Website: 2024. https://clu-in.org/download/techfocus/stabilization/s-s-manual-of-practice.pdf

CPCB India: 2015. https://cpcb.nic.in/uploads/hwmd/MoEFCC_guidelines_contaminatedsites.pdf

Dai, S., Ma, Y., Zhang, K. : Land Degradation Caused by Construction Activity: Investigation, Cause and Control Measures. Int J Environ Res Public Health., 19 (23), 16046, 2022. doi: 10.3390/ijerph192316046. PMID: 36498121; PMCID: PMC9738706.

https://doi.org/10.5194/egusphere-2025-271
Preprint. Discussion started: 17 July 2025
© Author(s) 2025. CC BY 4.0 License.

Daily, G. C., Matson, P. A. & Vitousek, P. M.: Ecosystem services supplied by soil. Nature Services: societal dependence on natural ecosystem, 113–132, 1997.

Damalas, C. A., Eleftherohorinos I. G.: Pesticide exposure, safety issues, and risk assessment indicators. Int J Environ Res Public Health. 8(5), 1402-19, 2011. doi: 10.3390/ijerph8051402. Epub 2011 May 6. PMID: 21655127; PMCID: PMC3108117.

Donato, M.M.F., Magoni,Michele Francesco Donato, Fabrizio Speziani, Lucia Leonardi, Grazia Orizio, Carmelo Scarcella, Alice Gaia, Pietro Apostoli, : Substantial decline of polychlorinated biphenyls serum levels 10years after public health interventions in a population living near a contaminated site in Northern Italy, Environment International, 95, 69-78, 2016. https://doi.org/10.1016/j.envint.2016.07.021.

Duarte, A. C., Cachada, A. & Rocha-Santos, T., eds. : Soil pollution: from monitoring to remediation. London, United Kingdom, Academic Press, an imprint of Elsevier. 296, 2018.

Duarte-Guardia, S., Peri, P. L., Borchard, N. et al. : Soils need to be considered when assessing the impacts of land-use change on carbon sequestration. Nat Ecol E, 3, 1642, 2019. https://doi.org/10.1038/s41559-019-1026-8

EC, European Union, website: 2024. https://ec.europa.eu/newsroom/jrcispra/items/846383/en

EEA, EU publication: retrieved 2024. https://www.eea.europa.eu/publications/how-pesticides-impact-human-health/project-vemmenhog-helping-farmers-reduce

EEA, EU Website: 2024. https://www.eea.europa.eu/en/european-zero-pollution-dashboards/indicators/long-term-impacts-of-sludge-spreading-on-agricultural-land

Elgh-Dalgren, K.: 2009. Remediation of materials with mixed contaminants : treatability, technology and final disposal (PhD dissertation, Örebro universitet). Retrieved from https://urn.kb.se/resolve?urn=urn:nbn:se:oru:diva-7993

Eurostat: 2020a. Sales of pesticides in the EU. 2024. https://ec.europa.eu/eurostat/web/products-eurostat-news/w/ddn-20240517-1.

EC: 2024 EU website https://ec.europa.eu/eurostat/web/products-eurostat-news/-/ddn-20200603-1

European Commission: 2020. Farm to fork strategy. European Commission, Brussels.

European Commission: Integrated Pest Management (IPM).
In: Sustainable use of pesticides, 2017. https:// ec. europa. eu/ food/ plant/
pesti cides/ susta inable_ use_ pesti cides/ ipm_ en.

Evangeliou, N., Balkanski, Y., Cozic, A., Hao, W. M., Møller A. P.: Wildfires in Chernobyl-contaminated forests and risks to the population and the environment: a new nuclear disaster about to happen? Environ Int., 73, 346-58, 2014. doi: 10.1016/j.envint.2014.08.012.

Evans, D. L., Quinton, J. N., Davies, J. A. C., Zhao, J., & Govers, G.: Soil lifespans and how they can be extended by land use and management change. Environmental Research Letters, 15 (9), 0940b2, 2020.

Fantke P., Friedrich R., Jolliet O.: Health impact and damage cost assessment of pesticides in Europe. Environ Int 49:9–17, 2012. https://doi.org/10.1016/j.envint.2012.08.001

FAO & ITPS: Status of the world's soil resources (SWSR): Main Report. Rome, Food and Agriculture Organization of the United Nations and Intergovernmental Technical Panel on Soils, 2015.

FAO: Status of the World's Soil Resources Report, Rome, 2018. ISBN 978-92-5-109004-6. https://openknowledge.fao.org/server/api/core/bitstreams/81533344-7e7c-473d-96d7-e18de59d6548/content

FAO and UNEP: Global assessment of soil pollution - Summary for policy makers. FAO, Rome, 2021. ISBN 978-92-5-134448-4. https://doi.org/10.4060/cb4827en.

FAO: FAO organized a two day Global seminar on strengthening regulations to protect pollinators from pesticides in the beginning of 2022. 2022. . https://openknowledge.fao.org/server/api/core/bitstreams/1ff7c8cc-61b9-44dd-b4e7-cdf2c5a46d8e/content

FAO: *Soils for nutrition: state of the art*. Rome, 2022.. https://doi.org/10.4060/cc0900en

FAO: Towards a New Green Revolution, Online Resource, Retrieved 03 December 2024. https://www.fao.org/4/x0262e/x0262e06.htm

FAO: Soils for nutrition: state of the art. Rome, 2022. https://doi.org/10.4060/cc0900en

FAO, ITPS, GSBI, SCBD, and EC. State of knowledge of soil biodiversity – Status, challenges and potentialities, Summary for policymakers, FAO, Rome, 2020. https://doi.org/10.4060/cb1929en

FAO.: Voluntary Guidelines for Sustainable Soil Management. Food and Agriculture Organization of the United Nations, 2017.. http://www.fao.org/3/i6874en/I6874EN.pdf

FAO.: 2018a. Be the solution to soil pollution. Outcome document of the Global Symposium on Soil Pollution., p. 32. Rome, 2018a. Food and Agriculture Organization of the United Nations. Available online at http://www.fao.org/3/ca0362en/CA0362EN.pdf

FAO: Proceedings of the Global Symposium on Soil Pollution 2018. Rome, Italy, Food and Agriculture Organization of the United Nations. 977, 2018b. Available online at http://www.fao.org/3/CA1087EN/ca1087en.pdf.

FAO.: The International Code of Conduct for the Sustainable Use and Management of Fertilizers. Food and Agriculture Organization of the United Nations, 2019. http://www.fao.org/3/mz476en/mz476en.pdf

Fisher, B. & Kerry Turner, R.: Ecosystem services: Classification for valuation. Biological Conservation, 141(5), 1167–1169, 2008. https://doi.org/10.1016/j.biocon.2008.02.019.

Fiskel J., D. G Fiskel: From Here to Sustainability: A Global Perspective on Sustainable Development, Chemistry Business, 2001.

Fred. M. and Harold, van Es: Building soils for better crops: ecological management for healthy soils | Sustainable Agriculture Network handbook series; bk. 10., Fourth edition. Sustainable Agriculture Research & Education (SARE), published by SARE supported by the National Institute of Food and Agriculture (NIFA), U.S. Department of Agriculture under award number 2019-38640-29881 -- t.p. verso. Identifiers: LCCN 2021018006 | ISBN 9781888626193 (paperback), University of Maryland Printing Services, USA, 2021.

Fuglie, K., Morgan, S., & Jelliffe, J.: World agricultural production, resource use, and productivity, 1961–2020 (Report No. EIB-268). U.S. Department of Agriculture, Economic Research Service, 2024. https://doi.org/10.32747/2024.8327789.ers https://www.ers.usda.gov/amber-waves/2024/september/global-changes-in-agricultural-production-productivity-and-resource-use-over-six-decades/

Gangola, S., Joshi, S., Bhandari, G., Pant, G., Sharma, A., Perveen, K., Bukhari, N. A., Rani, R.: Exploring microbial diversity responses in agricultural fields: a comparative analysis under pesticide stress and non-stress conditions. Front Microbiol.;14:1271129, 2023. doi: 10.3389/fmicb.2023.1271129.

Garcia, J.A.L., Grijalbo, L., Ramos, B., Fernández-Piñas, F., Rodea-Palomares, I., Gutierrez-Mañero, F.J.: Combined phytoremediation of metal-working fluids with maize plants inoculated with different microorganisms and toxicity assessment of the phytoremediated waste, Chemosphere, 90(11), 2654-2661, 2013. https://doi.org/10.1016/j.chemosphere.2012.11.042.

Gautam, K., Sharma, P., Dwivedi, S., Singh, A., Gaur, V. K., Varjani, S., et al.: A review on control and abatement of soil pollution by heavy metals: Emphasis on artificial intelligence in recovery of contaminated soil. Environ. Res., 115592, 115592, 2023. doi:10.1016/j.envres.2023.115592

Gómez-Sagasti, M. T., Alkorta, I., Becerril, J. M. et al.: Microbial Monitoring of the Recovery of Soil Quality During Heavy Metal Phytoremediation. Water Air Soil Pollut , 223, 3249–3262, 2012. https://doi.org/10.1007/s11270-012-1106-8.

Goldemund, H.: Soil Development and Properties, Soil Contamination and Amelioration, Editor(s): Jeffery Burley, Encyclopedia of Forest Sciences, Elsevier, 1241-1247, 2004. ISBN 9780121451608, https://doi.org/10.1016/B0-12-145160-7/00244-1.

© Author(s) 2025. CC BY 4.0 License.

Haines-Young, R. & Potschin, M.: Common International Classification of Ecosystem Services (CICES) V5.1. Guidance on the Application of the Revised Structure., 53, 2018. Nottingham, UK, Fabis Consulting Ltd. (Available online at https://cices.eu/).

Handford, C. E., Elliott, C. T., Campbell, K.: A review of the global pesticide legislation and the scale of challenge in reaching the global harmonization of food safety standards. Integr Environ Assess Manag. 11(4), 525-36, 2015. doi: 10.1002/ieam.1635.

Headrick, D. R., Johnson, L. L., & Hirsch, S.W.: The Earth and Its Peoples: A Global History. I. Boston, M. A: Houghton Mifflin, 2008.

Horta, A., B. Malone, U. Stockmann, B. Minasny, T.F.A. Bishop, A.B. McBratney, R. Pallasser, L. Pozza: Potential of integrated field spectroscopy and spatial analysis for enhanced assessment of soil contamination: A prospective review, Geoderma, 241–242, 180-209, 2015. https://doi.org/10.1016/j.geoderma.2014.11.024

Hu, Y., Wang, J., Yang, Y., Li, S., Wu, Q., Nepovimova, E., Zhang, X., Kuca, K.: Revolutionizing soil heavy metal remediation: Cutting-edge innovations in plant disposal technology, Science of The Total Environment, Volume 918, 2024, 170577, 2024. https://doi.org/10.1016/j.scitotenv.2024.170577.

Ikioukenigha, Michael, Abamba, Esther, Chikukula, Abdulmajeed, Dugeri, Dooshima, Ibeneme, Ugochukwu, Olukayode, Oluwaseyi, Okpro, Oghenerabome: Herbicides Effects on Soil Functions: A Review. Asian Soil Research Journal. 8. 34-41, 2024. https://doi.org/10.9734/asrj/2024/v8i4160.

ISO: 2024. https://www.iso.org/committee/54328.html

IUCN: 2024. https://iucn.org/resources/position-paper/iucn-position-paper-unccd-cop16

Jacquet, F., Jeuffroy, M. H., Jouan, J. et al.: Pesticide-free agriculture as a new paradigm for research, Agron. Sustain. Dev. 42, 8, 2022. https://doi.org/10.1007/s13593-021-00742-8

Jeyaseelan, A., Murugesan, K., Thayanithi, S., Palanisamy. S.B.: A review of the impact of herbicides and insecticides on the microbial communities, Environmental Research, 245, 2024, 118020, https://doi.org/10.1016/j.envres.2023.118020.

Jie, C., Jing, Z. C., Man, Z. T., and Zi, T. G.: Soil degradation: A global problem endangering sustainable development. J. Geogr. Scie. 12, 243–252, 2002. doi:10.1007/bf02837480.

Jones, R. J. A., Hiederer, R., Rusco, E. and Montanarella, L: Estimating organic carbon in the soils of Europe for policy support. European Journal of Soil Science, 56: 655-671, 2005. https://doi.org/10.1111/j.1365-2389.2005.00728.

Kenarova, A., Radeva, G., Traykov, I. & Boteva, S.: Community level physiological profiles of bacterial communities inhabiting uranium mining impacted sites. Ecotoxicology and Environmental Safety, 100, 226–232, 2014. https://doi.org/10.1016/j.ecoenv.2013.11.012.

Klaassen, C. D., Casarett, L. J. & Doull, J., eds. : Casarett and Doull's toxicology: the basic science of poisons. 8th ed edition. New York, McGraw-Hill Education. 1454, 2013.

https://doi.org/10.5194/egusphere-2025-271
Preprint. Discussion started: 17 July 2025
© Author(s) 2025. CC BY 4.0 License.

Klamerus-Iwan, A., Błońska, E., Lasota, J., Kalandyk, A. & Waligórski, P.: Influence of Oil Contamination on Physical and Biological Properties of Forest Soil After Chainsaw Use. Water, Air, & Soil Pollution, 226 (11): 389, 2015. https://doi.org/10.1007/s11270-015-2649-2

Köhler, H. R. & Triebskorn, R.: Wildlife Ecotoxicology of Pesticides: Can We Track Effects to the Population Level and Beyond? Science, 341(6147), 759–765, 2013. https://doi.org/10.1126/science.1237591.

Korkina, I. N. & Vorobeichik, E. L.: Humus Index as an indicator of the topsoil response to the impacts of industrial pollution. Applied Soil Ecology, 123, 455–463, 2018. https://doi.org/10.1016/j.apsoil.2017.09.025

Kreuger, J. Brink, N. : Losses of pesticides from agriculture. In: Pesticides: Food and Environmental Implications. IAEA/FAO International Symposium on Changing Perspectives in Agrochemicals, 24-27 Nov. 1987, 101-112, 1988. IAEA: Vienna.

Kreuger, J.: Pesticides in stream water within an agricultural catchment in southern Sweden, 1990-1996. The Science of the Total Environment 216: 227-251, 1998.

Kumar, R., Shanker, R., Singh, P., Yadav, M.K., Chaudhary, V., Kumar, M.: Genome editing towards pests and disease management in agricultural crops: Recent developments, challenges and future prospects, Physiological and Molecular Plant Pathology, 134, 102402, 2024 https://doi.org/10.1016/j.pmpp.2024.102402.

Kuppusamy, K.S., Megharaj, P.T.M., Naidu, R.: Bioremediation potential of natural polyphenol rich green wastes: A review of current research and recommendations for future directions, Environmental Technology & Innovation, 4, 17-28, 2015. https://doi.org/10.1016/j.eti.2015.04.001.

Lamastra, L., Suciu, N.A. & Trevisan, M.: Sewage sludge for sustainable agriculture: contaminants' contents and potential use as fertilizer. Chem. Biol. Technol. Agric. 5, 10, 2018. https://doi.org/10.1186/s40538-018-0122-3

Landrigan, P.J., Fulle, R., Acosta, N.J.R., Adeyi, O., Arnold, R., Basu, N. N., Baldé A.B., Bertollini, R., Bose-O'Reilly, S., Boufford, J. I., Breysse, P. N., Chiles, T., Mahidol C, Coll-Seck A.M., Cropper, M.L., Fobil, J., Fuster, V., Greenstone, M., Haines, A., Hanrahan, D., Hunter, D., Khare, M., Krupnick, A., Lanphear, B., Lohani, B., Martin, K., Mathiasen, K.V., McTeer, M.A., Murray, C.J.L., Ndahimananjara, J.D., Perera, F., Potočnik, J., Preker, A.S., Ramesh, J., Rockström, J., Salinas, C., Samson, L.D., Sandilya, K., Sly, P.D., Smith, K.R., Steiner, A., Stewart, R.B., Suk ,W.A., van Schayck, O.C.P., Yadama, G.N., Yumkella, K., Zhong, M. The Lancet Commission on pollution and health: Lancet. 3, 391(10119):462-512, 2018. doi: 10.1016/S0140-6736(17)32345-0. Erratum in: Lancet. 2018 Feb 3;391(10119):430, 2018. doi: 10.1016/S0140-6736(17)32817-9. PMID: 29056410.

Li, Y., Zhang, J., Miao, W., Wang, H., Wei, M.: Disposal of historically contaminated soil in the cement industry and the evaluation of environmental performance. Chemosphere. 134:279-85, 2015. doi: 10.1016/j.chemosphere.2015.04.048.

Ling, N., Wang, T. and Kuzyakov, Y.: Rhizosphere bacteriome structure and functions. Nat. Commun. 13, 836, 2022. https://doi.org/10.1038/s41467-022-28448-9

Liu Yu-Rong, Marcel, G. A., van der Heijden, Judith Riedo, Carlos Sanz-Lazaro, David, J. Eldridge, Felipe Bastida, Eduardo Moreno-Jiménez, Xin-Quan Zhou, Hang-Wei Hu, Ji-Zheng He, José L. Moreno, Sebastian Abades, Fernando Alfaro, Adebola R. Bamigboye, Miguel Berdugo, José L. Blanco-Pastor, Asunción de los Ríos, Jorge Duran, Tine Grebenc, Javier G. Illán, Thulani P. Makhalanyane, Marco A. Molina-Montenegro, Tina U. Nahberger, Gabriel F. Peñaloza-Bojacá, César Plaza, Ana Rey, Alexandra Rodríguez, Christina Siebe, Alberto L. Teixido, Nuria Casado-Coy, Pankaj Trivedi, Cristian Torres-Díaz, Jay Prakash Verma, Arpan Mukherjee, Xiao-Min Zeng, Ling Wang, Jianyong Wang, Eli Zaady, Xiaobing Zhou, Qiaoyun Huang, Wenfeng Tan, Yong-Guan Zhu, Matthias C. Rillig & Manuel Delgado-Baquerizo: Soil contamination in nearby natural areas mirrors that in urban green spaces worldwide, Nat Commun 14, 1706, 2013 . https://doi.org/10.1038/s41467-023-37428-6

Machado, de S., A.A., Lau, C.W., Till, J., Kloas, W., Lehmann, A., Becker, R. & Rillig, M.C.: Impacts of Microplastics on the Soil Biophysical Environment. Environmental Science & Technology, 52 (17), 9656–9665, 2018. https://doi.org/10.1021/acs.est.8b02212

Magoni, M., Donato, F., Speziani, F., Leonardi, L., Orizio, G., Scarcella, C., Gaia, A., Apostoli, P.: Substantial decline of polychlorinated biphenyls serum levels 10 years after public health interventions in a population living near a contaminated site in Northern Italy, Environment International, Volume 95, 2016, Pages 69-78, 2016. https://doi.org/10.1016/j.envint.2016.07.021.

Malakar, A., Snow, D. D., & Ray, C.: Irrigation Water Quality—A Contemporary Perspective. Water, 11(7), 1482, 2019. https://doi.org/10.3390/w11071482

Meyer, R.S., Cullen, B.R., Whetton, P.H., Robertson, F.A., Eckard, R.J.: Potential impacts of climate change on soil organic carbon and productivity in pastures of south eastern Australia, Agricultural Systems, 167, 34-46, 2018. https://doi.org/10.1016/j.agsy.2018.08.010.

Ministry of Environmental Protection (MEP): National soil contamination survey report. Beijing, China: Ministry of Environmental Protection, 2014. Available online at: http://www.mep.gov.cn/gkml/hbb/qt/201404/t20140417_270670.

Moher D, Liberati A, Tetzlaff J., Altman D.G., PRISMA Group.: Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. Ann Intern Med., 151, 264–9, W 64, 2009. https://doi.org/10.7326/0003-4819-151-4-200908180-00135.

https://doi.org/10.5194/egusphere-2025-271
Preprint. Discussion started: 17 July 2025
© Author(s) 2025. CC BY 4.0 License.

Moher D. Liberati A., Tetzlaff J, Altman, D.G.: PRISMA Group Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. PLoS Med.;6:e1000097, 2019. https://doi.org/10.1371/journal.pmed.1000097.

Montgomery, D. Dirt: The Erosion of Civilizations. Berkeley and Los Angeles, California: University of California Press. Bulliet R.W., Crossley P. K, 2008.

Nelson, E. A.R.L., Ravichandran, K. & Antony, U: The impact of the Green Revolution on indigenous crops of India. *J. Ethn. Food* **6**, 8, 2019. https://doi.org/10.1186/s42779-019-0011-9

Nikitin, E. D.: The role of soils in the life of nature (in Russian), Znanie, Moscow, 47, 1982.

Oliver, M. A.: Soil and human health: a review. European Journal of Soil Science, 48(4), 573–592, 2008. https://doi.org/10.1111/j.1365-2389.1997.tb00558.x

Orosun, M. M., Nwabachili, S., Alshehri, R.F. et al.: Potentially toxic metals in irrigation water, soil, and vegetables and their health risks using Monte Carlo models. Sci Rep. 13, 21220, 2023. https://doi.org/10.1038/s41598-023-48489-4

Page, M. J., McKenzie, J. E., Bossuyt, P. M. et al.: The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. Syst Rev 10, 89, 2021. https://doi.org/10.1186/s13643-021-01626-4.

Pappas, C., Foos, B.: Pesticide data program: 30 years of food residue data and trends. J Expo Sci Environ Epidemiol, 33(5), 805-812, 2023. doi: 10.1038/s41370-022-00482-1.

Parmesan, C.: Ecological and evolutoinary respnses to recent cloimate change. Annual Rev of Ecology Evolution and Systematics, 37, 637-669, 2006.

Pedro, A., Sanchez, Keith, D. Shepherd, Meredith J. Soule, Frank M. Place, Roland J. Buresh, Anne-Marie N. Izac, A. Uzo Mokwunye, Fred R. Kwesiga, Cyrus G. Ndiritu, Paul L. Woomer: Chapter 1: Soil Fertility Replenishment in Africa: An Investment in Natural Resource Capital, Book Editor(s):Roland J. Buresh, Pedro A. Sanchez, Frank Calhoun, 1997. https://doi.org/10.2136/sssaspecpub51.c1

Peña, A.: A comprehensive review of recent research concerning the role of low molecular weight organic acids on the fate of organic pollutants in soil. J. Hazard. Mat., 434, 128875, 2022. doi:10.1016/j.jhazmat.2022.128875

Perk, V. der. M.: Soil and water contamination: from molecular to catchment scale. London: Taylor and Francis, 2006. ISBN 0415409438.

Phillips, M.W.A.: Agrochemical industry development, trends in R&D and the impact of regulation. Pest Manag Sci, 76, 3348-3356, 2020. https://doi.org/10.1002/ps.5728

Piñeiro, V., Arias, J., Dürr, J. et al.: A scoping review on incentives for adoption of sustainable agricultural practices and their outcomes. Nat Sustain 3, 809–820, 2020. https://doi.org/10.1038/s41893-020-00617-y

https://doi.org/10.5194/egusphere-2025-271
Preprint. Discussion started: 17 July 2025
© Author(s) 2025. CC BY 4.0 License.

Potschin-Young, M., Czúcz, B., Liquete, C., Maes, J., Rusch, G. M. & Haines-Young, R.: Intermediate ecosystem services: An empty concept? Ecosystem Services, 27, 124–126, 2017. https://doi.org/10.1016/j.ecoser.2017.09.001.

Raj, A. Dubey, A., Malla, A.A., Kumar, A.: Pesticide pestilence: Global scenario and recent advances in detection and degradation methods, Journal of Environmental Management, 338, 117680, 2023. https://doi.org/10.1016/j.jenvman.2023.117680.

Raworth, K.: A Safe and Just Space for Humanity. Can we live within the doughnut?. Oxfam Discussion Papers, 2012. ISBN: 978-1-78077-059-8, Oxford: Oxfam. Retrieved April 27, 2024 from https://oi-files-d8-prod.s3.eu-west-2.amazonaws.com/s3fs-public/file_attachments/dp-a-safe-and-just-space-for-humanity-130212-en_5.pdf

Ray, R. Weil., Nyle C. Brady: The Nature and Properties of Soils," Fifteenth edition, Pearson Education, 2017. ISBN 9780133254488, LCCN 2016008568 | record available at http://lccn.loc.gov/2016008568.

Rebello, S., Nathan, V. K., Sindhu, R., Binod, P., Awasthi, M. K., & Pandey, A. (2021). Bioengineered microbes for soil health restoration: present status and future. Bioengineered, 12(2), 12839–12853. https://doi.org/10.1080/21655979.2021.2004645

Ritchie Hannah: Yields vs. land use: how the Green Revolution enabled us to feed a growing population, 2017. OurWorldinData.org. Retrieved from: 'https://ourworldindata.org/yields-vs-land-use-how-has-the-world-produced-enough-food-for-a-growing-population' [Online Resource, Retrieved 03 December 2024]

Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, F.S.I., Lambin, E., Lenton, T., Scheffer, M., Folke, C., Schellnhuber, H.J., Nykvist, B., de Wit, C., Hughes, T., van der Leeuw, S., Rodhe, H., Sörlin, S., Snyder, P., Costanza, R., Svedin, U., Falkenmark, M., Karlberg, L., Corell, R., Fabry, V., Hansen, J., Walker, B., Liverman, D., Richardson, K., Crutzen, P. & Foley, J. : Planetary Boundaries: Exploring the Safe Operating Space for Humanity. Ecology and Society, 14(2), 2009. https://doi.org/10.5751/ES-03180-140232

Rodríguez Eugenio, N., McLaughlin, M. J. & Pennock, D.: Soil pollution: a hidden reality. Rome, Italy, Food and Agriculture Organization of the United Nations. 156, 2018.

Rotterdam Convention: Rotterdam Convention, 2010. [Cited 26 December 2019]. http://www.pic.int/TheConvention/Overview/tabid/1044/language/enUS/Default.aspx.

Rotterdam Convention: Information archive of the chemicals recommended for listing in Annex III [Cited 8 June 2020], 2020a. http://www.pic.int/TheConvention/Chemicals/Recommendedforlisting/Informationarchive/tabid/8179/language/en-US/Default.aspx

https://doi.org/10.5194/egusphere-2025-271
Preprint. Discussion started: 17 July 2025
© Author(s) 2025. CC BY 4.0 License.

Rotterdam Convention: Annex III Chemicals [online]. [Cited 8 June 2020], 2020)b. http://www.pic.int/TheConvention/Chemicals/AnnexIIIChemicals/tabid/1132/language/en-US/Default.aspx

Rotterdam Convention: Status of ratifications of the Rotterdam Convention [online]. [Cited 26 January 2020], 2021. http://www.pic.int/Countries/Statusofratifications/tabid/1072/language/en-US/Default.aspx

Rotterdam Convention: Chemicals recommended for listing in Annex III. In: Rotterdam Convention [online]. [Cited 8 June 2020], 2020c. http://www.pic.int/TheConvention/Chemicals/RecommendedtoCOP/tabid/1185/language/en-US/Default.aspx

Saikanth, D. R. K., Supriya, Singh, B.V., Rai, A.V., Bana, S.R., Sachan, D.S., Singh, B.: Advancing Sustainable Agriculture: A Comprehensive Review for Optimizing Food Production and Environmental Conservation, International Journal of Plant & Soil Science, 35 (16):417-25, 2023. https://doi.org/10.9734/ijpss/2023/v35i163169

Sante, M. Di.: Rivista Italiana di Geotecnica 3/2020.

Sarker, A. Al Masud, Md. A., Deepo, D.M., Das, K., Nandi, R., Ansary, M.W.R., Islam, A.R.Md.T.: Biological and green remediation of heavy metal contaminated water and soils: A state-of-the-art review, Chemosphere, 332, 138861, 2023. https://doi.org/10.1016/j.chemosphere.2023.138861.

Sarker, A., Kim, D., & Jeong, W. T.: Environmental Fate and Sustainable Management of Pesticides in Soils: A Critical Review Focusing on Sustainable Agriculture. Sustainability, 16(23), 10741, 2024. https://doi.org/10.3390/su162310741

Sarker, A., Shin, W. S.; Masud, M. A. A., Nandi, R.; Islam, T.: A critical review of sustainable pesticide remediation in contaminated sites: Research challenges and mechanistic insights. Environ. Pollut. 341, 122940, 2024.

Saxena, G. and Bharagava, R.N.: Bioremediation of Industrial waste for environmental safety, 2020. https://link.springer.com/book/10.1007/978-981-13-1891-7

Schmidheiny, S. with the WBCSD: Changing Course, A global business perspective on development and the environment, The MIT Press, 1992.

Semple, K. T., Doick, K. J., Jones, K.C., Burauel, P., Craven, A. & Harms, H.: Defining bioavailability and bioaccessibility of contaminated soil and sediment is complicated. Environmental Science & Technology, 38(12), 228A-231A, 2004. https://pubs.acs.org/doi/pdf/10.1021/es040548w).

Shaikh, Parveen R. et al: Microbiological and Physicochemical Studies of Soil near Bhokar of Maharashtra, International Journal of Applied biology and Pharmaceutical technology, 3 (4), 342-347, 2012.

Shaikh, Isak R. & Shaikh, A.A.: Development of Some Eco-Efficient and Selective Chemical Processes and Products Using Sustainable and Green Chemistry Approaches. Drug Designing & Intellectual Properties International Journal, 2(4), 236-244, 2018.

https://doi.org/10.5194/egusphere-2025-271
Preprint. Discussion started: 17 July 2025
© Author(s) 2025. CC BY 4.0 License.

https://doi.org/10.32474/DDIPIJ.2018.02.000145 https://lupinepublishers.com/drug-designing-journal/fulltext/development-of-some-eco-efficient-and-selective-chemical-processes-and-products.ID.000145.php

Shaikh, Isak R.: Development of Some Ecoefficient and Selective Chemical Processes and Products using Sustainable and Green Chemistry Approaches, Ph.D. thesis, 2014. https://shodhgangotri.inflibnet.ac.in/handle/20.500.14146/26/browse?type=title&sort_by=1&order=ASC&rpp=20&etal=-1&null=&offset=981

Shaikh, Isak R.: Organocatalysis: Key Trends in Green Synthetic Chemistry, Challenges, Scope towards Heterogenization, and Importance from Research and Industrial Point of View, J. Cata., Article ID 402860, 35 pages, 2024,. https://doi.org/10.1155/2014/402860

Shaikh, Isak R.: Chemistry for Energy Conversion and Fossil Free Sustainable Enterprise, in: Sustainable Entrepreneurship, Renewable Energy-Based Projects, and Digitalization, 2020. ISBN 9781003097921, 1st Edition, Imprint CRC Press, UK

Shaikh, Parveen R., et al.: Microbiological and Physicochemical Studies of Soil near Bhokar of Maharashtra", International Journal of Applied biology and Pharmaceutical technology, 3 (4), 342-347, 2012.

Shaikh, Parveen R., et al.: The Impact of Landfill on Soil and Groundwater Quality of the Nanded City, Maharashtra", 4(7), 56-63, 2012.

Shaikh, Parveen R., et al.: Heavy metal contamination in soils near Siddheshwar dam Maharashtra, India", Research Journal of chemical Sciences 3(1), 6-9, 2013.

Shattuck, A., Werner, M., Mempel, F., Dunivin, Z., Galt, R.: Global pesticide use and trade database (GloPUT): New estimates show pesticide use trends in low-income countries substantially underestimated, Global Environmental Change, 81, 102693, 2023. https://doi.org/10.1016/j.gloenvcha. 102693

Šmejkalová, M., Mikanová, O., & Borůvka, L.: Effects of heavy metal concentrations on biological activity of soil micro-organisms. Plant, Soil and Environment, 49(7), 321-326, 2003. doi: 10.17221/4131-PSE.

Smith, P., Cotrufo, M. F., Rumpel, C., Paustian, K., Kuikman, P. J., Elliott, J. .A., McDowell, R., Griffiths, R. .I., Asakawa, S., Bustamante, M., House, J.I., Sobocká, J., Harper, R., Pan, G., West, P.C., Gerber, J.S., Clark, J.M., Adhya, T., Scholes, R.J. & Scholes, M.C.: Biogeochemical cycles and biodiversity as key drivers of ecosystem services provided by soils. Soil, 1(2), 665–685, 2015. https://doi.org/10.5194/soil-1-665-2015.

SOCI: 2024. https://www.soci.org/news/general-news/bill-proposed-to-improve-soil-quality

© Author(s) 2025. CC BY 4.0 License.

Stockholm Convention: Listing of POPs in the Stockholm Convention [online]. (Cited elsewhere first as early as in December 2019), 2021. http://www.pops.int/TheConvention/ThePOPs/AllPOPs/tabid/2509/Default.aspx

Stohs, S.J., Bagchi, D.: Oxidative mechanisms in the toxicity of metal ions. Free Radic Biol Med. 18(2), 321-36, 1995. doi: 10.1016/0891-5849(94)00159-h. PMID: 7744317.

Sumikura, M. and Shiiba, K. (2016) Insolubilization of hexavalent chromium in highly alkaline cement sludge by anaerobic bioremediation. Bioremediation Journal 20(3), 209–216. https://doi.org/10.1080/10889868.2016.1148008

Swaminathan, M.: Obituary: Norman E. Borlaug (1914–2009), Nature 461, 894, 2009. https://doi.org/10.1038/461894a

Syafrudin, M., Kristanti, R. A., Yuniarto, A., Hadibarata, T., Rhee, J., Al-onazi, W. A., Algarni, T. S., Almarri, A. H., & Al-Mohaimeed, A. M. : Pesticides in Drinking Water—A Review. International Journal of Environmental Research and Public Health, 18(2), 468, 2021. https://doi.org/10.3390/ijerph18020468

Tang, F. H. M., Malik, A., Li, M. et al.: International demand for food and services drives environmental footprints of pesticide use. Commun Earth Environ 3, 272, 2022. https://doi.org/10.1038/s43247-022-00601-8

Tarla, D. N., Erickson, L. E., Hettiarachchi, G. M., Amadi, S. I., Galkaduwa, M., Davis, L. C., Nurzhanova, A., & Pidlisnyuk, V.: Phytoremediation and Bioremediation of Pesticide-Contaminated Soil. Applied Sciences, 10(4), 1217, 2020. https://doi.org/10.3390/app10041217.

Telo da Gama, J.: The Role of Soils in Sustainability, Climate Change, and Ecosystem Services: Challenges and Opportunities. Ecologies, 4(3), 552-567, 2023. https://doi.org/10.3390/ecologies4030036

Thatoi, H., Das, S., Mishra, J., Rath, B. P. & Das, N.: Bacterial chromate reductase, a potential enzyme for bioremediation of hexavalent chromium: A review. Journal of Environmental Management, 146, 383–399, 2024. https://doi.org/10.1016/j.jenvman.2014.07.014

Torstensson, L. & Castillo M dP: Use of biobeds in Sweden to minimize environmental spillages from agricultural spraying equipment. Pesticide Outlook 8: 24-27, 1997.

Tripathi, A.D., Mishra, R., Maurya, K.K., Sing, R.B., Wilson, D.W.: Chapter 1 - Estimates for World Population and Global Food Availability for Global Health, The Role of Functional Food Security in Global Health, Academic Press, 3-24, 2019. ISBN 9780128131480, https://doi.org/10.1016/B978-0-12-813148-0.00001-3.

Tticescu, C., Georgescu, P. L., Arseni, M., Rosu, A., Timofti, M., Carp, G., & Cioca, L. I.: Optimal Solutions for the Use of Sewage Sludge on Agricultural Lands. Water, 13(5), 585, 2021. https://doi.org/10.3390/w13050585

UN: 2024. www.unccd.int/cop16

UNCED Rio de Janeiro: Report of the United Nations Conference on Environment and Development (UNCED), (Rio Declaration and Agenda 21), Brazil, 1992.

UNDP: 2024. https://www.undp.org/chemicals-waste/chemicals-and-waste/basel-rotterdam-and-stockholm-conventions

UNEA: Implementation plan "Towards a Pollution-Free Planet". United Nations Environment Assembly of the United Nations Environment Programme. [Cited 1 April 2021], 2018. https://papersmart.unon.org/resolution/uploads/k1804190.pdf

UNEP: Basel Convention on the Control of Transboundary Movements of Hazardous Waste and Their Disposal. 22 March. Basel, Switzerland, 1989.

UNEP.: Towards a Green Economy: Pathways to Sustainable Development and Poverty Eradication, 2011. Available online at: http://www.unep.org/greeneconomy/ Portals/88/documents/ger/GER_synthesis_en.pdf

UNEP: Resolution 3/6. Managing soil pollution to achieve sustainable development. (Cited first April 2019), 2017. https://papersmart.unon.org/resolution/uploads/k1800204.english.pdf

UNESCO: United Nations Decade of Education for Sustainable Development 2005-2014. The DESD at a glance. Paris: United Nations Educational, Scientific and Cultural Organisation, 2005.

UNFCC: 2024. https://unfccc.int/news/cop29-un-climate-conference-agrees-to-triple-finance-to-developing-countries-protecting-lives-and

UNFCC: 2024. https://unfccc.int/cop29, EU at UNFCC, 2024. https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal/climate-action-and-green-deal/eu-un-climate-change-conference/eu-cop29-climate-change-conference_en

UNGA: Transforming Our World: The 2030 Agenda for Sustainable Development. Resolution Adopted by the General Assembly on 25 September 2015, 42809, 1-13, 2015. https://doi.org/10.1007/s13398-014-0173-7.2

UNGA: Resolution 73/284. United Nations Decade on Ecosystem Restoration (2021–2030), 2019. https://undocs.org/pdf?symbol=en/A/RES/73/284

US Environmental Protection Agency (USEPA): Cleaning up the nation's waste sites: Markets and technology trends, Washington, DC, USA, 2004.

Vaidyanathan, G.: Obituary: M. S. Swaminathan (1925–2023), leader of India's 'green revolution.' Agricultural scientist who introduced crops to end famine in India in the 1960s. Nature 622, 453, 2023. doi: https://doi.org/10.1038/d41586-023-03175-3

https://doi.org/10.5194/egusphere-2025-271
Preprint. Discussion started: 17 July 2025
© Author(s) 2025. CC BY 4.0 License.

Wang, Y., Shi J., Wang, H., Lin, Q., Chen, X., Chen, Y.: The influence of soil heavy metals pollution on soil microbial biomass, enzyme activity, and community composition near a copper smelter. Ecotoxicol Environ Saf. May; 67(1), 75-81, 2007.. doi: 10.1016/j.ecoenv.2006.03.007.

WHO: Ten chemicals of major public health concern. In: World Health Organization, 2010. http://www.who.int/ipcs/assessment/public_health/chemicals_phc/en/

Wilson, A- & Conway, A.: Soil Washing Case Studies within the Remediation Sector. Paper presented at the ADIPEC, Abu Dhabi, UAE, 2024. doi: https://doi.org/10.2118/222965-MS

Xiong, L.X.Z., Ouyang, L., He, G., Liu, W. Cai, M.: Macrohabitat and microhabitat mediate the relationships between wetland multifaceted biodiversity and multifunctionality, CATENA, 241, 2024. https://doi.org/10.1016/j.catena.2024.108023.

Xiong, W. Li, Z. Liu, H. Xue, C. Zhang, R., et al.: The Effect of Long-Term Continuous Cropping of Black Pepper on Soil Bacterial Communities as Determined by 454 Pyrosquencing PLOS ONE, 10(8), e0136946, 2015. https://doi.org/10.1371/journal.pone.013694.

Yang Zhang, Y., Lei, M., Li, K., Ju, T.: Spatial prediction of soil contamination based on machine learning: a review. Front. Environ. Sci. Eng., 17(8), 93, 2023. https://doi.org/10.1007/s11783-023-1693-1

Yeheyo, H.A., Ealias, A.M., George, G. Giphin, G., Jagannathan, U.: Bioremediation potential of microalgae for sustainable soil treatment in India: A comprehensive review on heavy metal and pesticide contaminant removal, Journal of Environmental Management, 363, 121409, 2024. https://doi.org/10.1016/j.jenvman.2024.121409

Zhang, Z., Yan, X., Jones, K.C. et al.: Pesticide risk constraints to achieving Sustainable Development Goals in China based on national modeling. npj Clean Water 5, 59, 2022. https://doi.org/10.1038/s41545-022-00202-0

Zhong, H., Lyu, H., Wang, Z., Tian, J., Wu, Z.: Application of dissimilatory iron-reducing bacteria for the remediation of soil and water polluted with chlorinated organic compounds: Progress, mechanisms, and directions, Chemosphere, Volume 352, 141505, 2024. https://doi.org/10.1016/j.chemosphere.2024.141505