When the soil pays the price: how agrochemicals are poisoning our Fields and What We Can Do About It

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Introduction

Modern agriculture has achieved remarkable gains in productivity through the use of fertilizers, pesticides, herbicides and other agrochemicals. These inputs have played a crucial role in ensuring food security for a rapidly growing population. However, excessive and indiscriminate use of agrochemicals has created a new challenge in the form of soil pollution. Soil pollution, defined as the alteration of soil's physical, chemical and biological conditions through human intervention resulting in quality degradation, has emerged as one of the most pressing but least visible environmental crises of our time. Understanding the causes, impacts and remediation strategies of agrochemical pollution is therefore essential for maintaining healthy soils and productive farming systems.

Agrochemicals: A Double-Edged Sword

Agrochemicals are substances used in agriculture to enhance crop production and protect crops from pests, diseases and weeds. They include chemical fertilizers, insecticides, fungicides and herbicides (Table 1). While these inputs have significantly increased agricultural productivity, their improper use often results in contamination of soil and water resources.

When applied beyond recommended levels, agrochemicals may accumulate in soil, alter nutrient cycling processes, reduce microbial diversity and adversely affect beneficial soil organisms. Over time, such changes can impair soil fertility and ecosystem functioning, ultimately reducing crop productivity.

India alone has 293 pesticides registered for use, yet 104 of these continue to be manufactured and applied domestically despite being banned in two or more other countries (Nayak and Solanki, 2021). Globally, herbicides dominate pesticide consumption at 56 per cent, while in India insecticides lead at 51 per cent, reflecting the country's heavy reliance on chemical pest control (Fig. 1).

Table 1. Classification of agrochemicals and their primary agricultural use

Category	Sub-types / Examples	Primary Function
Pesticides / Plant-protection chemicals	Insecticides, Fungicides, Herbicides, Rodenticides, Nematicides, Acaricides, Molluscicides	Control pests, diseases and weeds
Plant-growth regulators	Growth promoters (e.g., Gibberellin), Growth retardants	Modify plant growth and development
Fertilizers	Simple/straight (Urea, SSP), Complex/micronutrients (DAP, MOP, $ZnSO_4$)	Supply essential macro- and micronutrients
Soil conditioners / Animal husbandry chemicals	Antibiotics, Hormones	Improve soil structure; used in livestock management
Biopesticides	Neem (Azadirachtin), Bacillus thuringiensis, Nuclear Polyhedrosis Virus	Eco-friendly pest control alternatives

Source: Mandal *et al.* (2020)

How Agrochemicals Pollute Soil

Soil pollution occurs when chemical substances accumulate in concentrations that negatively affect soil health and environmental quality. Several pathways contribute to agrochemical pollution:

- **Excessive Fertilizer Application**

Continuous application of high doses of fertilizers can lead to nutrient imbalances, soil acidification and accumulation of salts. Long-term fertilizer use may alter soil pH, affecting nutrient availability and microbial activity.

- **Pesticide Residues**

Many pesticides persist in soil for extended periods. Repeated application can result in residue build-up, affecting non-target organisms including beneficial microbes, earthworms and insects involved in nutrient cycling.

- **Herbicide Accumulation**

Herbicides intended to control weeds may influence soil biological activity and interfere with beneficial microbial populations. Their persistence varies depending on soil type, climate and management practices.

- **Indirect Environmental Effects**

Agrochemical pollutants may move beyond agricultural fields through runoff, leaching and volatilization, contaminating groundwater, surface water and surrounding ecosystems.

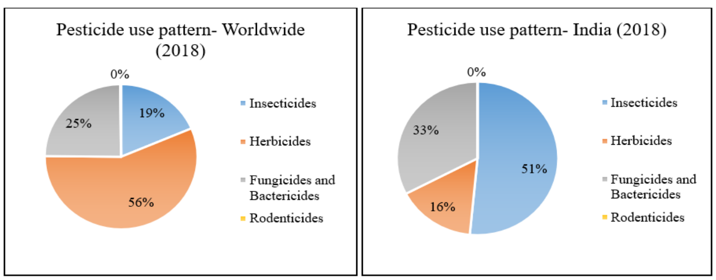

Fig. 1. Pesticide use pattern – Worldwide (2018): Herbicides 56%, Fungicides 25%, Insecticides 19%. India (2018): Insecticides 51%, Herbicides 16%, Fungicides 33%. Most consumed insecticides in India include Chlorpyriphos, Cypermethrin and Malathion; fungicides include Sulphur and Mancozeb (Nayak and Solanki, 2021).

Impact on Soil Physical Properties

Healthy soils require stable structure, adequate porosity and efficient water infiltration for sustained productivity. A long-term fertilizer experiment at Punjab Agricultural University, Ludhiana, showed that integrated application of farmyard manure (FYM) with recommended NPK fertilizers significantly improved aggregate stability and infiltration compared to unfertilized soils (Brar *et al.*, 2015). The combined use of organic and inorganic nutrient sources increased aggregate mean weight diameter and cumulative infiltration, reflecting better soil physical quality. Improved aggregation enhances aeration, water movement, root growth and overall soil resilience, highlighting the importance of integrated nutrient management for maintaining long-term soil health.

Effects on Soil Organic Carbon and Fertility

Soil organic carbon (SOC) is a key indicator of soil health, influencing nutrient availability, water retention, aggregation and biological activity. Long-term application of FYM along with NPK fertilizers significantly increased SOC compared to unfertilized plots (Brar *et al.*, 2015). After 36 years, the SOC pool increased from 7.3 Mg ha^{-1} in the control to 11.6 Mg ha^{-1} under 100 per cent NPK plus FYM, with higher carbon sequestration rates. These results demonstrate that integrating organic amendments with chemical fertilizers enhances soil carbon storage, supports nutrient cycling and promotes sustainable crop production.

Influence of Insecticides on Soil Processes

Pesticides can influence soil processes beyond pest control. In a rice-growing soil study, phorate and carbofuran increased nitrogen availability in the rhizosphere, with phorate showing a greater effect (Borkar *et al.*, 2018). Although pesticide residues were detected in soil, their levels in harvested rice grains remained below the maximum residue limit of 0.1 mg kg^{-1}. However, long-term accumulation of pesticide residues may disrupt microbial communities involved in nutrient cycling and organic matter decomposition, posing potential ecological risks.

Herbicides and Soil Biological Health

Soil microorganisms play a vital role in nutrient cycling, decomposition and soil fertility. A study by Sah (2022) showed that hand-weeded chickpea plots had higher populations of rhizobium, bacteria, fungi and actinomycetes, along with greater nodulation and grain yield, compared to herbicide-treated or untreated plots. The findings indicate that excessive herbicide use may adversely affect beneficial microbial communities, potentially reducing nutrient mineralization, biological nitrogen fixation and long-term soil productivity.

Long-Term Fertilization and Soil Health

The impact of fertilizers depends on their method and duration of application. A 40-year study under a finger millet-maize system showed that integrated application of 100 per cent recommended NPK with FYM increased grain yield by 17.08 per cent in finger millet and 12.62 per cent in maize compared to NPK alone (Shanmugasundaram *et al.*, 2019). The treatment also improved soil nutrient status, hydraulic conductivity and infiltration while reducing bulk density. These findings demonstrate that integrating organic amendments with fertilizers enhances both crop productivity and long-term soil resilience.

Ecological Consequences of Soil Pollution

The effects of agrochemical pollution extend beyond the soil environment. Degraded soils can trigger a cascade of environmental problems including:

- Decline in soil biodiversity
- Reduced nutrient-use efficiency
- Increased nutrient leaching into groundwater

- Contamination of rivers, lakes and reservoirs
- Deterioration of food quality through residue accumulation
- Enhanced greenhouse gas emissions from disturbed soil systems

As soil quality declines, farmers often respond by increasing chemical inputs, creating a cycle of dependency that further accelerates degradation.

Sustainable Strategies for Amelioration

The solution to agrochemical pollution does not lie in eliminating all inputs but in using them judiciously and integrating them with sustainable soil management practices (Table 2).

- **Bioremediation**

Bioremediation utilizes microorganisms to degrade toxic compounds present in soil. Aziz *et al.* (2014) demonstrated that bacterial species such as *Pseudomonas aeruginosa* and *Bacillus subtilis* effectively degraded malathion residues under laboratory conditions. Their findings suggest that beneficial microorganisms can serve as environmentally friendly tools for detoxifying polluted soils.

- **Integrated Nutrient Management**

Combining organic manures with chemical fertilizers improves nutrient-use efficiency while reducing environmental risks. Long-term studies consistently show that FYM combined with NPK enhances soil organic carbon, aggregate stability and infiltration compared with fertilizer-only treatments (Brar *et al.*, 2015).

- **Use of Beneficial Microorganisms**

Biofertilizers and microbial inoculants help restore biological activity in polluted soils. These organisms facilitate nutrient cycling, organic matter decomposition and suppression of soil-borne pathogens.

- **Precision Application of Agrochemicals**

Applying fertilizers and pesticides according to soil-test recommendations and crop requirements minimizes waste and reduces pollution risks. Precision agriculture technologies can further improve application efficiency.

- **Crop Rotation and Cultural Practices**

Crop diversification, green manuring and residue recycling contribute to soil health restoration. Such practices reduce dependency on agrochemicals while improving biological activity and nutrient cycling.

- **Adoption of Integrated Pest Management**

Integrated Pest Management (IPM) combines biological, cultural and mechanical methods with limited chemical intervention. This approach reduces pesticide consumption while maintaining effective pest control.

Table 2. Summary of amelioration strategies for agrochemical-contaminated soils

Strategy	Mechanism	Key Advantage
Bioremediation (*Pseudomonas*, *Bacillus*)	Microbial enzymatic degradation of organophosphates	Low cost, eco-friendly, high efficacy at contaminated sites
Integrated Nutrient Management (NPK+FYM)	Increases SOC, improves soil structure and microbial activity	Reduces fertilizer dependency over time; improves yield stability
Biopesticides (neem, *B. thuringiensis*, NPV)	Targeted pest control; rapidly biodegradable	No persistent soil residues; safe for non-target organisms
Crop rotation and legume inclusion	Improves nitrogen cycling; diversifies rhizosphere biology	Reduces pest pressure; rebuilds soil organic matter
Judicial herbicide selection (pendimethalin)	Pre-emergence action with minimal microbial disruption	Controls weeds with least damage to beneficial soil microflora
Vermicompost and biochar additions	Increases SOC, CEC and water retention	Immobilises heavy metals; improves soil aggregation
Banning persistent chemicals (DDT, BHC)	Removes source of long-lived soil contamination	Prevents accumulation and food chain entry of persistent toxins

Towards Sustainable Soil Stewardship

The future of agriculture depends on maintaining healthy and productive soils. Soil should not be viewed merely as a medium for crop growth but as a living ecosystem that supports food production, environmental quality and climate resilience.

The evidence from long-term experiments clearly demonstrates that integrated approaches combining organic amendments, beneficial microorganisms and balanced fertilizer use can improve soil health while sustaining crop productivity. Sustainable soil management therefore requires a shift from input-intensive agriculture toward ecosystem-based farming practices.

Conclusion

Agrochemicals have played a vital role in enhancing agricultural productivity, but their indiscriminate use has contributed significantly to soil pollution and environmental degradation. Excessive application of fertilizers, pesticides and herbicides can adversely affect soil structure, organic carbon status, microbial diversity and ecosystem functioning. Long-term studies have shown that integrating organic manures with balanced fertilizer use improves soil physical, chemical and biological properties while sustaining crop yields. Bioremediation, integrated nutrient management, precision agriculture and integrated pest management offer promising pathways for mitigating agrochemical pollution. Protecting soil health today is essential for ensuring food security, environmental sustainability and agricultural resilience for future generations.

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