Pesticides and Soil Health: Problem and Solutions for Sustainable Agriculture

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ABSTRACT

Soil is the foundation of life, serving as a reservoir of water and nutrients and providing essential ecosystem services. Soil supports the dietary needs of many organisms while also fulfilling the industrial needs of humans. However, climate change and artificial interference have compromised soil's optimal functioning, with one significant factor being the injudicious use of pesticides. While pest control has been a fundamental aspect of agriculture since its inception, the benefits of synthetic chemicals come at a considerable cost to ecosystem health. Reducing pesticide use could help mitigate climate change and biodiversity loss through sustainable agricultural practices. This article discusses the evolution of pesticide use in agriculture, analyzing their impacts, especially on soil ecosystems. It highlights the environmental concerns associated with conventional pesticides and explores sustainable solutions such as Integrated Pest Management (IPM), bioremediation, permaculture, precision agriculture, conservation agriculture, the use of green pesticides, and digital agriculture, among others. These strategies are assessed for their potential to foster more sustainable and resilient agricultural systems.

Abbreviations: DDT-Dichlorodiphenyltrichloroethane; FAO-Food and Agriculture Organization; VOC-Volatile Organic Compounds; SOC- Soil organic Carbon; DOM- Dissolved

Organic Matter; TPs-Transformation Products; WHO- World Health Organization; AI-Artificial intelligence; ML- Machine Learning; SI- Sustainable intensification; AOPs- Advanced oxidation processes.

INTRODUCTION

As a result of ongoing agricultural and industrial practices, the environment is continuously exposed to xenobiotics. Most of these chemicals such as pesticides are highly resistant to natural degradation mechanisms. Pesticides are mostly synthetic and are ubiquitous. They are toxic by design and function as biocides. To control pests, weeds, and diseases in plants, various pesticides like herbicides, termiticides fungicides, rodenticides, insecticides, algicides, molluscicides, bactericides, miticides/acaricides, and nematicides are used. They shield crops from the detrimental influences of pests and diseases by attacking particular systems or enzymes in the pests and help ensure a steady and sustainable food supply.

Generally, pesticides are used more than the requirement of the soil or plants. Soil is considered healthy when it continues to sustain life forms as a vital ecosystem. Soil regulates water, filters pollutants, and provides medium and support for plants. Soil contains a plethora of microorganisms that provide nutrients to the soil and also play a role in other significant processes such as sequestration of CO_2. Any disturbance through artificial means breaks this microbial bridge between plants and soil. Pesticides can also linger in the soil for years and continue to affect soil adversely. However, various sustainable approaches in agriculture, such as the adoption of integrated pest management, the use of green pesticides, and the implementation of conservation practices, can be employed to mitigate these effects and promote environmental balance.

History of man-made chemicals in agriculture

The International Labour Organization (ILO) estimates that agriculture employs 28% of the global workforce, with around 1 billion people currently engaged in this sector. With a history spanning about 10,000 years, agricultural development has undergone significant changes. The history of pesticide use in agriculture can be divided into following three phases:

PHASES	Duration	Approaches used
PHASE I	**Before 1870s**	**Use of Natural compounds** S, Hg, As compounds, dung, hand weeding, pyrethrum etc.
PHASE II	**Between 1870 and 1945**	**Use of Inorganic synthetic materials** Cu/S compounds, Bordeaux Mixture etc.
PHASE III	**After 1945**	**Use of synthetic pesticides** DDT, β-Hexachlorocyclohexane (BHC), aldrin, parathion, captan,2,4-D triazolopyrimidine, stobilurin,oragnophosphate insecticide etc., GM Crops

Agriculture has shifted from labor-intensive and organic methods to industrial practices with large monocultures and chemical inputs. This global transition, driven by surplus ammonium nitrate and chemical industry changes post-World War II, has occurred over the past 60 years (Hathaway 2016). The use of synthetic pesticides has further increased substantially all over the globe to meet the rising demands of the population. From the 1950s to 2000, global pesticide production expanded at an annual rate of approximately 11%, increasing from 0.2 million tons to over

5 million tons (Carvalho 2017). Pesticide manufacturing in India began in 1952, with the production of benzene hexachloride, followed by Dichlorodiphenyltrichloroethane (DDT).

Current status of usage

Globally, around 2 million tons of pesticides are used annually, with the distribution shown in a pie chart (Figure 1). The World Health Organization (WHO) reports a rising trend in pesticide use in developing countries, like India increasing its pesticide production from 5,000 metric tonnes in 1958 to 85,000 metric tonnes by the mid-1990s. India ranked second in Asia in pesticide production during 2005–2006 and became the largest producer in the region with 90,000 metric tons in 2008. In 2020, India used over 61,000 tonnes of pesticides, with production rising to 258,130 tonnes between 2022 and 2023, and 33,000 tonnes of agrochemicals exported, while 104 of 293 registered pesticides are currently manufactured. Typically, insecticides represent the most acute toxicity among herbicides. Pesticide production in India is led by insecticides and fungicides, with insecticides' shares decreasing from over 70% in 2003-04 to 39% in 2016-17, while the proportions of fungicides, herbicides, and rodenticides have increased (Subash *et al*. 2017). Cotton crops account for 45% of pesticide usage in India, with paddy and wheat following in usage frequency.

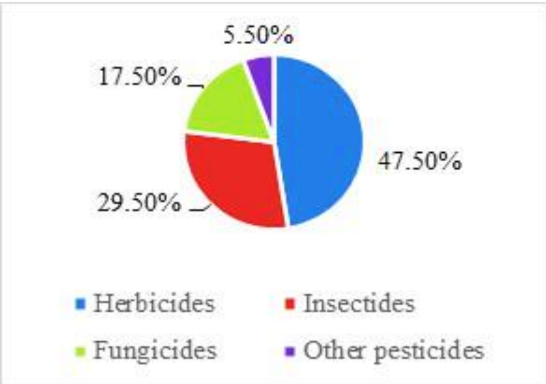

Fig. 1. Global use of different pesticides.

Impact of pesticides

Positive aspects

Pesticides help in food security as they are utilized in crop protection and preservation of food. Worldwide, around 9,000 insect and mite species, 50,000 plant pathogens, and 8,000 weed species damage crops, with pesticides reducing crop loss from pests to 35%–42%. If pesticides were not used, fruit production would experience a 78% loss, vegetable production a 54% loss, and cereal production a 32% loss. Many of them have also prevented vector-borne diseases, including Malaria, dengue, Japanese encephalitis, leishmaniasis, yellow fever, etc. They are used for veterinary purposes to treat flea or tick infestations and as household insecticides in gardens and institutions for sanitary indoor use. Pesticides also help control food prices by maintaining production levels, protecting forests and wildlife from invasive species, and preserving recreational areas and sports turf.

Harmful aspects especially on soil

Pesticides are employed to protect plants from pests, but only 0.1% of the total applied amount hit their targets (Carriger *et al*. 2006). The rest contaminate soil or affect other organisms and plants, posing a severe risk to endangered species especially. Climate change heightens annual yield losses from pests and pathogens, estimated between 20% and 40% of global production, by driving more frequent outbreaks of diseases, insects, and viruses, and enhancing pesticide resistance (Lykogianni *et al*. 2021). The rise in pesticide use worsens the issue, with agricultural workers facing considerable risks, including poisoning affecting 1 in 5,000 annually and about 200,000 fatalities from severe exposure, making soil remediation a pressing concern (Twagirayezu *et al*. 2024). Pesticide exposure can cause different types of cancers such as prostate cancer, for which farm populations are more at risk compared to the general public. Pesticides release volatile organic compounds (VOCs) that can form harmful ground-level ozone, contributing 6% to total ground ozone pollution. These VOCs can damage non-target organisms and plants, with phenoxy herbicides like 2,4-D causing harm to nearby trees and shrubs if they drift or vaporize onto foliage. Pesticide use contributes to the decline of insect populations and species extinction, alongside factors like habitat loss, climate change, and pollution. Pesticide malpractice, including improper application and counterfeit products (which are more prevalent in developing countries), causes health issues, food safety concerns, and water and soil contamination. This also highlights how all constituents of the ecosystem are interconnected and can affect one another.

Soil as a part of the ecosystem is maintained and nurtured by various biotic and abiotic elements. It is vital in nutrient cycling, connecting all biota and with their abiotic counterparts. Pesticides and Transformation products (TPs) that affect soil ecosystems can be either (a) hydrophobic and persistent, such as organochlorine pesticides like DDT and heptachlor, which also bioaccumulate, or (b) Polar pesticides which primarily encompass herbicides along with carbamates, fungicides, and certain TPs of organophosphorus insecticides. Insoluble compounds tend to adhere to soil particles while other compounds pollute the groundwater through leaching. Pesticide residues have been reported from groundwater and precipitation all around the world and reached even as far as Antarctica. Availability and efficacy of pesticides are also affected by pesticide degradation (such as photolysis, chemical breakdown, and microbial degradation), along with pesticide transport (volatilization, wash-off, and leaching). Incorrect use, spills, and leaks of pesticides lead to environmental contamination, with residues found in 70% of global croplands, particularly in vegetable, fruit, and orchard soils. Tang *et al*. (2021) reported that 64% of the world's arable land (about 24.5 million km²) is at risk of pesticide pollution from multiple active ingredients, with 31% at high risk. This high-risk area includes 34% in regions with significant biodiversity, 5% in water-scarce areas, and 19% in economically disadvantaged nations. Asia, home to countries like China, Japan, Malaysia, and the Philippines, contains the largest high-risk areas, many of which are considered 'food bowl' regions crucial for feeding the global population.

As one of the most complex and varied ecosystems, soil can harbor between 10 and 100 million organisms in a small quantity, representing more than 5,000 different taxa (Ramirez *et al*. 2015). Overuse of pesticides and other chemical control practices has been identified by the Food and Agriculture Organization (FAO, 2020) as the chief driver of soil biodiversity loss over the last decade. Soil organisms, constituting about a quarter of global biodiversity, are crucial for ecosystem services and soil health. Soil accommodates actinomycetes, protozoa, fungi, bacteria, earthworms, ants, ground-nesting bees, beetles, etc. that face detrimental effects due to exposure to pesticides. The study by Gunstone *et al*. (2021) found that 70.5% of the parameters tested exhibited adverse effects on invertebrates due to pesticide exposure. Pesticide compounds have been reported to affect earthworm biomass and cholinesterase activity. Similarly, carbendazim decreased survival rates and glyphosate (the active ingredient in the roundup) reduced biomass in nematodes. Due to an intensification of agriculture, climate change, invasive species, and relentless use of pesticides, up to 40% of insect species may face extinction insect species shortly. Their role in pollinating plants, maintaining soil health, recycling nutrients, and controlling pests is crucial, and their decline could lead to catastrophic ecosystem collapse through cascading effects on the food chain.

Pesticides also affect microbes involved in nutrient recycling such as nitrifying bacteria, archaea, sulfur-oxidizing bacteria, etc. A man-made systemic herbicide triclopyr inhibits soil bacteria that convert ammonia into nitrite. The addition of these chemicals jeopardizes the pristine connection between legume and their symbiotic partners and also decreases root growth and root sites available to microbes. Another broad-spectrum systemic herbicide glyphosate reduces the growth and activity of free-living nitrogen-fixing bacteria in soil. Soil Enzymes such as dehydrogenase, β-glucosidase, fluorescein diacetate hydrolase, cellulase, urease, aryl-sulfatase, and acid/alkaline phosphatase, etc. play crucial roles in the carbon, nitrogen, sulfur, and phosphorus cycles. While specific enzymatic activities provide insights into these cycles, pesticides—especially with long-term use—can significantly alter soil microbial communities and reduce soil productivity. Additionally, pesticide residues notably affected microbial diversity and community structure in orchard soils, with significant changes in 43 genera increasing and 111 genera decreasing, revealing *Bacillus* and *Sphingomonas* as the most sensitive genera under pesticide influence (Lu *et al*. 2024). Pesticides alter soil microbes' behavior, reducing soil respiration, microbial biomass, and diversity. Herbicides can impact specific fungi, while some bacteria may increase in treated water. Pesticides like oryzalin, rifluralin, triclopyr, and oxadiazon are known to harm various mycorrhizal fungi, which assist in plant nutrient absorption.

Dissolved organic matter (DOM) in the soil boosts the persistence of pesticides by binding to them and reducing the rate at which microbes decompose these substances. For instance, DOM slows the rate of photolysis of carbofuran, a broad-spectrum insecticide and the level of inhibition correlates directly with the binding capacity of the specific DOM sample. As soil is the major reservoir of carbon, its degradation releases carbon which contributes to global warming. Soil carbon pools store around 2,500 billion tonnes of Soil organic Carbon (SOC), but intensive farming practices lead to significant SOC losses and a global release of up to 1,500 Gt CO_2 since 1751 (Zhang *et al*. 2021). Variations in climate especially enhanced temperature can affect frequency, doses, and amount of pesticide use. A warm climate can support many pest species to thrive, and the use of pesticides is going to be increased to combat pest invasion. However, this relation is complex as more soil moisture or precipitation can dilute pesticides. Both these conditions of higher temperature and soil moisture are also related to the increased activity of the soil microbes. Rising temperatures can enhance the volatilization and degradation of pesticides, while pyrethroids and DDT are considered more toxic under lower temperatures.

Additionally, a broad-spectrum agricultural pesticide methyl bromide (MeBr) causes stratospheric ozone layer depletion and affects soil biodiversity and groundwater. Increased exposure to harmful UV rays affects plant growth which further increases soil erosion.

Different pesticide residues or their mixtures can have synergistic or compounding effects in the soil. The combined use of glyphosate and diflufenican amplified their detrimental effects on soil biological activity and the persistence of both herbicides in the soil. The heightened vulnerability of some plants to disease further drives up the need for pesticide use. Excessive reliance on pesticides has driven the evolution of pests and insects, making them impervious to chemical treatments. It generates a vicious cycle with subsequently increased application of pesticides to be effective on the pest or not effective at all.

Sustainable Solutions

Many collaborative and international efforts are made to fight with menace of hazardous pesticides. Of the chemicals regulated by the Rotterdam Convention and Stockholm Convention, 73% and 70% are classified as pesticides, respectively. Along with these conventions, Basel conventions and the voluntary Code of Conduct of FAO, advocate for a life cycle approach and furnish the tools required for pesticide management. These conventions deal with issues like trade, use, monitoring, and institutional capacities. According to WHO, developing countries use only 25% of pesticides produced but 99% of deaths due to pesticides occur in these nations. The scenario is worst for agriculture-based economies like India. This is due to a lack of strong educational, health, and regulatory infrastructure and a low level of awareness regarding pesticides. However, pragmatic considerations and cost-benefit analysis especially for developing nations don't phase out pesticides in one go. As the global population is expected to reach 9.7 billion by 2050, food production must increase by 15% in the next decade and by 50% by 2050 (Lykogianni *et al*. 2021). Yet we do believe gradual and sustainable approaches are the best way forward. Some of the sustainable approaches are discussed as follows:

Polyculture involves growing multiple crops simultaneously in the same space. It offers environmental benefits such as soil protection, temperature stabilization, water retention, improved fertility, and enhanced biological control against weeds, pests, and diseases. However, it requires more initial investment, and infrastructure, and can complicate farm management.

Conservation Agriculture- According to FAO, "CA is a farming system which promotes maintenance of a permanent soil cover, minimum soil disturbance, and diversification of plant species". Agrochemicals such as pesticides are applied in ways that do not interfere with, or disrupt, biological processes. By combating soil erosion and climate change, enhancing carbon sequestration, strengthening drought resilience, improving water and nutrient efficiency, and fostering soil biodiversity while cutting costs, it emerges as a pivotal approach to sustainable agriculture.

Integrated Pest Management (IPM)- IPM is a comprehensive strategy that integrates natural predators, habitat manipulation, biological and chemical controls, and pest-resistant varieties to ensure long-term plant protection. Cultural control methods, including deep ploughing, burning crop residues, soil solarization, synchronous planting, trap crops, cover crops, crop rotation, tillage, pest-free seeds, and physical methods such as fencing, manipulation of temperature, humidity, energy, and sound, are effective for pest suppression. Although IPM is cost-effective and reduces crop loss, its adoption is hindered by factors like limited awareness and technology, highlighting the need for greater education on its benefits and components. IPM remains a prominent strategy for reducing pesticide use through bioecological methods, agroecological methods advocate for a comprehensive approach to developing a 'healthy' agroecosystem.

Agroecological practices enhance ecological processes, environmental and public health, and reduce agricultural impacts like soil degradation, water contamination, greenhouse gas emissions, resource depletion, and social inequities. These involve crop diversification, intercropping, agroforestry, integrated crop-livestock systems, organic agriculture, permaculture, natural farming, and biodynamic methods and soil management, progressing into intricate systems with various elements like combined crop-livestock operations and farmer networks. While many agroecological practices, such as biofertilizers, natural pesticides, crop rotations, intercropping, agroforestry, and cover crops or mulching, currently face limited adoption and modest future prospects, methods like organic fertilization, reduced tillage, drip irrigation, and cultivar choice and biological pest control are already well-integrated and hold greater potential for future expansion.

Crop rotation, a sustainable practice involving the sequential planting of different crops, enhances soil health, and resource efficiency, reduces erosion, and fertilizer needs, disrupts pests, and restores soil nutrients. Yang *et al*. (2024) found that it increased yields, reduced N_2O emissions, and improved greenhouse gas balance, while legumes increased soil carbon and health. However, it may require more field preparation and face challenges like pests and diseases from plant residues.

Agroforestry, integrates trees and shrubs into farming systems to provide economic and ecological benefits. The diverse plant layers enhance habitats for beneficial insects, like predators and parasitoids, helping control pests and reducing the need for insecticides, herbicides, and pesticide drift. Agroforestry increases soil organic carbon, boosts nutrient availability, improves microbial activity, effectively regulates soil erosion, and alleviates soil acidity in humid and sub-humid tropics.

Permaculture fosters sustainable, diverse systems that reduce energy, pesticide, and freshwater usage, restore ecosystems, and promote both ecological and social well-being. According to Bill Mollison, one of the founders of permaculture, "Permaculture is the conscious design and maintenance of agriculturally productive ecosystems which have the diversity, stability, and resilience of natural ecosystems." Permaculture practices significantly improve nutrient bioavailability, and increase organic carbon concentrations in mainly larger soil fractions, positively affecting soil properties and macroaggregation.

Bioremediation Phytoremediation can be a good ecological approach to treating already contaminated soil. Several plants such as alfalfa, rye grass, reed canarygrass, and soybean have a notable ability to gather Organochlorine pesticides (OCPs), including DDT and its breakdown products, aldrin, endrin, and chlordane, in their aboveground biomass.

Microbial bioremediation using pesticide-tolerant rhizobacteria helps reclaim polluted lands by degrading pesticides and improving nutrient availability. It also promotes plant growth and soil health through the supply of phytohormones, protects against pathogens, and reduces ethylene-induced stress. However, bioremediation is limited by the need for specific conditions, high costs, and potential environmental disruption especially for other native microbes. While effective in labs and seen as "green," real-world use is challenging but still attracts investment due to its potential.

Green pesticides- Green pesticides, often as effective as chemical pesticides, present an attractive and profitable alternative to synthetic options. Biopesticides, including phytopesticides (plant-based), microbial pesticides (microorganism-based), and nanobiopesticides (nanoparticles from biological sources), are eco-friendly, cost-effective, and free from harmful residues and greenhouse gas emissions. Major biopesticides include *Trichoderma, Bacillus thuringiensis,* nuclear polyhedrosis virus, and neem-based products. The use of plant essential oils or their constituents in pesticides was successfully exhibited in controlling a variety of pests, including nematodes and viruses. For instance, the oil extracted from *Melaleuca alternifolia*, known as tea tree oil, effectively fights the Tobacco Mosaic Virus (TMV) on tobacco plants.

In India, biopesticides currently account for about 4.2% of the pesticide market and are expected to grow to 50% by 2050, with an annual growth rate of 2.5%. Despite government promotion and a projected 10% yearly growth, the biopesticide market remains relatively small compared to synthetic pesticides (Chakraborty *et al*. 2023). However, their narrow target range and short shelf life may limit long-term pest control. The storage of biopesticides also requires special facilities and skills, which need to be developed across the supply chain.

Advanced oxidation processes (AOPs)- AOPs such as plasma oxidation, the Fenton process, ozonation, and photocatalysis can degrade pesticides in soils into more biodegradable and less toxic forms using powerful oxidizing agents like hydroxyl radicals (•OH) and sulfate radicals ($SO4^{•-}$). However, these processes require further research for optimization and scalability.

Digital Agriculture- Sustainable intensification (SI) in agriculture seeks to increase yields, expand cultivable land, and boost biomass for bio-energy, food, feed, and fiber production while minimizing environmental impact. It improves nutrient quality, makes agriculture greener and more productive, and reduces greenhouse gas emissions. SI can be supported by technology, such as the Internet of Things (IoT), remote sensing, big data, wireless sensor networks, AI, ML, smart irrigation systems, and drones. Digital agriculture includes concepts like smart farming and precision agriculture, which involves applying digital technologies and innovations across agricultural systems, and has the potential to revolutionize crop management and irrigation. Digital tools enhance sustainability by monitoring crop stress, nutrient deficiencies, pests, and soil conditions, supporting regenerative practices, optimizing water use, and reducing pesticide use. However, challenges like data quality, data management privacy concerns, connectivity in remote areas, and high initial costs hinder widespread adoption. Despite varying maturity levels across technologies, ongoing research, and collaboration are vital for maximizing digital agriculture's potential.

Lechenet *et al*. (2017) projected that a 42% reduction in pesticide usage could be achieved with no adverse effects on productivity or profitability on 59% of the farms they analyzed. So, myths about the absolute link between productivity and pesticide use need to be debunked. However, the economic feasibility of pesticide use in food production relies on externalizing the costs of damage and environmental contamination to society, masking the true economic and environmental impact of these practices.

CONCLUSION

Pesticides are reducing the diversity of micro-organisms and are also causing threats to insects, especially pollinators. In this way, they are threatening food security for the very purpose they are intended to use. However, a reduction in food wastage can decrease the demand for pesticides. Demand-supply scenarios need to be revisited based on socio-economic and environmental aspects. Farm policies should discourage pesticide-intensive food systems. Data based on Acute or long-term exposure, demographics, on different soil and climates, all need to be thoroughly investigated. Currently, very few pesticides are recognized as carcinogens by international institutions. With the increase in the number of possible candidates, regulatory mechanisms for the use of banned pesticides must be effectively implemented. Rigorous risk analysis of pesticides must be done before their approval. Residues of banned pesticides are also present in the soil and groundwater. It will require coordinated and long-term efforts to examine and redress them. The cumulative effect of residues of different pesticides also needs to be further investigated as it is the mixture that is commonly found in agricultural soils. Leakage of any storage sites or spill events can pose an enormous threat to the environment. Native crops and varieties that are naturally more resistant to pests, need to be promoted. Low-cost alternatives in the market will help small-scale crops, which currently supply mainly major crops.

Unless we mend our way of producing food, the plummeting number of species amid the 6th mass extinction can't be stopped. Some species may fill the vacuum but their disproportionately larger populations will not do any good either. So, it is very important to halt or reverse these dreadful events. Ecological methods can increase biodiversity in the soil and above ground as well. The dual purpose of the availability of quality food and the health of the soil can only be served by a sustainable approach that maintains harmony between the ecosystem and the industrial progress. Our ancestors also practiced farming in harmony with nature. Soil is given utmost importance and revered as mentioned in verse 3 of Bhoomi Sukta (Hymn to the Earth), Atharva Veda:

यस्यांसमुद्रउतसिन्धुरापोयस्यामन्नंकृष्टयःसंबभूवुः।

यस्यामिदंजिन्वतिप्राणदेजत्सानोभूमिःपूर्वपेयेदधातु।।

[In whom the waters of the ocean and rivers are intertwined; in whom the food is contained and manifested through cultivation, in whom all lives reside; may she bestow us with that life.]

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