Impact of Pollution on Agricultural Ecosystem and Integrated Mitigation Strategies for Climate - Resilient Regenerative Sustainable Crop Production System

Shashikant Kumar, Sandeep Bodkhe

Agricultural ecosystems face unprecedented pollution challenges that threaten global food security and environmental sustainability. This chapter provides a comprehensive examination of how various pollution types – including air pollution, soil contamination, water pollution, heavy metal accumulation, pesticide residues, and nutrient pollution–impact agricultural productivity, soil health, biodiversity, and ecosystem sustainability. Based on the recent studies, we prepare the synthesis of existing knowledge of the pollution processes, quantify the effects on crop harvests and ecosystem services, and assess mitigation policies. Evidence indicates that 64% of global agricultural land faces pesticide pollution risk, with documented declines of 70% in insect biomass and 50% in farmland bird populations in affected regions. Heavy metals and agrochemicals persist in soils, disrupting microbial communities essential for nutrient cycling and reducing crop productivity by up to 40%. However, sustainable practices including integrated pest management, precision agriculture, bioremediation, and agroecological approaches offer promising pathways toward pollution reduction while maintaining agricultural productivity. This chapter emphasizes that addressing agricultural pollution requires integrated approaches combining technological innovation, policy reform, and farmer education to ensure long-term sustainability of food production systems.

Keywords: *Agroecosystems, Soil Contamination, Environmental Pollution, Environmental Impact, Climate Resilient Regenerative Agriculture, Pesticide*

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Introduction

Agricultural ecosystems are complicated buffer systems between human food production requirements and environmental sustainability. The current agricultural methods have significantly boosted food supply in the world, they have also brought with them unparalleled pollution, which is jeopardizing the sustainability of such systems (Mahmood et al., 2024; Musa Khan & Bhatt, 2023). Explosion of agriculture by more frequent use of synthetic fertilizers, pesticides, and mechanization has become a paradox: the very resources on which agriculture relies are frequently destroyed by these practices (Apoorva & Kundlas, 2024).

Pollution of agricultural ecosystems occurs in a variety of pathways and different types of pollutants with different mechanisms of action and different environmental impacts. Crop physiology and yields are influenced by air pollution both by agricultural activities and external factors. Taxation of soil by heavy metals, pesticides and surplus nutrients causes poor soil health, diminished microbial community and thus, a reduction of nutrient process. Farm runoff pollutes water, leading to eutrophication, groundwater contamination, and degradation of aquatic ecosystems (Nuruzzaman et al., 2025). These forms of pollution hardly exist as stand-alone, they also interact with each other in a synergistic manner to produce complex environmental challenges (Sharma et al., 2024).

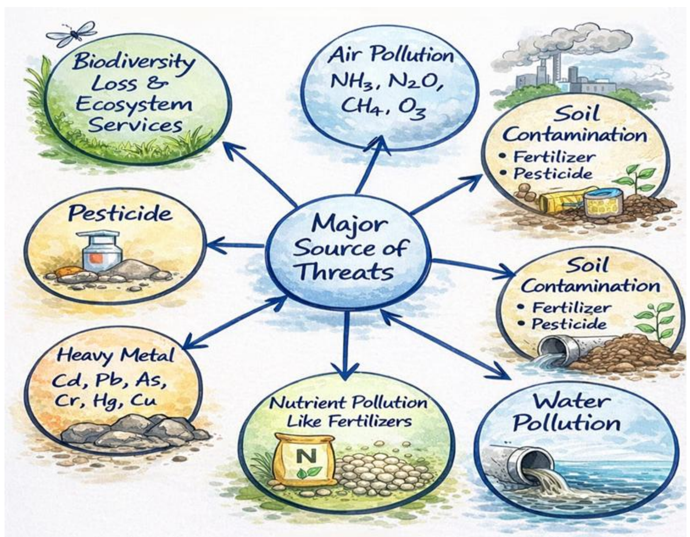

Figure. 1 Major source of pollution on agricultural ecosystems

It is astonishing how widespread agricultural contamination is all over the globe. According to recent estimates, 64% of the total agricultural land around the world is at risk of pesticide pollution, and 31% of it is a high-risk zone (Tang et al., 2021). The agricultural nitrogen pollution in Europe alone cost EUR 70 billion to EUR 320 billion every year (Sud, 2020). The agricultural sector has been a major source of pesticides pollution (98%) to the environment, and 90% of water sources in farms are polluted with pesticides (Ali et al., 2021). Such statistics demonstrate the necessity of an in-depth insight and effective mitigation measures.

This chapter discusses diverse effects of pollution on agricultural ecosystems, and is a synthesis of the new research to offer a holistic picture of the source of pollution (see in Figure 1), how they can affect, and solutions to the problem. We dwell on six big categories of pollution: air pollution, soil pollution, water pollution, heavy metal contamination, pesticide pollution and nutrient pollution. In each category, we discuss the mechanisms behind them, measure the effects on crop productivity and ecosystem health, and discuss evidence-based mitigation measures like climate resilient agriculture. We argue that these types of pollution are interconnected and that solutions aimed at ensuring that the agricultural systems are sustainable to reach the goal of feeding the increasing population without compromising the integrity of the environment are to be implemented in an integrated manner.

1. Air Pollution and Agricultural Ecosystems

Sources and Types of Air Pollutants

Agricultural ecosystems are the source as well as the recipient of air pollution. The major sources of agriculture are the emission of ammonia (NH_3) and nitrogenous fertilizers by animals and other livestock, nitrous oxide (N_2O) by fertilized soils, methane (CH_4) by animals and rice paddy, and particulate matter by tillage activities and biomass burning (Mahmood et al., 2024). The manmade sources of agriculture type include industrial emission, vehicle exhaust, and combustion of fossil fuel, a source of nitrogen oxides (NO_3), sulfur dioxide (SO_2), ozone (O_3), and other particulate emissions (Adejumo & Owoade, 2020). One of the most important sources of agricultural air pollution is the livestock sector that produces massive levels of greenhouse gases, such as methane and nitrous oxide (Mahmood et al., 2024). Farming activities like bush burning, pesticide spraying, and others only increase the amount of carbon dioxide in the air and release toxic substances into the air. The gas flaring in agricultural areas causes more than 250 toxins; these toxins may acidify the soil and strip it of nutrients thereby making farm lands less productive (Adejumo & Owoade, 2020).

Air Pollution Effects Mechanisms

The impacts of air pollutants on the agricultural systems are varied. Ammonia or nitrogen oxides may result on plant surfaces and soil and modify nutrient ratios and soil chemistry. Ozone causes plant tissue damage induced by oxidative stress, which enters into the leaves via stomata and forms reactive oxygen species that disrupts photosynthesis and cellular activity. Stomata may be physically covered by particulate matter, limiting the exchange of gases and photosynthesis rate. Sulfur and nitrogen compounds lead to acidic deposition, which changes the pH of the soil, impacting the nutrient content and microbial activity (Adejumo & Owoade, 2020). According to recent findings regarding the air pollution associated with nitrogenous fertilizer, air pollutants, especially NH_3 and N_2O, have a greater harmful impact on the ecosystem health than soil/water pollutants (Wang et al., 2022). These compounds lead to the risk of ecosystem health in terms of species-years, rice production being the most likely to have the highest ecosystem health risk (560 species.yr) in China, then maize (413 species.yr) and wheat (252 species.yr) (Wang et al., 2022).

Impacts on Crop Productivity and Quality

Air pollution using various routes has a great influence on crop productivity. Exposure to ozone decreases the rate of photosynthesis and increases the rate of leaf senescence and biomass. Though deposition of nitrogen may be beneficial in the provision of nutrients, it may cause nutrient imbalance and predisposition to pests and diseases. Acidic deposition leads to poor soil quality that lowers the nutritional value of crops and decreases the productivity of farmlands with time (Adejumo & Owoade, 2020). Special focus should be given to the effects of the atmospheric environment on agricultural production since the optimization of the use of chemical fertilizers may play a significant role in the realization of Sustainable Development Goals (Wang et al., 2022). These effects are further enhanced by climate change, which has been directly caused by agricultural greenhouse gas emissions and this leads to changes in soil moisture, soil quality, crop resilience, and an expected yield decrease of between 5-15%(Adejumo & Owoade, 2020) (See details in Table 1).

Table 1. Air pollution sources, mechanisms, and impacts on agricultural ecosystems.

Pollutant Source	Major Pollutants	Impact Mechanism	Agricultural Effects
Agricultural activities (fertilizers, livestock, rice paddies, burning of crop residues)	NH_3, N_2O, CH_4, PM	Deposition on plants/soil, greenhouse forcing	Yield reduction, soil acidification, ecosystem health risk
Industrial & transport emissions	NO_x, SO_2, O_3, PM	Oxidative stress, acidic deposition	Leaf injury, reduced photosynthesis, nutrient imbalance
Ozone exposure	O_3	ROS formation in leaves, stomatal uptake	Reduced biomass, early senescence, lower crop quality
Particulate matter deposition	PM	Stomatal blockage, light interception	Decreased photosynthesis and productivity
Combined pollution & climate change	GHGs, acidic gases	Altered soil chemistry, climate stress	5-15% yield decline, reduced crop resilience

2. Soil Pollution in Agricultural Systems

Sources of Soil Contamination

The sources of soil pollution in agricultural ecosystems are varied with numerous anthropogenic sources. The main ones are the overuse of synthetic fertilizers, pesticides, and herbicides; the use of contaminated water in irrigating fields; the use of sewage sludge and industrial wastes; and the atmospheric deposition of pollutants (Kaparwan et al., 2020; Musa Khan & Bhatt, 2023). Diffuse soil pollution is a major contributor of modern agricultural practices that are based on the use of considerable amounts of agrochemicals, and which has no identifiable source of chemical outflow (Nuruzzaman et al., 2025).

The use of chemical fertilizers and pesticides is one of the most long-lasting pollutants that stay in the soil and impact the soil structure, composition, microflora, and other organisms negatively (Baweja et al., 2020; Hossain et al., 2022). The presence of such contaminants in the soil worsens the soil characteristics by diminishing the organic carbon levels, presence of salts, compaction and imbalanced nutrients (Rashmi et al., 2020). Intensive agriculture also contributes by means of monocropping that exhausts certain nutrients and diminishes the diversity of microorganisms and by means of the traditional form of farming that impairs the quality of soil and decreases the quantity of organic matter (Apoorva & Kundlas, 2024; Mahmood et al., 2024).

Effects on Soil Health and Microbial Communities

Agricultural pollution has one of the most critical effects in soil health deterioration. The pesticides lower the respiration rate of the soil by 35% because of attacks on the life of microorganisms (Ali et al., 2021). The chemicals disrupt the good soil organisms such as earthworms, fungi and actinomycetes among others, which are necessary in keeping the soil fertile by their usual biochemical activities (Vivas Darío, 2020). Chemical pesticides and fertilizers impair soil health including the nutrient cycles maintained by soil microbial communities, and the agrochemicals stay in the environment and affect related ecosystems (Hossain et al., 2022).

Recent studies show complicated interactions between enrichment of soil nutrients and structure of microbial community dynamics. Nutrient-rich soils with copiotrophic bacteria exhibit better potential to grow and more plant-beneficial bacteria, and lower bacterial functional potential than nutrient-poor soils with oligotrophs (Yan et al., 2025). This trade-off between bacterial functional potential and growth rate due to nutrients has notable implications in optimization of nutrient management strategy under precision agriculture. Phthalic acid esters (PAEs) are common organic pollutants in agricultural soils, which have a profound impact on soil and plant-associated microbial communities, where DEHP, DnBP, and DiBP have high levels of detection and concentration (Kong et al., 2024). Heavy metals disrupt the biochemistry and activity of the microorganisms in the soil, declining the number of microorganisms and changing the composition of the community (Kaparwan et al., 2020; Rad et al., 2022). Poor agricultural practices worsen the quality of soil and affect soil microorganisms, and high-input agriculture affects the microorganisms especially negatively (Jacob, 2024).

Consequences for Crop Production

The effects of soil pollution on the agriculture productivity are direct and come in several ways. The impact of heavy metal pollution is adverse on the growth of plants, accretion of dry matter, and yield; its food contamination causes health hazards to consumers (Kaparwan et al., 2020). Agrochemicals lower the permeability of soils, biodiversity and productive potential, causing erosion and ecosystem disequilibrium (Vivas Darío, 2020). The intensive farming methods decrease the long-term agricultural production and harvests, which pose an obstacle to the sustenance of productive soil (Apoorva & Kundlas, 2024).

The degradation, compaction, and depletion of organic carbon deteriorate the general health of soils, whereas monocultures cause the deficiency of certain nutrients and a decrease in the diversity of microorganisms, which nourish plants (Apoorva & Kundlas, 2024). Pesticide pollution lower crop growth and productivity and accumulate in the soil and crops, with consequences on human health (Chaudhary et al., 2023). The fact that these pollutants are persistent implies that previously contaminated soil is hazardous to the agricultural productivity over a long period of time because of their non-decayability and long biological half-lives (Singh & Singh, 2020).

3. Water Pollution in Agricultural Systems

Sewage Wastewater Irrigation

Sewage wastewater is extensively used to irrigate crops in water deficient and peri urban areas, which enhances the crop yields in the short term but has long term effects of persistent contamination of the soil, crops, livestock, and human health. Types of contaminants, ways, and recorded case statistics that depict the levels of risk and accumulation are as follows.

Long term monitoring and meta-analysis indicate that untreated wastewater has high levels of toxic metals such as Ni, Cr, Cd, Pb, and Zn exceeding international standards and vegetables grow in such water and accumulate metals 3-9 times higher than those in freshwater irrigated vegetables (Othman et al., 2021).

Microbial loads are high: *Escherichia coli* in wastewater irrigated soils was of the order of 2×10^6 CFU g^{-1} and approximately 15 CFU g^{-1} in edible plant parts, and the total coliforms were of the order of 1.4×10^6 CFU g^{-1} in soils and 55 CFU g^{-1} in vegetables. Metadata health risk metrics suggest the estimated daily intake (EDI) and human risk indexes (HRI) of 0.01-8, and Cd and Pb are often above safe levels of the HRI indexes (Othman et al., 2021). These trends are supported by regional case studies: peri urban Pakistan sites are found to have HRI values of more than 1 in a variety of crops with spinach and wheat having high HRI values of 6.4 and high levels of plant metal transfer factors of Cr, Ni and Pb (Mishra et al., 2023).

Wheat study reported : mean grain levels of Cd 4.88 mg kg^{-1}, Ni 89.2 mg kg^{-1}, Pb 19.62 mg kg^{-1} and Zn 67.9 mg kg^{-1} values exceeding the WHO/FAO limit and gave HRI >1 both in children and adults (Atta et al., 2023). Central India Sewage irrigation over long periods (longer than 20 years) raised soil Cr up to 51.5 mg kg^{-1} and enhanced soil fertility measures (SOC ≈+14%, P ≈+44%), which are concomitant yield gains and contamination risks (Hassan et al., 2023). These statistics emphasize the necessity of monitoring, treatment, crop choice, and management to avoid the soil degradation and transferring the food chain.

Table 2. FAO guidelines on the safe reuse of treated wastewater for agricultural applications

Category of Agricultural Reuse	Level of Treatment Required	Specified Quality Standards
Irrigation of crops for direct human consumption using treated wastewater	Secondary treatment followed by filtration and disinfection	pH: 6.5–8.4 Suspended Solids (SS): < 30 mg/L Biochemical Oxygen Demand (BOD): < 30 mg/L *Escherichia coli*: < 200 MPN/100 mL
Irrigation of non-food crops using treated wastewater	Secondary treatment with disinfection	pH: 6.5–8.4 Suspended Solids (SS): < 30 mg/L Biochemical Oxygen Demand (BOD): < 30 mg/L *Escherichia coli*: < 200 MPN/100 mL

Heavy Metal Contamination

Agricultural systems are facing increasing and significant challenges associated with heavy metal contamination caused by metal toxicity, bioaccumulation potential and long-term environmental persistence. The main heavy metals that one should be concerned with are cadmium (Cd), lead (Pb), arsenic (As), chromium (Cr), mercury (Hg), and copper (Cu) (Kaparwan et al., 2020).

Heavy metal pollutants have a wide range. Phosphate manure is a pollutant of cadmium, and the input of phosphate manure brings 1-10 g Cd/ha/year. Application of sewage sludge though offering organic matters and nutrients presents various heavy metals. Industrial sources of atmospheric deposition, mining, and burning of fossil fuels increase the content of metals in soil. Application of contaminated water, especially industrial wastewater, as irrigation to agricultural soils transfers heavy metals directly to the soils (Singh & Singh, 2020).

The toxicity of the heavy metals occurs in a variety of ways. They produce reactive oxygen species (ROS) leading to oxidative cell damage. Metals are bound to sulfhydryl groups within the proteins and prevent enzyme activities that are required in metabolism. They also take the place of necessary nutrients in biochemical activities interfering with the plant nutrition. Cadmium has negative interactions with the absorption of calcium and zinc and lead affects iron metabolism (Kaparwan et al., 2020).

The effects of heavy metal contamination on crop productivity are huge and enormous. The effects of heavy metal toxicity include reduced germination, retarded root growth, impaired photosynthetic performance, and dealing with visible effects of the toxicity, such as chlorosis and necrosis. The yield losses are between 15-40%, based on the type of metals, levels of the metals and the species of crops. Cadmium and lead contamination are especially sensitive to rice, wheat, and vegetables. There are very high risks of bioaccumulation in the food chains. Accumulation of heavy metals in crops depends on the content of the soil polluting the crop with different levels of metal and species depending on the metal. Metal concentrations are usually higher in leafy vegetables and root crops as compared to grains. Rice is an effective cumulative of cadmium and in the contaminated areas; the amount of cadmium in the grain is above the safety levels. Chronic health impacts on human beings such as kidney damage, bone disease, and cancer are the results of human exposure of polluted food (Singh & Singh, 2020).

Microbial communities of the soil are very sensitive to the presence of heavy metals. Metals decrease microbial biomass, change community composition, and prevent enzyme functions. Research shows the decrease of microbial diversity and enzyme activities by 30-50% and 20-60% at polluted locations (Kaparwan et al., 2020). The effect of these alterations is the impairment of nutrient cycling, organic matter decomposition and other important functional processes of the soil.

Pesticide Pollution

Pesticide pollution is among the most widespread types of agricultural pollution, with medium and high risks of pollution on 64% of the world agricultural lands (Tang et al., 2021). Pesticides are an important tool in modern agriculture, with pesticides consumption in the world going above 4 million tons per year. The organophosphates, pyrethroids, neonicotinoids, triazines are divided into pesticides based on their target organism (insecticides, herbicides, fungicides) and chemical structure (organophosphates). The chemicals have environmental fate, which relies on water solubility, vapor pressure, and persistence. Half-lives are between days and decades, and the lifespan of organochlorine pesticides lasts years whereas new compounds usually decay in weeks to months (Ali et al., 2021).

Effects on non-target organisms are far-reaching and thoroughly recorded. Insecticides impact on useful insects such as pollinators, pest natural enemies as well as decomposers. Neonicotinoid insecticides, which are commonly applied to seed treatment and as foliar insecticides, are very toxic to the bees and other pollinators. Research records that there are 50-90% declines in the populations of pollinators in high-neonicotinoid usage areas (Tang et al., 2021). Herbicides also impact on the non-target plants, diminishing the amount of flora and food to support the pollinators and other wildlife. Fungicides also affect soil fungi such as mycorrhizae that are necessary in the nutrition of plants and other processes in climate resilient Regenerative Agriculture.

The effects of biodiversity are dire. In Europe, the literature on long-term studies reports 70 per cent of decrease in insect biomass and 50 per cent reductions in the population of farmland birds in the past decades, attributing pesticide use as the leading factor (Sud, 2020). Aquatic ecosystems are especially susceptible where populations of invertebrates and fish are reduced by run off of pesticides. Amphibians demonstrate significant decrease in farmland, where contact with pesticides is a factor in causes of reproductive issues and developmental defects. The development of pesticide resistance compromises the effectiveness of pest control. More than 500 arthropod pests have become resistant to the use of either one or more of the pesticide classes and demand higher application levels or more toxic substitutes (Dhananjayan et al., 2020). This results in a pesticide treadmill where more pesticides need to be used to control and more pesticides are required and consequently, environmental effects increase. The health implications of human health are acute poisoning and chronic effects of exposure. Exposure to pesticides has been associated with neurological, reproductive, endocrine, and carcinogenic. The agricultural workers are the most exposed to their risks, as it is estimated that 385 million cases of acute pesticide poisoning happen each year across the globe (Ali et al., 2021).

Biodiversity Loss and Ecosystem Services

Agricultural pollution promotes a drastic decline in biodiversity, including pollinators, soil life, and aquatic life. The losses undermine ecosystem services that support agricultural productivity and environmental sustainability (Osumanu & Kosoe, 2023).

This is of great concern as pollinators reduce, especially in relation to crop pollination. Animal pollination contributes about 235-577 billion dollars annually to agricultural activities in the world with about 75% of crops pollinated by animals. Nevertheless, there are significant population drops of pollinators worldwide. Research records 70% declines in the biomass of insects in agricultural landscapes in past decades (Sud, 2020). Neonicotinoid and other pesticides are the major causes of direct toxicity and sublethal effects on foraging behavior, navigation, and reproduction. These effects are added to by habitat loss due to agricultural intensification and loss of floral resource to herbicides.

The biodiversity of soil contributes to some of the vital ecosystem processes such as nutrient cycling, organic matter decomposition, soil structure, and pest suppression. Thousands of species of bacteria, fungi, protozoa, nematodes, arthropods and earthworms can be found in agricultural soils. Nevertheless, the high agricultural activities decrease the biodiversity of the soil significantly. The level of heavy metal pollution lowers the diversity of the microbes by 30-50 %. The application of pesticides reduces the population of earthworms by 50-90% and the abundance of useful arthropods (Kaparwan et al., 2020; Tang et al., 2021).

The agricultural pollution threatens the aquatic biodiversity immensely. Eutrophication is a result of nutrient pollution leading to the development of hypoxic environments which kill sensitive species. The pesticide contamination has impact on aquatic invertebrates, fish and amphibians. Research indicates that agricultural streams experience 50-70% decrease in diversity of aquatic invertebrates in comparison to reference sites (Rad et al., 2022).

The past decades saw a 50% decrease in the populations of farmland birds in Europe caused by agricultural intensification and the use of pesticides (Sud, 2020). The use of insecticides lowers the population of insect prey and herbicides destroy seed sources. Monoculture farming simplifies the habitat and lowers food diversity and nesting habitat.

There are economic impacts of ecosystem services loss. The drop in pollinators jeopardizes hundreds of billions of crop production every year. The degradation of soil biodiversity diminishes the ability of soil to suppress pests and augmenting reliance on pesticides. Deterioration of water quality leads to higher treatment cost and low fishery productivity. These wastages defy the sustainability and food security of agriculture (Osumanu & Kosoe, 2023).

Mitigation Strategies and Sustainable Practices

To curb agricultural pollution, there is a need to employ the concerted, multi-disciplinary, integrated solutions that incorporate the use of technology, management, and policy frameworks. There are several methods that demonstrate potential to cut down pollution and at the same time be productive, resilient and sustainable (Chaudhary et al., 2023; Sharma et al., 2024) (See details in Figure 2).

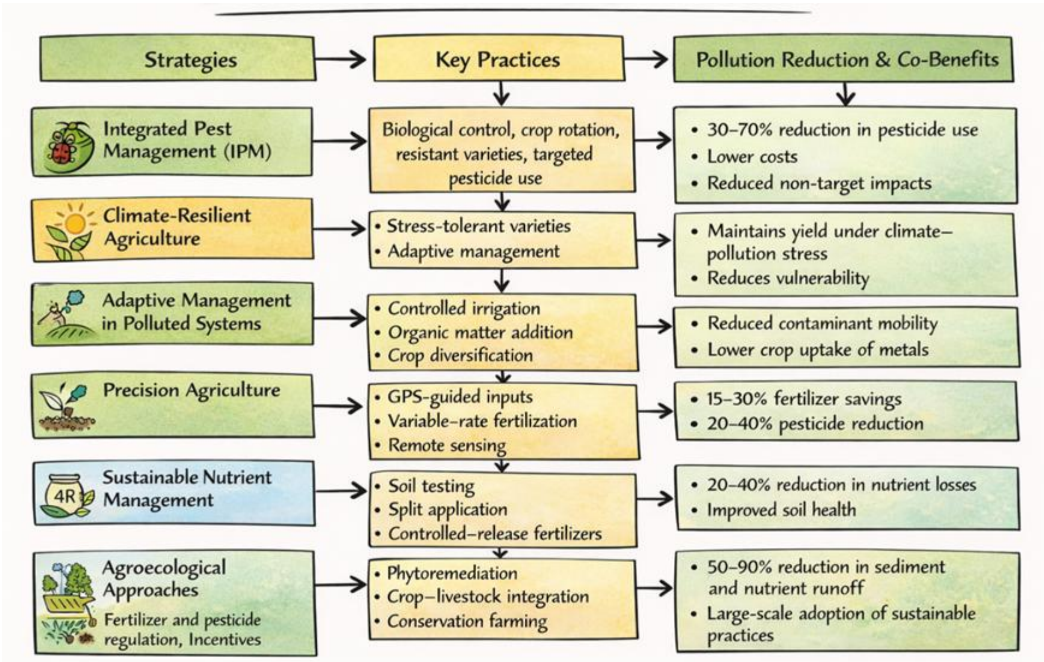

Figure 2. Conceptual frameworks for mitigation of agricultural pollution

Integrated Pest Management (IPM): Integrated Pest Management (IPM) will help to decrease the reliance on pesticides by applying several strategies: biological control with the help of natural enemies, cultural controls such as crop rotation and resistant varieties, mechanical control, and the reasonable application of pesticides only when needed. Application of Nano-technology, Ecological Engineering and other Eco-friendly management strategies are newly emerging tools for IPM under the backdrop of pollution and global climate crisis. The results of IPM programs show the reduction of pesticide use by 30-70% and the preservation or increase of the effectiveness of pest control. Such economic benefits are decreased input costs and high prices of low-pesticide products (Dhananjayan et al., 2020).

Climate resilient agriculture: Refers to the practices and varietal selection that sustains productivity in climatic stressful environments and acts as solutions to the pollution related vulnerabilities in agroecosystems. Climate resilient agriculture is intended to enhance productivity, adaptive capacity, and greenhouse gas emissions reduction to maintain food systems in a climate-and pollution-stressed world. Resilience is essential in the interaction of the presence of pollutants, drought, and heat to increase crop stress and food safety risks (Prasad et al., 2026).

Adaptation to polluted systems: Major strategies involve application of specific irrigation control measures to restrict movement of the pollutants, enhancement of soil organic matter, carbon farming, carbon sequestration to tie-up the metals, crop rotation and diversification to break accumulation pathways and water/soil quality monitoring to inform crop selection (Safdar et al., 2024).

Drought resistant and stress tolerant varieties: Deployment of drought tolerant and stress resilient crops has less water demand and less exposure of roots to contaminated moisture which decreases translocation in certain situations and allows yields to be sustained under the combined stressors (Prasad et al., 2026).

Reducing pollution sustainable agriculture techniques: Sustainable agricultural techniques can include conservation agriculture, conservation tillage, precision nutrient application, optimal irrigation timing, precision water management, agroforestry and crop residue cover that enhance soil health and decrease leaching and runoff of pollutants and inputs as well as reduce inputs and emission (Safdar et al., 2024).

Combination with pollution mitigation: Combining resilience with pollution control e.g. by using treated effluent, phytoremediation strips, tolerant crop rotations, and soil amendments to immobilize metals make co-benefits: long-term productivity, fewer contaminant uptakes, fewer health hazards to the population (Safdar et al., 2024).

Precision Agriculture: Precision Agriculture maximizes the inputs by site-specific management. Some of the technologies are GPS-guided machinery, variable rate application, crop monitoring remote sensing systems, and decision support systems. Accurate nitrogen control helps in saving 15-30% of fertilizers and retain yield hence, reducing losses to the environment and cost of production. Precision treatment of pesticides lowers usage by 20-40% because of targeted response of the affected regions (Mahmood et al., 2024).

Nutrient Management: Nutrient management practices enhance the efficiency of fertilizers and minimize on losses to the environment. The 4R nutrient stewardship model (Right source, Right rate, Right time, Right place) maximizes the use of fertilizers. These include nutrient status testing of the soil, split application, which is applied in line with demand of the crop, controlled release fertilizers, and nitrification inhibitors, which minimize losses in nitrogen. The cover crops absorb the remnants of nutrients hence avoiding leaching and enhancing the health of soil. Research shows that with better management, the losses of the nutrients are reduced by 20-40% (Debnath et al., 2020). Integrated Nutrient management strategies, application of Nano-technology enhance the efficiency of nutrients and mitigate the harmful effects of pollutants in Agro-Ecosystem.

The Bioremediation Technologies: Bioremediation Technologies provide environmentally friendly clearing of polluted soils. Rhizobacteria that promote growth in plants are known as plant growth-promoting rhizobacteria (PGPR) which promotes degradation of heavy metals and pesticides. Phytoremediation involves the use of plants to remove, stabilize or decompose contaminants. Hyperaccumulator plants accumulate heavy metals in tissues that can be harvested, and thus they can be removed off soils. Microbial consortia break the pesticide residues and other organic pollutants. Recent developments show that multi-contaminated soils can be effectively remedied with the help of synthetic microbial consortia (Chaudhary et al., 2023; Sharma et al., 2024).

The Agroecological Approaches: Agroecological approaches transform the agricultural systems to improve the ecological processes and minimize the use of external inputs. Some of the practices are diversified crop rotations, agro forestry, integrated crop livestock systems, and conservation farming. Such systems increase biodiversity, enhance soil health, increase resistance to environmental stresses, and mitigate pollution. Prolonged research has proved to be as productive or more so than standard systems with significantly reduced environmental effects (Adedibu, 2023).

Buffer Zones and Riparian Vegetation: Buffer zones and riparian vegetation handle transportation of pollutants to water bodies. Vegetated buffers help to trap sediments, absorb nutrients as well as filter pesticide run-offs. Research demonstrates that properly constructed buffer systems can reduce 50-90% of the sediment and nutrient loads (Rad et al., 2022).

Policy and Regulatory Frameworks are essential for widespread adoption of sustainable practices. The good policies involve the registration of pesticides, regulation of the use of fertilizers, water quality, and conservation practices incentive programs. Ecosystems services provide farmers with compensation of stewardship of the environment. Market incentives are created through certification programs of sustainable production. Knowledge to be transferred and technology adopted through the educational and extension services (Moldavan et al., 2024).

Future Directions and Recommendations

- Improved study of accumulative and synergistic impacts of multiple agricultural contaminants (e.g., pesticides, fertilizers, and heavy metals, microplastics and so on) in complicated combinations, as well as of the interactions among them and the effects of climate change on the behavior and fate of those formed.
- Development and field-scale optimization of advanced bioremediation technologies, such as engineered microbial consortia, hyperaccumulator plants, pollution resistant crop varieties, to reduce yield losses at contaminated locations.
- Acceleration of high-precision agricultural technologies available to the small-scale farmers in the developing world, including low-cost real-time sensors to monitor soil, water and air, controlled-release fertilizers, and biodegradable, low-persistent pesticides.
- Policy reforms on a basis of polluter-pays, ecosystem services payment, tax benefits on sustainable production, and harmonized international standards to avoid pollution displacement without disrupting food security, livelihoods of farmers, and environmental protection.
- Systemic changes (agroecological systems, diversified landscapes (crop rotations, intercropping, agroforestry), circular nutrient management, and extensive education/capacity building through extension services and participatory stakeholder networks).

Conclusion

Agricultural pollution is known to be a devastating impact to the soil, water, air quality, biodiversity, ecosystem services, and human health with widespread pesticide contamination of 64% of the global agricultural lands and excessive use of fertilizers contributing to water pollution and climate change. However, there are feasible ways out in the form of integrated pest management, precision agriculture, Climate smart Regenerative Agricultural practices, better management of nutrients and bioremediation, as well as agroecological methods that can help reduce pollution and maintain productivity and sustainability. Coordinated execution requires the long-term investment in research, favorable policies, educating farmers, and working with multiple stakeholders. Conclusively, the switch to resilient, low-input systems is necessary to balance increased food demands with environmental sustainability, farmer sustainability, and climate change. The problem can be solved by tackling pollution in advance changes based on evidence and continual innovation as a means of ensuring food security in the world and the well-being of the planet to support and sustain the future generations of the world.

Conflict of Interest Statement

The authors declare no conflict of interest.

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