



Review Article

Ecological Implications of Agrochemical Wastes on Non-Target Flora and Fauna: A Regional Appraisal with Reference to Bijnor District, Uttar Pradesh, India

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Abstract

The widespread use of agrochemicals, including pesticides, fertilizers, and plant growth regulators, has substantially increased agricultural productivity, but their indiscriminate application carries serious ecological risks. This review examines the classification, dispersal pathways, and ecological consequences of agrochemical wastes, with a regional focus on Bijnor District, Uttar Pradesh, India. Residues enter soil, water, and air through percolation, runoff, and volatilization, and subsequently undergo bioaccumulation and biomagnification. In non-target flora, exposure produces herbicide-induced physiological disturbance, suppression of soil microbial communities, and reduced plant diversity. Faunal effects include population declines among pollinators, earthworms, amphibians, fish, birds, and small mammals arising from direct toxicity, habitat contamination, and secondary poisoning. Studies from western Uttar Pradesh report pesticide residues in surface water, food crops, and wildlife, indicating the regional severity of contamination. Climate change compounds these pressures by promoting pest resistance, extending pathogen ranges, and accelerating eutrophication, with consequences for ecological stability and crop yield. The evidence reviewed here underlines the need for sustainable agrochemical management that protects environmental health without compromising agricultural resilience.

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Statement of Sustainability: Agrochemicals have been central to raising crop yields and securing food supplies, yet their excessive and unregulated use has caused soil degradation, water contamination, biodiversity loss, and serious risks to human health. Persistent residues accumulate in ecosystems, disturbing microbial balance and harming non-target species such as pollinators, fish, and birds. Sustainable practice requires a balanced approach that promotes integrated pest management, organic fertilizers, and biopesticides while educating farmers in safe handling and routine soil testing. Policy must therefore give weight to ecological resilience alongside productivity, so that agriculture can meet global food demand without compromising environmental health or the interests of future generations.

1. Introduction

Agrochemicals are the diverse group of chemical inputs used in crop production and allied farming activities; they include pesticides, chemical fertilizers, plant growth regulators, soil conditioners, and veterinary drugs (Dhananjayan et al., 2020). These compounds are applied to control pests and diseases and to regulate or promote crop growth (Gyeltshen et al., 2021), and they contribute to higher yields, the maintenance of soil nutrient status, and the protection of crops from infection (Dhananjayan et al., 2020). Approximately 25% of global crop production is lost each year to insect pests, weeds, and diseases, a loss that agriculture can ill afford given the food-security challenges ahead; consequently, the role of agrochemicals continues to expand (Koli et al., 2019). Modern agriculture depends heavily on these inputs, which raise yields cost-effectively and have become central to feeding a rapidly growing global population. In many developing countries, agrochemicals underpinned the success of the Green Revolution, during which production rose several-fold above earlier levels (Abhilash & Singh, 2002; 2009). The same inputs, however,

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adversely affect environmental and human health as production intensifies (Gyeltshen et al., 2021). Indiscriminate and excessive application by farmers has aggravated the problem, and unbalanced use degrades the environment and poses numerous challenges to agricultural ecosystems (Mandal et al., 2020). Every pesticide is, by design, intended to disrupt the normal physiological activity of the organism against which it is applied, or at least to repel it; the underlying premise is that a pest is an unwanted organism in an unwanted place, to be eliminated or rendered physiologically dysfunctional (Gore & Aryan, 2015).

Meeting global food demand nonetheless requires a sustainable approach, and within this context the use of agrochemicals remains largely unavoidable; the challenge facing farmers is therefore considerable, and the role of these inputs continues to grow (Federation of Indian Chambers of Commerce and Industry [FICCI], 2016). Agricultural activities that rely on chemical inputs are usually evaluated in terms of economic efficiency and the benefit of increased yield at reduced cost, whereas markedly less attention is paid to their potential environmental consequences (Udeigwe et al., 2015).

Pesticides are used primarily to raise crop yields by killing insect pests and weeds and by reducing or preventing plant diseases, whereas fertilizer application supplies the nutrients that soils require to support crop growth and higher productivity (Jangir et al., 2016; Kakraliya et al., 2017; Meena et al., 2020; Varma et al., 2017). Other agrochemicals, including growth-promoting hormones, soil stimulants, feed additives, and veterinary drugs, are used extensively in crop production, livestock rearing, and allied activities, again with the primary aim of increasing output at lower cost (Zhang et al., 2018). Pesticides applied to control pests persist in the environment for some time after they have performed their intended function, and this persistence produces side effects in non-target organisms because the residues accumulate in their tissues (Abd et al., 2025).

Pesticide exposure has been linked to numerous human health problems, including hormonal imbalance, reproductive dysfunction, chest congestion, immune suppression, cancer, and neurological disorders such as brain damage (Figure 1; Bisht et al., 2019; Sharma & Singhvi, 2017; Sharma et al., 2019; Sun et al., 2018). These substances enter human tissues through contaminated water and food and through inhalation of contaminated air. The World Health Organization and the Food and Agriculture Organization have jointly established Codex Alimentarius maximum residue limits, which define the pesticide concentrations considered acceptable in food intended for human consumption.

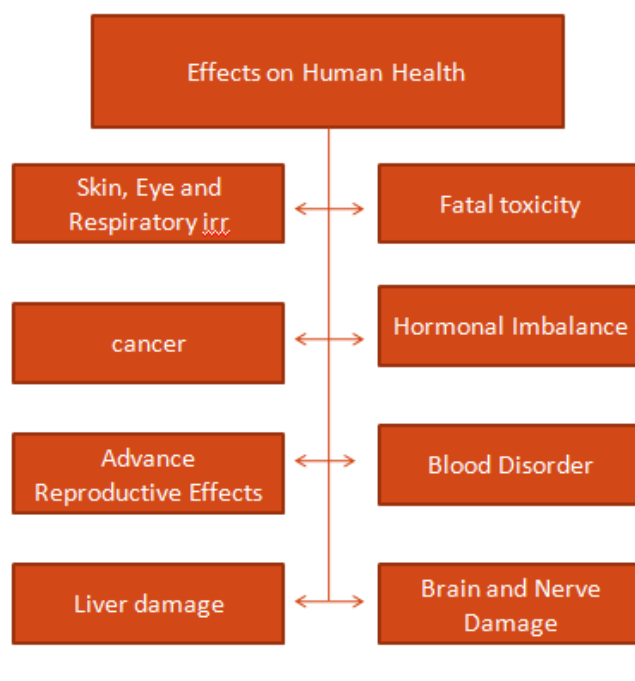


Figure 1. Major impacts of agrochemicals on human health.

2. Classification and Dispersal Pathways of Agrochemical Wastes

2.1. Types of Agrochemical Wastes

A wide range of agrochemicals are employed in modern agriculture to safeguard crop production and maintain the global food supply. Their use plays a vital role in ensuring both the quality and availability of food for large-scale consumption. Broadly, agrochemical wastes comprise plant-protection chemicals (pesticides), plant growth regulators, and fertilizers (Mandal et al., 2020). The plant-protection compounds, collectively termed pesticides, are classified further as herbicides, insecticides, algicides, fungicides,



rodenticides, nematicides, and molluscicides according to their target organism (Dhananjayan et al., 2020).

2.1.1. Fertilizers

Fertilizers are plant growth-promoting inputs, largely inorganic in composition, that supply the essential macronutrients nitrogen, phosphorus, and potassium. Modern agronomic practice relies heavily on combinations of these three nutrients to optimize crop productivity. Nitrogen is particularly important for leaf and stem development, being a fundamental constituent of proteins and nucleic acids. During the Green Revolution, widespread fertilizer use in industrial agriculture produced marked increases in crop yield by enriching soils directly and, in some formulations, by improving water retention and aeration. Application rates are normally guided by soil fertility tests or by estimates of crop nutrient removal, with non-leguminous crops depleting more soil nitrogen than nitrogen-fixing legumes. Prolonged and excessive reliance on chemical fertilizers nevertheless threatens soil health, because long-term use can reduce soil organic matter, accelerate acidification, and disrupt the structure and activity of beneficial microbial communities, thereby undermining fertility. In these respects chemical fertilizers differ from organic fertilizers, which are produced by composting animal manure, human waste, and plant residues. Application of organic fertilizers has been reported to improve soil organic matter, soil structure, aggregate stability, nutrient uptake, water-retention capacity, cation exchange capacity, nutrient use efficiency, and microbial activity (Liu et al., 2024). Long-term fertilization trials also show that repeated mineral inputs alter the accumulation, availability, and plant uptake of heavy metals in cultivated soils (Zhou et al., 2015).

2.1.2. Pesticide Residues

Pesticides are chemical or biological agents formulated to kill, repel, or otherwise control organisms that exceed the economic threshold level and threaten crop or livestock productivity. They function as biocides and are therefore toxic by design. The term pesticide is collective, encompassing insecticides, herbicides, fungicides, algacides, rodenticides, molluscicides, and nematicides, most of which are formulated to act on specific target pests.

2.1.3. Herbicides

Herbicides are chemical agents formulated to eliminate unwanted plants and are used chiefly in row-crop agriculture to raise productivity by reducing weed competition. They act through diverse molecular mechanisms that inhibit weed growth and survival. Compounds such as glyphosate, imazethapyr, and thifensulfuron are absorbed by the leaves and translocated to metabolic sites, where they disrupt the synthesis of essential amino acids; interference with these biochemical pathways suppresses plant development and allows the crop to dominate. Herbicides in common use include the acetanilides, alachlor, barban, chlorbromuron, chlorophenoxy compounds, dalapon, diuron, glyphosate, linuron, monuron, neburon, pendimethalin, pentachlorophenol, propham, sweep, 2,4-D, and 2,4,5-T (Mandal et al., 2020).

2.1.4. Insecticides

Insecticides are designed to kill insect pests, typically by disrupting essential physiological processes. Most act on the nervous system by interfering with normal signal transmission. Organophosphates and carbamates, for example, inhibit acetylcholinesterase, the enzyme that regulates nerve impulse transmission; inhibition allows acetylcholine to accumulate at neuromuscular junctions, causing overstimulation, paralysis, and death. Other insecticides, such as lindane, endosulfan, and fipronil, target the GABA receptor and block the entry of chloride ions, producing hyperexcitable nerve activity that manifests as tremors and convulsions before mortality. Representative compounds include the organic nitrogen insecticides benzoylphenylurea and chlordimeform; the organophosphates acephate, azinphos-methyl, bromophos, chlorpyrifos, coumaphos, diazinon, dimethoate, dioxathion, disulfoton, fenitrothion, fonofos, leptophos, malathion, methamidophos, parathion, phenthoate, phorate, phosmet, profenofos, and trichlorfon; the organochlorines aldrin, chlordane, DDT, dieldrin, dicofol, endosulfan, endrin, fipronil, heptachlor, lindane, and gamma-hexachlorocyclohexane; the carbamates aldicarb, carbaryl, carbofuran, carbosulfan, and cartap; and the insect growth regulators azadirachtin, benzoylphenylurea, diflubenzuron, methoxyfenozide, pyriproxyfen, spinosad, and tebufenozide (Mandal et al., 2020).

2.1.5. Fungicides and Bactericides

Fungicides and bactericides are applied to suppress fungal and bacterial pathogens of crops. Compounds in widespread use include bayleton, blue copper, chlorothalonil, copper hydrochloride, copper oxychloride, copper sulphate, dithane, the dithiocarbamates, mancozeb, metalaxyl, polytrin, Ridomil, the thiocarbamates, thiovit, and the triazoles (Mandal et al., 2020).

2.2. Routes of Dispersal into the Environment

2.2.1. Soil Percolation and Leaching

Most pesticides applied for agricultural and other purposes accumulate in the soil after application, and repeated or indiscriminate use increases the residue load. Edaphic factors and soil microbial diversity determine the subsequent fate of the applied compound, which may undergo degradation, adsorption, or transport to other regions (Hussain et al., 2009). A large number of transformation



products derived from a wide range of pesticides has been documented (Barcelo & Hennion, 1997; Roberts, 1998; Roberts & Hutson, 1999). In general, pesticide degradation depends on several physicochemical properties of the soil and on soil processes, including adsorption and desorption, plant uptake, surface and subsurface transport, volatilization, microbial metabolism, and chemical conversion (Mandal et al., 2020). The magnitude of bioaccumulation and biomagnification of any agrochemical is directly proportional to its persistence and lipophilicity.

2.2.2. Runoff into Water Bodies

Pesticide contamination of water is a worldwide concern, and statutory bodies in many countries have conducted studies to regulate pesticide concentrations in drinking water and so reduce the risk to human health (Sjerps et al., 2019).

Pesticide residues enter water bodies through several pathways, including agricultural runoff, point-source spillage, and the cleaning of spray equipment. Once introduced, these contaminants disperse within aquatic systems and threaten both ecological integrity and human health. Rainfall and irrigation also mobilize residues into surface waters (Larson et al., 2010).

2.2.3. Spray Drift and Volatilization

Pesticides are lost to the environment by several routes, the most important of which are volatilization into the atmosphere, aerial drift, runoff to surface waters in dissolved and particulate form, and leaching into groundwater (Mandal et al., 2020). Spraying also contributes to air pollution, because a proportion of the applied chemical escapes into the atmosphere directly or through subsequent volatilization.

3. Ecological Effects on Non-Target Flora

3.1. Effects on Natural Vegetation

Pesticide sprays may strike non-target vegetation directly, or they may drift or volatilize from the treated area and contaminate air, soil, and neighbouring plants. Some drift occurs during every application, even where ground-based equipment is used (Glottelty & Schomburg, 1989).

3.2. Impact on Aquatic Macrophytes

Aquatic macrophytes are a diverse assemblage of photosynthetic organisms visible to the naked eye and drawn from several divisions of the kingdom Plantae, including the Chlorophyta, Bryophyta, Pteridophyta, and Spermatophyta (Toivonen & Huttunen, 1995). Macrophytes belonging to the more primitive divisions are less abundant than the vascular forms. They assimilate nutrients dissolved in the water body and convert them into biomass (Escobar & Escobar, 2017), and they have been used, either alone or as components of constructed wetlands, to remove toxic compounds from various types of wastewater (Akinbile et al., 2016). Because macrophytes take up dissolved contaminants directly, herbicide residues reaching surface waters suppress their growth and reduce the capacity of the water body to assimilate nutrients.

3.3. Herbicide-induced Physiological Changes in Wild Plants

Herbicides are designed to kill plants, so it is unsurprising that they injure or kill desirable species when applied directly to them or when they drift or volatilize onto them (Aktar et al., 2019). Many ester formulations have been shown to volatilize from treated plants in vapour concentrations sufficient to cause severe damage to adjacent vegetation (Straathoff, 1986). The resulting physiological effects include chlorosis, inhibited amino acid synthesis, impaired photosynthetic efficiency, and reduced seed set in exposed wild populations.

3.4. Soil Microbial Flora and Mycorrhizal suppression

The soil microbial community is strongly affected by the application of agrochemicals, with consequences for ecosystem function and long-term soil productivity. Pesticides act as environmental stressors on the microbial assemblages that inhabit agricultural soils: they suppress beneficial taxa, reduce microbial diversity, and alter essential ecological functions. High application rates intensify these effects, depressing microbial activity and impairing nutrient cycling and soil fertility (Mandal et al., 2020).

Pesticides alter both the composition and the overall diversity of the beneficial soil microbiome. Some populations are suppressed or eliminated while others proliferate under exposure, producing an imbalance that impoverishes the agricultural soil microbiota. Of particular concern is the inactivation of nitrogen-fixing and phosphorus-solubilizing organisms, which are central to nutrient cycling and soil fertility; pesticide application has been shown to depress populations of *Azospirillum* and to lower ammonification rates in cultivated soils (Srinivasulu et al., 2012). Such disruption compromises soil health, reduces productivity, and carries long-term consequences for agroecosystems. Other studies indicate that certain microbial populations use the applied pesticides as a source of energy or nutrients and are thereby favoured, utilizing the compounds as sources of carbon, sulphur, and electrons under suitable conditions (Parte et al., 2017). This selection increases the abundance of particular microbial groups while reducing overall diversity, although it may broaden functional diversity by favouring organisms capable of degrading xenobiotic compounds.



Suppression of arbuscular mycorrhizal colonization under repeated fungicide application further limits phosphorus acquisition by host plants.

4. Ecological Effects on Non-Target Fauna

Pesticides applied to agricultural land over long periods affect non-target organisms. When these compounds are used to prevent or control pathogenic pests, the organisms most severely affected are the beneficial insects and parasitoids responsible for pollination and natural predation (Vickerman, 1988). Indiscriminate use also depletes and disturbs populations of other soil invertebrates, including nematodes, mites, earthworms, and spiders, together with the soil microbiota (Dhananjayan et al., 2020).

4.1. Terrestrial Invertebrates (Earthworms, Ants, and Beetles)

Earthworms represent the largest share of the soil invertebrate community, accounting for more than 80% of the population (Yasmin & D'Souza, 2010). They maintain soil quality by decomposing organic matter into humus through their metabolism and by helping to retain soil moisture (Dhananjayan et al., 2020), and they are consequently regarded as among the best indicator organisms for soil quality (Paoletti, 1999). Where high volumes of agrochemicals continue to be applied, the density and diversity of earthworm populations decline. Several studies have documented effects of soil pesticide residues on earthworm growth, behaviour, and reproduction, and standardized laboratory tests confirm that these effects are concentration dependent (Yasmin & D'Souza, 2010).

4.2. Pollinators (Bees, Butterflies, and Hoverflies)

The term pollinator denotes any biotic agent that mediates pollination, and the group includes honey bees, fruit flies, beetles, and birds (Dhananjayan et al., 2020). Pollinators also serve as bio-indicators, because they are sensitive to environmental stress. Where their populations are reduced by predation, habitat alteration, or chemical residues, natural pollination is impaired and the floral composition of the agroecosystem becomes unbalanced (Kevan, 1999). Because honey bees account for approximately 80% of pollination services, the effects of pesticides on this group have been reported widely (Dhananjayan et al., 2020), and several studies have confirmed the toxicity of pesticides to honey bee populations (Blacquiere et al., 2012). Documented effects include abnormal foraging behaviour, reduced learning and memory, impaired reproductive capacity, and lower efficiency of pollen collection, culminating in colony collapse disorder (Gill et al., 2012).

4.3. Amphibians and Reptiles

Amphibians are ectothermic vertebrates whose physiology favours the accumulation of chemical residues. A rapid global decline in amphibian populations has prompted extensive assessment of the responsible factors: 7.4% of all amphibian species have been listed as critically endangered, and more than 43% of species are experiencing population decline (Stuart et al., 2004). Although several causes have been proposed, the accumulation of pesticide residues appears to be among the principal ones (Dhananjayan et al., 2020). Amphibians are particularly vulnerable to environmental contaminants because of their permeable skin, limited immune defences, and dependence on both aquatic and terrestrial habitats, characteristics that also make them useful indicators of ecological stress. Christin et al. (2013) found that frogs (*Rana pipiens*) inhabiting agricultural fields were smaller and lighter than conspecifics from less contaminated areas.

4.4. Aquatic Invertebrates and Fish

Water contamination arises from several sources, including agricultural runoff, industrial effluent, spray drift, dust deposition, and rainfall. Within aquatic systems, pesticide residues and their degradation products disperse widely and persist in the water column, in sediments, and in biota. These compounds may leave the system through volatilization, co-distillation, or bioaccumulation in fish, which subsequently transfer residues to humans, birds, and other animals through consumption; leaching through soil layers also allows certain pesticides to reach groundwater. Surface water contamination therefore poses risks to aquatic flora and fauna and to human health. Aquatic organisms determine the trophic status of water bodies, and chemical pollution can destabilize ecosystem balance and reduce water quality. Sarkar et al. (1997) examined organochlorine contamination of marine and estuarine sediments along the west coast of India and reported measurable concentrations of total HCH, aldrin, dieldrin, endrin, and total DDT. Sediments of the Ganga plain rivers show comparable enrichment with trace metals derived from urban and agricultural sources (Singh et al., 1997, 2002).

Fish are among the most suitable indicator organisms in both freshwater and marine ecosystems, because they interact closely with the physical, chemical, and biological characteristics of their environment. They form a critical link in aquatic food chains and webs, feeding on phytoplankton, zooplankton, and sediment detritus, and thereby accumulating chemical residues (Dhananjayan et al., 2020). Fish are sensitive to enzymatic and hormonal disturbance, and the biochemical changes induced by pesticide stress lead to metabolic disruption, inhibition of key enzymes, retarded growth, and reduced fecundity and longevity. The liver, kidney, brain, and gills are the organs most vulnerable in fish exposed to a toxicant-bearing medium (Malik & Maurya, 2015).



According to the United States Environmental Protection Agency, trifluralin, an active ingredient of the herbicide Snapshot, is highly to very highly toxic to both cold-water and warm-water fish (U.S. EPA, 1996), and a series of tests showed that it also causes vertebral deformity (Koyama, 1996). Several cases of pesticide poisoning in dolphins have been reported. Because of their high trophic position and the comparatively low activity of their drug-metabolizing enzymes, aquatic mammals such as dolphins accumulate elevated concentrations of persistent organic pollutants (Tanabe et al., 1988) and are correspondingly vulnerable to toxic effects.

4.5. Birds and Small Mammals: Secondary Poisoning and Food-chain Effects

Birds are valuable bio-indicators of chemical contamination because they accumulate residues from across the ecosystem. Although they regulate insect populations and help maintain ecological balance, they are frequently exposed to pesticides by several routes, with consequences for their survival. Accumulation of residues in the tissues of terrestrial and aquatic birds and reductions in cholinesterase activity have been reported worldwide (Muralidharan et al., 2012; Smith et al., 2010). Direct ingestion of granular formulations and treated seed, direct exposure to sprays, and feeding on contaminated food and water are among the routes leading to mortality (Fishel, 2013). Persistent residues induce adverse physiological effects in birds, including behavioural alteration, eggshell thinning, and impaired reproduction. Among the agrochemicals, fungicides and insecticides pose the greatest threat to farmland birds; ground-nesting species in the United States have proved highly susceptible to the acute toxicity of pesticide residues (Mineau & Whiteside, 2013). Residues also reach mammals, including humans, through the same food chains. Srivastava et al. (2011) monitored pesticide residues in market basket samples of vegetables from Lucknow, Uttar Pradesh, and although the organochlorine concentrations recorded lay below established tolerances, continuous consumption of produce carrying even moderate contamination can lead to accumulation in consumer tissues and to chronic, potentially fatal effects (Gore & Aryan, 2015).

5. Case Examples and Regional Studies

5.1. Observations from Bijnor and Western Uttar Pradesh

Like many other countries, India has relied extensively on pesticides and other chemical inputs to protect crops and raise agricultural productivity, and a large number of pesticides are currently registered for use. India is the leading producer of pesticides in Asia and ranks prominently in global consumption. Although these inputs have contributed materially to yield improvement and food security, their unregulated and indiscriminate application has raised serious concerns for ecological sustainability and long-term health. Bankar et al. (2012) analysed 120 samples of four fresh vegetables drawn from three major markets in Uttar Pradesh: no residues were detected in 58.33% of samples, 28.33% contained residues at or below the maximum residue limit, and 13.33% exceeded it. The practice of irrigating leafy vegetables with wastewater is intended to yield socio-economic benefit, but produce grown in wastewater-irrigated areas may carry heavy metals at concentrations that constitute a public health hazard, making the practice unsafe and unsustainable in the long term. Gupta and Kanaujia (2014) examined the impact of pesticides on the black kite (*Milvus migrans govinda*), a beneficial raptor, in the Bundelkhand region, and the broader pattern of pesticide use and its consequences in Uttar Pradesh has been reviewed by Gore and Aryan (2015).

Bhutani and Ahamad (2019) surveyed farmers in Najibabad, Bijnor District, and found that respondents generally had limited knowledge of fertilizers and were largely unaware of soil-testing facilities. Manure was the principal input before 2000, after which chemical fertilizers became dominant. In recent years, however, chemical fertilizer use has declined as farmers have increasingly adopted organic alternatives out of concern for harmful effects. Purchasing decisions are strongly influenced by peer advice, with nearly 60% of farmers consulting others before buying fertilizer. A similar shift was observed for pesticides: although India is a major producer, overall consumption remains low by global standards, and chemical pesticide use has fallen while the use of biopesticides has risen sharply. Farmers in the study area now favour natural preparations such as neem and onion extracts. Nationally, insecticides account for 76% of pesticide use, compared with 44% globally. Pesticides have therefore contributed to higher yields and to the control of disease vectors, but they continue to pose significant risks to health and to the environment.

5.2. Comparable Studies from Similar Agroclimatic Zones

The prolonged persistence of certain agrochemicals in the environment leads to contamination of food and feed, with a series of consequent harmful effects. Heavy metals present in agricultural systems compound these risks, reducing crop quality and posing long-term threats to ecological and human health.

Chaudhary and Chaudhary (2012) assessed groundwater used for drinking in parts of Meerut District, Uttar Pradesh, and found that some samples contained marginally elevated concentrations of sodium, calcium, potassium, and magnesium. These elevated cation concentrations were attributed to the unsafe discharge of effluent from sugar mills, paper and pulp mills, and distilleries, to untreated domestic wastewater from villages and towns, and to the intensive use of pesticides and fertilizers in agriculture.

The organochlorine pesticides most commonly encountered in surface waters of the Sharda River region in Lakhimpur Kheri, Uttar Pradesh, were dieldrin, heptachlor epoxide, isomers of hexachlorocyclohexane, and DDT. In several instances the concentrations



detected exceeded the target levels set by the European Union, particularly for gamma-hexachlorocyclohexane and p,p'-DDT. Their occurrence in these waters is attributable both to the intensive use of chemical pesticides in agriculture and to transboundary pollution (Maurya & Kumar, 2013).

Yadav et al. (2013) measured iron, cadmium, nickel, lead, copper, and zinc in vegetables irrigated with water from different sources in the industrial area of Naini, Allahabad. Concentrations in irrigation water followed the order $\text{Fe} > \text{Zn} > \text{Cd} > \text{Pb} > \text{Ni} > \text{Cu}$, whereas soils at industrially contaminated sites followed the order $\text{Fe} > \text{Ni} > \text{Zn} > \text{Cu} > \text{Cd} > \text{Pb}$. Uptake and translocation factors from soil to the edible parts of the vegetables differed appreciably among the elements examined.

Groundwater contamination by heavy metals has become a conspicuous problem over the past two decades as a result of industrial effluent discharge, untreated domestic waste, and the increasing use of agrochemicals in farming (Gore & Aryan, 2015).

6. Environmental and Agricultural Consequences

6.1. Climate Change and Pest Dynamics

Heavy application of agrochemicals carries serious environmental consequences, particularly where the applied compounds are not fully taken up by the crop and are released into surrounding ecosystems. Outbreaks of disease and insect pests frequently coincide with anomalous climatic conditions such as erratic rainfall, drought, and fluctuating humidity, all of which depress yield. Climate change is also likely to influence pesticide use, because pests and diseases are expected to appear more frequently (Koli et al., 2019). In broad terms, climatic change is expected to widen the geographical distribution of pests and pathogens, to increase the risk of invasion by migrant pests, and to accelerate the development of pesticide resistance. A longer crop growing season will allow more time for pest and pathogen populations to build up, and pesticide use itself is projected to rise by a factor of 2.4 to 2.7 by 2050 (Tilman et al., 2001).

6.2. Disruption of Ecological Balance

Insect pests respond to climate change in diverse ways, ranging from shifts in phenology to changes in community composition and ecological dynamics. Forest ecosystems, which occur across a wide range of climatic zones, possess sufficient resilience to persist under changing conditions. The movement of pests into new territory where natural enemies are absent can nevertheless trigger sudden outbreaks, causing extensive tree mortality and reducing forest productivity. Increased pest incidence in agricultural systems is likewise expected to cause substantial economic loss as climate change increases the abundance and activity of insect pest populations (Koli et al., 2019).

6.3. Impact on Crop Yield and the Loss of Beneficial Organisms

Plant disease arises from the interaction of three factors: a susceptible host, a virulent pathogen, and environmental conditions that favour infection. Rising temperatures, altered rainfall patterns, and prolonged drought can intensify disease severity and reshape the evolutionary relationship between plants and their pathogens. Pathogen biology is closely regulated by environmental parameters: propagule production and germination are strongly modulated by temperature, relative humidity, and the duration of leaf surface wetness, particularly in foliar pathogens, and these variables together determine viability, infectivity, and epidemiological success. The capacity of a pathogen to overwinter or oversummer in the absence of a suitable host is similarly governed by temperature and humidity. Pathogens adapted to high latitudes often tolerate a broad range of thermal conditions, so continuing climate change is expected to enhance their fitness and thereby raise the likelihood of outbreaks and large-scale epidemics. Dry conditions act directly on pathogens, as reported for the invasive exotic *Heterobasidion irregulare* in central Italy, which is better adapted to dispersal under a Mediterranean climate than the native *Heterobasidion annosum* (Garbelotto et al., 2010). Temperature and moisture are pivotal in regulating the reproductive capacity of many plant pathogens, and climate change is projected to compromise plant health and, in some contexts, to increase the incidence of pests and diseases by creating conditions favourable to pathogen proliferation. More frequent infection by *Phytophthora infestans* has been reported in Finland and attributed to climate change (Hannukkala et al., 2007), and high temperatures in Canada and the United States have been associated with large-scale outbreaks of bark beetles (Bentz et al., 2010; Woods, 2011; Woods et al., 2010).

6.4. Eutrophication and Algal Blooms in Aquatic Systems

Eutrophication is characterized by excessive plant and algal growth arising from increased availability of one or more of the factors that limit photosynthesis, such as light, carbon dioxide, and nutrients (Schindler, 2006). It is a natural process that proceeds gradually over centuries: as lakes age they accumulate sediment, which eventually fills the basin and alters water quality and ecosystem balance. Human activity has greatly accelerated the process, a phenomenon termed cultural eutrophication, which occurs when excess nutrients, principally nitrogen and phosphorus, enter aquatic ecosystems through both direct discharge and diffuse sources, with severe consequences for drinking water supplies, fisheries, and recreational waters. The most visible outcome is the formation of dense algal blooms, which are often malodorous, reduce water clarity, and degrade water quality. By intercepting light, blooms suppress the growth of submerged plants in shallow zones and cause their die-off, and reduced visibility also impairs the ability of



visual predators to capture prey, disrupting food chains. When dense blooms senesce, microbial decomposition depletes dissolved oxygen and creates hypoxic or anoxic dead zones that cannot support most organisms; such zones occur in many freshwater lakes, including the central basin of Lake Erie, during summer (Arend et al., 2011). By lowering dissolved oxygen concentrations, eutrophication increases fish mortality and degrades the quality of ponds and lakes, disturbing their ecological balance and reducing their suitability for industrial, recreational, and domestic use. Unchecked, it can alter the structure of a water body rapidly: small freshwater systems progressively lose capacity through sedimentation and silting, and many ponds and lakes may eventually lose their aquatic character altogether and become terrestrial. Fertilizer runoff into the previously stable ecosystem of the Pagasitikos Gulf, Greece, produced eutrophic conditions and algal blooming (Triantafyllou et al., 2001). Research attention to this problem has grown considerably, and eutrophication, acidification, and contamination by toxic substances are all expected to become more serious threats to freshwater resources and ecosystems.

Lake Apopka is a large (125 km²), shallow (mean depth 12.5 m) lake in Florida, United States, which became hypereutrophic as a result of phosphorus loading from floodplain farms; it has been reported to carry high concentrations of nutrients, phytoplankton (chlorophyll a, 80 micrograms per litre), and suspended matter (Coveney et al., 2002).

The lakes of the Pampa plains, Argentina, are shallow, polymictic, and eutrophic to hypertrophic, and they fluctuate widely in water renewal time and salinity; organic discharge renders them highly turbid (Quiros et al., 2002).

During the second half of the twentieth century the Lake Victoria ecosystem in Kenya underwent drastic change, the most conspicuous element of which was the decline of many endemic fish populations. Remnant populations of some species that had disappeared from Lake Victoria itself now occur abundantly in the Yala Swamp lakes (Aloo, 2003).

Nutrients, and phosphorus and nitrogen in particular, are the principal drivers of eutrophication and of the decline of aquatic ecosystems. Where large quantities of phosphorus enter lakes and rivers, commonly through agricultural runoff, eutrophication accelerates and the natural balance of aquatic life is disturbed. Excess phosphorus alters competition between macrophytes and algae, generally favouring rapid algal growth over higher plants, and this enrichment reduces biodiversity and alters community structure. In rivers and streams, phosphorus accumulates in sediment, where it becomes available to benthic algae and rooted plants and so intensifies the problem. Organic fertilizers such as cattle dung, pig dung, and poultry manure likewise influence phytoplankton diversity and abundance, illustrating the direct effect of nutrient input on aquatic productivity. A shallow eutrophic wetland receiving domestic sewage and agricultural runoff at Ujjain, India, was heavily infested with water hyacinth (Billore et al., 1998), and extensive algal blooming has been recorded in Udai Sagar Lake, India, which became eutrophic through discharges from phosphate mines, chemical factories, distilleries, and domestic sources (Das, 1999). Nutrients reach aquatic environments through natural processes such as rock weathering, soil leaching, and rainfall, but also through human activity, particularly agricultural runoff and domestic sewage; surface runoff rich in agricultural waste has been found to enrich Lake Kastoria, Greece (Kaussouris et al., 1991).

The Baltic Marine Environment Protection Commission identifies eutrophication as the greatest single threat to aquatic ecosystems, and anthropogenic pressures have driven major ecological change across the Baltic Sea, including shifts in plankton, benthic fauna, algae, and fish communities. Despite legislation in many regions aimed at controlling direct nutrient discharge, eutrophication and cyanobacterial blooms remain widespread in surface waters globally. Water resource managers therefore employ a range of strategies to reduce nutrient loading and mitigate the ecological effects of cultural eutrophication. These include diverting nutrients away from the water body, adjusting nutrient ratios to limit algal growth, mixing the water column to prevent stratification, shading lakes or ponds with liners or dyes to reduce light penetration, and applying algacides or herbicides to suppress blooms. Reducing nutrient input is often difficult and costly, however, particularly in agricultural regions where non-point sources dominate, and even where external loading is reduced, internal release from sediments can continue to degrade water quality. Biomanipulation offers a further route to restoration by altering food-web structure, typically through the removal of planktivorous fish by harvesting or the introduction of piscivores; large-bodied grazers such as *Daphnia* then become dominant and help to control phytoplankton and improve water clarity.

7. Monitoring, Risk Assessment, and Regulatory Framework

Monitoring is the maintenance of regular surveillance through measurements taken at fixed intervals over an indefinite and usually long period, and the duration of that period is fundamental to the design and purpose of every environmental monitoring programme. Two considerations underlie the monitoring of the natural environment: first, to establish baselines that represent the current status of ecosystem components, and second, to detect change over time, particularly change that exceeds the natural variation in those baselines. Closely related to both is the aim of explaining why the observed changes are occurring (Vaughan et al., 2001).

7.1. Methods of Ecotoxicity Testing

Ecotoxicity tests are used within environmental hazard assessment frameworks to establish the intrinsic hazard of chemical substances that may be released into the environment. Hazard assessment normally follows a tiered approach. Short-term, or acute,



tests are applied first, with organism survival the most common endpoint. Longer-term, or chronic, tests, in which sublethal effects on growth or reproduction are the usual endpoints, are then applied where the results of the short-term tests, combined with large safety factors, suggest a possible environmental risk (Crane et al., 2008). Schemes of this kind, such as those required under the Registration, Evaluation, Authorisation and Restriction of Chemicals regulations, are typical of the tiered testing strategies developed worldwide and supported by international bodies such as the Organisation for Economic Co-operation and Development (Crane et al., 2008).

7.2. Indian and Global regulations on Agrochemical Disposal

Global pesticide consumption has exceeded four million tonnes annually since 2010, and India is among the largest consuming countries. The first pesticide manufactured in India, in 1948, was the organochlorine DDT, and the sector has since developed into a major agrochemical industry (Abhilash & Singh, 2009). As of 1 March 2021, a total of 293 pesticides and 738 formulations were registered for use in India.

7.2.1. Waste Disposal Options

Disposal options for pesticides are limited by environmental sensitivity and by licensing controls, and for the most part they involve either licensed landfill disposal, possibly with pretreatment for lightly contaminated wastes, or high-temperature incineration at 1200 degrees Celsius with scrubbing facilities for designated toxic and hazardous waste types (Johnson, 1998).

7.2.2 Waste disposal contractors

Engaging a reputable contractor is essential, and the standing of any contractor should be investigated thoroughly before services are secured. A formal contract must be agreed in order to establish legal acceptance of mutual responsibility and liability. The contractor's disposal facilities must be audited before first use and at least annually thereafter to confirm that the necessary standards are maintained. The disposal route for every waste consignment must be discussed and agreed with the contractor, and a certificate of disposal must be obtained stating that the waste has been dealt with in the agreed manner. Payment of invoices should be withheld until that certificate has been received (Johnson, 1998).

7.2.3. Waste Transfer Stations

Some contractors use waste transfer stations to accumulate wastes before segregating them into similar types for disposal elsewhere. Such facilities are widely used and are acceptable provided that the station is fully licensed with the local authority, that the contractor concerned is reputable, that a complete cradle-to-grave record is maintained for all waste consigned to the station, and that the full disposal route is agreed with the contractor beforehand and full certification of disposal is provided on completion (Johnson, 1998).

7.2.4. Transport

Strict regulation is essential to the management of waste disposal. In an increasing number of countries, vehicles used to transport waste must be registered officially with the relevant authorities, and it is therefore the responsibility of the waste disposer to ensure that only properly registered vehicles are used for collection and transport. This requirement maintains accountability, deters illegal dumping, and ensures that waste is handled in compliance with environmental and safety standards. Where such regulation does not exist, the disposer must satisfy itself that the contractor's vehicles are roadworthy, that loads are secure and not overloaded, that a copy of the waste manifest and emergency telephone contacts are carried in the vehicle, that the driver has received safety and emergency training, and that the appropriate hazard warning signs are displayed prominently (Johnson, 1998).

8. Sustainable Approaches and Mitigation Strategies

8.1. Integrated Nutrient and Pest Management

Integrated nutrient and pest management emphasizes the connection between soil fertility and plant health, so that nutrient management and pest control are applied in a complementary manner. The approach recognizes that well-nourished plants are more resilient to pests and diseases, whereas imbalanced fertilization increases vulnerability to infestation. By combining the two, integrated management seeks to achieve optimal productivity, improved produce quality, and environmental sustainability.

Balanced nutrition strengthens the natural defence mechanisms of plants against pests and pathogens, and several cultural practices complement nutrient management directly. Crop rotation with legumes enriches soil nitrogen while disrupting pest life cycles; organic mulches and compost improve fertility and create conditions unfavourable to pests; and sound irrigation management prevents the water stress that predisposes crops to pest and disease attack. Optimizing crop production in this way, within a circular-economy framework that returns nutrients and organic residues to the soil, reduces dependence on external chemical inputs (Rodino et al., 2024).



The benefits of integrated nutrient and pest management are correspondingly broad. Optimal nutrition enhances crop vigour and productivity, the incidence of pests and diseases falls, and chemical input requirements decline, which in turn minimizes environmental and health risks. Soil fertility and microbial activity improve, and production becomes more sustainable while delivering higher economic returns.

8.2. Bioremediation and Phytoremediation

Bioremediation is a clean-up approach that uses living organisms, including native microorganisms, their enzymes, and plants, to transform hazardous contaminants into less harmful compounds. Because it relies on natural biological processes, it offers an environmentally sustainable alternative to conventional physical and chemical treatments, which carry a greater risk of secondary pollution.

A principal advantage of bioremediation is that substantial reductions in pollutant load can be achieved with minimal environmental disturbance. Depending on site conditions and treatment objectives, it may be conducted *in situ*, with contaminants treated where they occur, or *ex situ*, with polluted material removed and treated under controlled conditions elsewhere.

8.2.1. In situ Bioremediation

In situ techniques treat polluted soil at its original location. Because the soil need not be excavated or transported, these approaches are comparatively inexpensive and cause little environmental disturbance. Nutrients and microorganisms are added to the contaminated site so that natural biological processes can degrade the harmful substances present.

The efficiency of *in situ* methods is generally confined to shallow soil layers, usually to a depth of about 30 to 60 cm, because oxygen does not readily penetrate further. Successful treatment requires careful control of oxygen supply, nutrient concentration, moisture, and temperature so that microbial growth is sustained. A common practice is the application of aqueous solutions enriched with oxygen and nutrients, which enables the indigenous bacteria to degrade pollutants more effectively.

Several specific techniques are used. Natural attenuation relies on unassisted natural processes to reduce contamination; bioventing supplies oxygen to the soil to stimulate microbial activity; biosparging injects air into groundwater to enhance pollutant breakdown; and bioslurping combines air injection with vacuum extraction to remove hydrocarbons from soil and water. *In situ* remediation is therefore a sustainable and cost-effective approach, although its success depends on maintaining favourable conditions at the contaminated site.

8.2.2. Ex situ Bioremediation

Ex situ remediation involves removing contaminated soil or water from the polluted site and treating it elsewhere. This route is generally chosen where *in situ* methods are insufficiently effective or where results are required more quickly. Although *ex situ* treatment can shorten the time needed to reach clean-up targets, it is usually more expensive, because it entails transporting polluted material, establishing treatment facilities, and complying with additional environmental regulation. Social, legal, and logistical considerations also affect its feasibility.

Ex situ processes fall into two categories, slurry phase and solid phase. In slurry-phase treatment, contaminated soil is mixed with water and nutrients in a reactor, producing a slurry in which microorganisms interact more effectively with the pollutants and break them down into less harmful substances; the water is subsequently separated from the soil and tested to confirm that contaminants have been removed or reduced before further use or disposal. In solid-phase treatment, polluted soil is treated above ground using specialized equipment, with moisture, oxygen, nutrient concentration, and temperature controlled to support microbial activity while preventing the escape of pollutants to the surrounding environment.

Ex situ remediation is thus a controlled and effective strategy for hazardous sites. It demands higher expenditure and careful management, but it offers faster pollutant removal and greater flexibility in applying biological and chemical treatments under optimized conditions.

8.2.3. Phytoremediation

Phytoremediation is a plant-based clean-up technology and a form of bioremediation that exploits the natural capacity of plants to remove or neutralize pollutants such as pesticides from contaminated soil, water, and adjacent environments. It is regarded as safe, inexpensive, and environmentally benign, because it operates at the contaminated site without the addition of further chemicals.

Different plant organs mediate different clean-up processes. In phytotransformation, or phytodegradation, plant enzymes convert toxic compounds into less harmful or more stable forms; in phytoextraction, plants absorb pollutants into their tissues, particularly the roots and leaves; in phytovolatilization, plants release certain pollutants to the atmosphere in a less harmful form; in phytostabilization, plants trap or immobilize pollutants within the soil so that they cannot spread; and in rhizofiltration, plant roots filter pollutants from water. Each mechanism is considered in turn below.

Phytotransformation. Plant enzymes act as natural catalysts of degradation. Laccase and peroxidase break down complex toxic compounds, dehalogenase removes halogen substituents, nitrilase degrades nitrile pollutants, and nitroreductase reduces nitro



compounds. Together these enzymes either render pollutants less harmful or immobilize them so that further damage is prevented.

Phytostabilization. Phytostabilization, also termed phytoimmobilization, is the process by which plants retain contaminants at the root-soil interface. The pollutants become less mobile and are prevented from spreading, so that they are less likely to be taken up by living organisms, to leach into water, or to enter food chains. The cell walls of plant roots contain compounds such as humic substances and lignin that bind both organic and inorganic pollutants, and root exudates act directly on soil metals, causing them to precipitate as insoluble compounds and so locking them in place. The process is most effective in grasses, herbs, and marsh species with fibrous root systems.

Phytoextraction. Phytoextraction, also called hyperaccumulation, uses plants known as hyperaccumulators to remove pollutants from soil and soil water. These plants take up contaminants through the roots and translocate them to the stems and leaves; because the pollutants accumulate in the above-ground tissues, the biomass can subsequently be harvested. This makes it possible both to remediate polluted soils and to recover useful metals for reuse, although the harvested crop must be disposed of with care.

Phytovolatilization. In phytovolatilization, plants take up toxins and release them to the atmosphere. Pollutants absorbed by the roots are either converted to volatile forms or released unchanged through transpiration. The process is most pronounced in dense stands, where the rate of volatilization of soil chemicals is highest, and the pollutants leave the plant through the stems, trunk, and leaves.

Rhizofiltration. Rhizofiltration uses plant root systems to treat water contaminated with toxic substances. Plants absorb pesticides and other harmful compounds from groundwater and accumulate them in their tissues. The technique is particularly suited to the treatment of surface water, wastewater, and groundwater rather than to the restoration of polluted soils. Sunflower (*Helianthus annuus*), common reed (*Phragmites australis*), Indian mustard (*Brassica juncea*), aquatic moss (*Fontinalis antipyretica*), and species of willow (*Salix*), poplar (*Populus*), duckweed (*Lemna*), and water starwort (*Callitriche*) have all shown strong potential for pollutant removal, and *Phragmites australis* has proved particularly successful in eliminating contaminants from wastewater.

8.3. Precision Farming and Controlled Application Technologies

Precision farming was defined by Pierre C. Robert, widely regarded as the founder of the discipline, not merely as the introduction of new technology but as an information revolution enabled by that technology, which yields a more precise system of farm management. In practice it means applying the right quantity of an input at the right time and in the right place within a field (Das et al., 2018). Precision farming rests on information gathered through systematic field survey, and its principal components are outlined below.

Computer systems. Information technologies support management strategy and decision-making, and they require the acquisition, management, and analysis of spatial and temporal data. In precision farming, the knowledge required is that needed to manage within-field variability and to inform management decisions (Das et al., 2018).

Global Positioning System. GPS operates through a constellation of satellites and has made precision agriculture practicable. It provides the accurate positioning needed to implement variable-rate technology in the field, allowing input application by machinery to be controlled, farm equipment to be located to within a few centimetres, and fertilizer and pesticide rates to be prescribed according to local soil properties (Das et al., 2018).

Geographic Information System. A GIS holds base maps of topography, soil type, nutrient status, soil moisture, pH, fertility, and weed and pest intensity, and it can integrate these with other data and interface with decision-support tools, so that recommended rates of nutrients or pesticides can be applied on a site-specific basis (Das et al., 2018).

Remote sensing. Remote sensing is valuable in precision agriculture because it yields data on field parameters comparatively easily. The reflected sunlight observed comprises ultraviolet, visible (red, green, and blue), and infrared wavelengths. Green plants absorb red and blue wavelengths and reflect green and infrared, so measuring reflected wavelengths with multispectral cameras allows plant vigour to be assessed and problems such as disease, nutrient deficiency, and waterlogging to be identified. Soil colour can likewise be correlated with organic matter content and moisture. Reflectance of sunlight or of an artificial source is used in precision agriculture in the form of vegetation indices (Das et al., 2018).

9. Conclusion

This appraisal of agrochemical wastes in Bijnor District and comparable regions of Uttar Pradesh reveals a consistent pattern. Agrochemicals have raised agricultural productivity substantially, but their indiscriminate use has produced significant ecological consequences. Residues enter soil, water, and air and undergo bioaccumulation and biomagnification, disturbing non-target flora through loss of plant diversity, suppression of soil microorganisms, and physiological injury, while non-target fauna, including pollinators, earthworms, amphibians, fish, birds, and small mammals, suffer toxicity, reproductive disorder, and population decline. Regional studies confirm the presence of pesticide residues in crops, surface water, and wildlife, indicating both the severity of contamination and its long-term implications for food security and public health. Climate change compounds these pressures by promoting pest resistance, extending pathogen ranges, and accelerating eutrophication, thereby destabilizing ecological balance



and reducing crop resilience.

Addressing these problems requires coordinated action rather than isolated measures. Integrated nutrient and pest management, wider adoption of biopesticides and organic amendments, precision application technologies, and bioremediation of contaminated sites together offer a practicable route to reducing chemical loading without sacrificing yield. These measures depend, however, on effective regulation of pesticide registration and disposal, on accessible soil-testing and extension services, and on sustained monitoring of residues in soil, water, and biota. Systematic, long-term monitoring in Bijnor District and comparable agroclimatic zones remains a priority, since the regional evidence base is still fragmentary and largely confined to isolated surveys. Future research should quantify residue loads in local soils, surface waters, and indicator taxa, and should evaluate the effectiveness of the mitigation strategies reviewed here under the specific agronomic and socio-economic conditions of western Uttar Pradesh.

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