

# A Study on Agrochemical Impacts on Environmental and Public Health in India: A Comprehensive Review

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**Abstract** - The rapid evolution of agricultural methodologies in India has precipitated a substantial escalation in the utilization of agrochemicals, encompassing fertilizers, insecticides, herbicides, and fungicides. While these substances have demonstrably aided in augmenting crop productivity and ensuring national food security, their excessive application and insufficient regulatory oversight have engendered significant environmental and public health concerns. This review consolidates current literature regarding the ecological and health effects of agrochemicals in India, emphasizing critical pathways of contamination, including soil degradation, water pollution, and bioaccumulation within food chains. This examination investigates the toxicological consequences for human health, focusing on both acute and chronic effects observed in agricultural labourers and the wider population. Furthermore, the analysis considers socio-economic ramifications, particularly those affecting smallholder farmers, alongside the deficiencies present in current regulatory structures. The study emphasizes the importance of sustainable alternatives, including integrated pest management, organic farming, and precision agriculture. The report's conclusions indicate recommendations for reducing the risks of agrochemicals. These recommendations also aim to maintain long-term agricultural productivity and promote environmental sustainability.

**Keywords:** Agrochemicals, pesticides, fertilizers, environmental pollution, public health, India, sustainable agriculture, toxicology, groundwater contamination.

## INTRODUCTION

India's significant role in the global agrochemical market is primarily driven by the need to ensure agricultural production for its population, which exceeds 1.4 billion people (Wang et al. 2026). The Green Revolution, a movement that took root in the 1960s, represented a significant shift for India. The extensive implementation of high-yielding crop varieties, coupled with the intensive application of chemical fertilizers and pesticides, has shifted the country from being food-deficient to emerging as a leading agricultural producer.

Punjab, Haryana, and Uttar Pradesh have evolved into prominent centres of high-input agriculture, with agrochemical application serving as a fundamental component of modern farming methodologies (Shukla *et al.* 2022). The utilization of these inputs has resulted in substantial improvements in crop productivity, thereby enhancing food security and fostering economic expansion within the agricultural domain. Conversely, the heightened utilization of agrochemicals has engendered considerable concerns about environmental preservation and public well-being (Mondal *et al.* 2025).

The excessive and often indiscriminate application of fertilizers and pesticides has disrupted natural ecological equilibrium, thereby contributing to soil degradation, water contamination, and a reduction in biodiversity. Furthermore, the continued use of chemical fertilizers, particularly those with nitrogen like urea, has caused nutrient imbalances, a decrease in soil organic matter, and a reduction in microbial activity (Alom *et al.* 2025). These changes negatively impact soil fertility, which poses a risk to the sustainability of agricultural systems. The water resources in agricultural regions have experienced significant adverse effects (Ingrao *et al.* 2023).

The infiltration of nitrates and pesticide residues into groundwater, along with their runoff into surface water bodies, has resulted in extensive contamination. Elevated nitrate concentrations in potable water pose considerable health risks, while the eutrophication of freshwater bodies disrupts aquatic environments. Moreover, the persistent presence and accumulation of certain pesticide residues in the environment have raised concerns about their enduring ecological consequences and their entry into the food web. In recent decades, the harmful effects of agrochemical exposure on human health have become increasingly clear. Agricultural workers, often lacking sufficient protective gear and proper instruction, face significant dangers when handling and applying pesticides. As a result, skin irritation, breathing problems, and cases of poisoning are frequently reported as immediate health effects (Soltaninia *et al.* 2025).

The chronic health ramifications linked to extended exposure are especially concerning, including cancer,

neurological conditions, endocrine disruption, and reproductive anomalies. Moreover, the presence of pesticide residues in food items presents a risk to the wider population through low-level, prolonged exposure, thereby underscoring substantial public health concerns. The application patterns of agrochemicals within India exhibit significant regional disparities. High-input agriculture tends to be focused in irrigated areas that have improved access to markets, infrastructure, and extension services, resulting in a significant reliance on fertilizers and pesticides. Conversely, regions that rely on rain and have limited resources typically utilize smaller amounts of agrochemicals. However, these areas frequently encounter issues like improper handling, insufficient awareness, and limited access to safer alternatives (Zhou, Li, and Achal 2025).

These factors can lead to environmental damage and health problems for local communities. As a result, regions with both high and low inputs face unique yet considerable risks linked to the use of agrochemicals. The consumption of fertilizers in India has seen a significant rise over the past decades, with nitrogen-based fertilizers representing the largest portion of this increase. Although these inputs play a crucial role in improving crop productivity, excessive application has resulted in diminishing returns and negative environmental impacts, including greenhouse gas emissions like nitrous oxide. Similarly, the use of pesticides continues, involving various chemical types such as organophosphates, organochlorines, and synthetic pyrethroids (Kashyap, Garg, and Arora 2024a).

Despite regulations limiting the use of highly dangerous pesticides, the application of many harmful chemicals continues. This ongoing problem arises from several interconnected issues: insufficient enforcement of existing rules, a lack of proper monitoring of pesticide use, and inadequate training for agricultural workers. Moreover, these challenges are worsened by social and economic factors, including the prevalence of small farms, financial difficulties, and limited access to important information. Farmers' decisions about using agrochemicals are significantly affected by these factors. Often, the immediate need to protect crops and increase production takes precedence over concerns about the long-term environmental and health consequences (Buralli et al. 2025).

Consequently, unsustainable practices persist, thereby reinforcing a dependency on chemical inputs. In light of these complex challenges, a thorough evaluation of the effects of agrochemicals on environmental and public health within the Indian context is of critical significance. This review synthesizes contemporary research on the ecological consequences of agrochemical usage, specifically addressing

soil degradation, water contamination, and biodiversity loss, while also considering the associated threats to human well-being. This study aims to examine the social and economic factors, as well as the policy-related obstacles, that influence the use of agrochemicals (Tachie-Menson *et al.* 2025).

Furthermore, this study examines sustainable alternatives, including integrated pest management, organic farming, and precision agriculture. These methods offer potential strategies for reducing the use of chemicals while maintaining agricultural productivity. This analysis aims to improve how policies and practices are developed. The main goal is to find a way to feed the world's population while also protecting the planet and promoting the well-being of all people.

### **Classification and Usage of Agrochemicals**

Agrochemicals encompass a broad range of chemical substances used to enhance agricultural productivity and protect crops from pests, diseases, and nutrient deficiencies. Based on their functional roles, they are primarily classified into pesticides, fertilizers, and emerging agrochemical formulations (Anim *et al.* 2025a).

#### **Pesticides**

In India, pesticides are widely used in agriculture to manage different pests and diseases. Insecticides, herbicides, fungicides, and rodenticides represent the primary categories of pesticides. These substances are used to manage insect populations, control weeds, prevent fungal infections, and reduce rodent populations. Organophosphates, carbamates, organochlorines, and neonicotinoids are commonly encountered chemical classes (Reddy, Reddy, and Mathur 2024a). While organophosphates and carbamates are widely used due to their efficacy, they are also associated with acute toxicity. Organochlorines, although known for their persistence and bioaccumulation, have faced restrictions or bans in numerous areas; nonetheless, their residues remain prevalent in the environment. Neonicotinoids, a relatively new group of chemicals, are seeing increased use (Verma 2026). This has raised alarms about their potential harm to pollinators and other organisms not intended to be affected. As a result, there's a growing call for further study and perhaps new rules to mitigate these effects (Hooven *et al.* 2019).

#### **Fertilizers**

Fertilizers are essential for maintaining soil health and maximizing agricultural productivity. These substances mainly provide essential macronutrients, such as nitrogen (N), phosphorus (P), and potassium (K), which are crucial for plant growth and development. In India, the predominant form of fertilizer consumption is nitrogen-based fertilizers, especially

urea. Using these inputs significantly boosts productivity. However, using them too much and distributing them unevenly has caused nutrient depletion, soil acidification, and environmental pollution. The excessive use of nitrogen fertilizers leads to the leaching of nitrates into groundwater and the release of nitrous oxide, a powerful greenhouse gas, which presents significant environmental and climate-related issues (Fang *et al.* 2023).

### Emerging Agrochemicals

Recent advancements in agricultural science have resulted in the creation of innovative agrochemicals, such as genetically engineered biopesticides and nano-fertilizers. Biopesticides, which are derived from natural organisms or their by-products, are viewed as environmentally friendly alternatives to traditional pesticides. Nano-fertilizers, designed to improve nutrient utilization through controlled release, offer prospects for reducing input volumes and lessening environmental detriment. However, the long term ecological and health ramifications of these novel inputs, including potential effects on biodiversity and human well-being, remain inadequately understood, thereby underscoring the necessity for further research and regulatory scrutiny (Tadesse Mawcha *et al.* 2025).

### Environmental Fate and Transport

After application, agrochemicals engage with various environmental elements, initiating intricate transport and transformation processes. Their mobility and longevity are contingent upon a combination of chemical attributes, soil properties, climatic factors, and agricultural methodologies. Groundwater systems are vulnerable to agrochemical infiltration through leaching, a process particularly pronounced in regions experiencing high rainfall or extensive irrigation. Furthermore, precipitation runoff facilitates the transport of these chemicals into surface water bodies, encompassing rivers, lakes, and reservoirs. Consequently, this contributes to the exacerbation of water pollution and the promotion of eutrophication (Ghorbani *et al.* 2024).

Volatilization causes certain chemicals to be released into the atmosphere, allowing them to spread over long distances and potentially settle in areas where they weren't meant to be. Moreover, how these chemicals interact with soil particles can either slow down their movement or cause them to be released into the environment gradually. This depends on factors like the soil's makeup, the chemical properties of the substances, and the current environmental conditions (Boonupara *et al.* 2023).

The lasting effects of agrochemicals are significantly influenced by their chemical structure and the environmental

conditions they encounter (Verma, 2025.). Certain compounds undergo rapid degradation, whereas others, especially persistent organic pollutants, tend to linger in soils and aquatic systems for prolonged durations. The extended duration of this persistence heightens the likelihood of bioaccumulation and biomagnification within food chains, consequently elevating ecological and human health risks (Kumar *et al.* 2025).

### ENVIRONMENTAL IMPACTS

The widespread application of agrochemicals within Indian agricultural practices has engendered considerable environmental repercussions, thereby influencing soil composition, water resources, atmospheric conditions, and the overall state of biodiversity. These effects often exhibit interconnectedness, which can intensify existing ecological disturbances and undermine the long-term viability of agricultural ecosystems (Kashyap, Garg, and Arora 2024b).

### Soil Health Degradation

Soil health is essential for agriculture, and it's crucial for sustainable farming. In contrast, the long-term and excessive use of agricultural chemicals harmed soil quality. A major effect is the decrease in microbial diversity. Soil microorganisms, including bacteria and fungi, are crucial for nutrient cycling. However, they are quite sensitive to the effects of chemicals. As a result, their decline disrupts important biochemical processes, such as nitrogen fixation and the breakdown of organic matter. Moreover, the use of synthetic fertilizers over time leads to a decrease in the amount of organic carbon found in the soil. Organic matter plays a crucial role in sustaining soil structure, enhancing water retention, and promoting fertility (Kabato *et al.* 2025).

The depletion of this resource results in a decline in soil resilience and productivity as time progresses. Soil acidification, a consequence of overusing agrochemicals, is particularly pronounced with nitrogen-based fertilizers; these substances alter soil pH, thereby limiting the availability of essential nutrients. Furthermore, in irrigated regions, the improper application of fertilizers can induce salinization, a phenomenon characterized by the accumulation of soluble salts that degrade soil structure and impede plant development. Consequently, the combined impacts of these changes interfere with nutrient cycling, ultimately threatening the long-term sustainability of agricultural practices (Awoonor *et al.* 2025).

### Water Pollution

Water contamination is one of the most critical environmental issues associated with agrochemical use, with

both groundwater and surface water systems being affected (Verma 2025b).

### **Groundwater Contamination**

The infiltration of agrochemicals, especially nitrates from fertilizers and pesticide residues, into groundwater represents a significant issue in India. This phenomenon is particularly evident in areas characterized by extensive irrigation practices and elevated fertilizer usage. High levels of nitrate in drinking water pose a significant public health risk and have been linked to conditions like methemoglobinemia, especially in young children. Moreover, the presence of pesticide residues in groundwater presents enduring health hazards because of their lasting nature and possible toxic effects (Bouselsal *et al.* 2025).

### **Surface Water Eutrophication**

Agricultural runoff also has detrimental effects on surface water bodies, such as rivers, lakes, and reservoirs. During rainfall or irrigation events, agricultural fields contribute excess nutrients, mainly nitrogen and phosphorus, to these water systems (Verma 2025a). The enrichment of nutrients results in eutrophication, which is marked by an overabundance of algal growth. Algal blooms diminish light penetration and lower dissolved oxygen levels during decomposition, leading to hypoxic conditions that negatively impact aquatic organisms. Ecological disturbances can result in the death of fish, a decline in aquatic biodiversity, and a decline in water quality (Madjar, Vasile Scăețeanu, and Sandu 2024).

### **Air Pollution and Climate Impact**

Agrochemicals play a role in atmospheric pollution via mechanisms like volatilization and gas emissions. Some pesticides and fertilizers have the potential to volatilize into the atmosphere following their application, resulting in the widespread dispersion of chemical residues across extensive regions. This mechanism impacts local air quality and also enables the long-range movement of pollutants. The emission of nitrous oxide (N<sub>2</sub>O) from nitrogen-based fertilizers presents a considerable issue. Nitrous oxide serves as a powerful greenhouse gas, exhibiting a global warming potential that far exceeds that of carbon dioxide. The release has implications for climate change and is also involved in the depletion of stratospheric ozone. Furthermore, the release of ammonia from fertilizers can lead to the creation of secondary particulate matter, which exacerbates the deterioration of air quality. The atmospheric effects underscore the wider ecological impact of agriculture reliant on agrochemicals (Modu 2025).

### **Biodiversity Loss**

The extensive use of agrochemicals significantly impacts biodiversity, especially influencing non-target organisms in both terrestrial and aquatic ecosystems. Pollinators, including bees, face significant risks from pesticide exposure, particularly from systemic chemicals like neonicotinoids, which can negatively affect their navigation, reproduction, and overall survival. The reduction in pollinator populations presents a significant challenge to agricultural output and the balance of ecosystems. Birds and aquatic organisms experience impacts from both direct toxicity and indirect exposure. The introduction of pesticides into aquatic environments poses significant risks to fish, amphibians, and invertebrates, leading to disruptions in the intricate dynamics of food webs within these ecosystems. In terrestrial ecosystems, the consumption of contaminated prey can result in secondary poisoning in avian and mammalian species (Sponsler *et al.* 2019).

Furthermore, the enduring presence of specific agrochemicals in the environment promotes biomagnification, a phenomenon where harmful substances accumulate and intensify in concentration at elevated trophic levels. This situation poses a significant threat to wildlife and simultaneously raises serious concerns regarding human health due to the potential consumption of contaminated food products. In summary, the loss of biodiversity caused by agrochemicals weakens ecosystem resilience and diminishes the ability of natural systems to deliver vital services like pollination, pest control, and nutrient cycling (Okuthe, Dube, and Mafunda 2025).

## **HUMAN HEALTH IMPACTS**

The widespread use of agrochemicals in agriculture has raised significant concerns regarding their adverse effects on human health. Exposure occurs through multiple pathways, including occupational handling, environmental contamination, and dietary intake. The health impacts can be broadly categorized into acute and chronic effects, with certain populations being particularly vulnerable (Muñoz-Bautista *et al.* 2025).

### **Acute Effects**

Short-term exposure to agricultural chemicals, particularly pesticides, can lead to immediate toxic effects. This type of exposure frequently occurs among agricultural workers engaged in the mixing, spraying, and handling of chemicals, typically without sufficient protective measures in place. Acute poisoning manifests through a spectrum of symptoms, including headaches, dizziness, nausea, vomiting, and respiratory difficulties, in addition to skin and ocular

irritation. Severe cases can lead to convulsions, loss of consciousness, and, in some instances, death. Organophosphate and carbamate pesticides, frequently employed in agriculture, are particularly well-known for their neurotoxic effects; these substances inhibit acetylcholinesterase, thereby causing excessive stimulation of the nervous system. The high number of acute pesticide poisonings in rural India highlights the critical need for better safety measures and increased awareness among agricultural workers (Damalas and Koutroubas 2016).

### **Chronic Diseases**

Prolonged contact with agrochemicals, even at low levels, has been linked to various long-term health issues. Epidemiological studies have consistently shown connections between pesticide exposure and a range of cancer diagnoses, including non-Hodgkin lymphoma, leukaemia, prostate cancer, and breast cancer. These observed associations are attributable to the carcinogenic characteristics inherent in specific chemical substances and their capacity to instigate genetic mutations, potentially precipitating the eventual manifestation of these malignancies (Latifovic et al. 2020).

The interplay between diverse agrochemicals and hormonal control presents a significant concern regarding endocrine disruption. Such disruptions have the potential to impact growth, metabolic functions, and reproductive health, possibly resulting in developmental challenges in paediatric populations and fertility issues in adults. Moreover, research has linked long-term exposure to pesticides with neurodegenerative disorders, including both Parkinson's and Alzheimer's diseases (Zlatnik 2016).

The accumulation of chemical residues in the nervous system can lead to neurotoxicity, which then causes lasting damage to neurons. Documented cases of reproductive disorders and developmental abnormalities include infertility, miscarriages, and congenital birth defects. The consequences of these effects raise significant concerns for agricultural communities that endure extended and recurrent exposure to agrochemicals, as they may face increased health risks, including chronic illnesses and long-term neurological impairments (Botnaru et al. 2025).

### **Vulnerable Populations**

Certain demographic segments display increased susceptibility to the adverse effects of agrochemicals. Agricultural workers represent the cohort with the greatest exposure due to their direct and regular interactions with these chemicals. In many developing regions, including India, access to personal protective equipment (PPE) is limited, and

compliance with safety protocols is often inadequate, increasing the likelihood of exposure (Ahmad et al. 2024a).

Young individuals demonstrate a greater vulnerability due to their developing physiological systems, higher metabolic rates, and greater intake of food and water relative to their body weight. Exposure during important stages of development can have long-lasting effects on health. Pregnant women constitute a notably high-risk demographic, as their exposure to agrochemicals can adversely affect fetal development, leading to low birth weight, developmental delays, and congenital anomalies. The identified vulnerabilities point to the urgent need for targeted interventions and improved regulatory frameworks to protect vulnerable populations (Quarta et al. 2024).

### **Dietary Exposure**

People are significantly exposed to agrochemicals through their diet, in addition to their jobs and the environment. Food items, including fruits, vegetables, grains, and dairy products, often contain pesticide and agrochemical residues. Even with the establishment of maximum residue limits (MRLs) by regulatory agencies to ensure food safety, concerns remain regarding the combined and interactive effects of different chemical residues (Anaduaka et al. 2023).

Chronic exposure to low doses of substances via dietary intake, while often asymptomatic in the short term, can nonetheless precipitate long-term health hazards, encompassing carcinogenic, neurotoxic, and endocrine-disrupting consequences. Moreover, deficiencies in the monitoring and enforcement of food safety regulations in specific areas intensify these risks, thereby underscoring the necessity of comprehensive surveillance mechanisms and heightened public consciousness (Peivasteh-roudsari et al. 2023).

### **Socio-Economic Implications**

Besides the environmental and health issues, the use of agrochemicals has significant socioeconomic consequences, particularly for farming communities in developing countries.

### **Farmer Health and Economic Burden**

Health complications arising from agrochemical exposure impose a substantial economic burden on farmers. Medical expenses for treating acute poisoning and chronic illnesses can be considerable, especially for smallholder farmers with limited financial resources. In addition, illness-related loss of labour productivity further reduces household income and agricultural output. This dual burden of increased healthcare costs and reduced earnings exacerbates economic vulnerability

and can contribute to cycles of debt and poverty (Demi and Sicchia 2021).

### **Agricultural Sustainability**

The overreliance on agrochemicals has implications for the long-term sustainability of agricultural systems. Declining soil fertility, pest resistance, and environmental degradation necessitate increasing quantities of chemical inputs to maintain crop yields. This results in rising input costs and diminishing economic returns for farmers. Consequently, many farmers become trapped in a cycle of dependency on agrochemicals, where short-term productivity gains are offset by long-term ecological and financial challenges (Chen and Xu 2025).

### **Rural Inequality**

Rural inequality is exacerbated by the uneven distribution of agrochemical impacts, disproportionately affecting small and marginal farmers. Farmers often face significant obstacles when trying to access education, extension services, and safer alternatives like bio-pesticides or organic farming methods. Furthermore, their limited financial means impede their capacity to invest in protective gear or embrace sustainable technologies (Thiede *et al.* 2020).

Consequently, smallholder farmers face greater exposure to risks and increased economic vulnerability compared to larger farmers with more resources. Moreover, differences in how easily people can access information and the level of institutional support available lead to inconsistent use of secure agricultural methods. This could potentially result in lower crop yields and increased health risks for agricultural workers and their communities. Addressing these inequities is essential for fostering equitable and enduring advancement within agricultural development. The ramifications of agrochemicals on both human well-being and socio-economic conditions highlight the imperative for holistic approaches that prioritize public health in conjunction with agricultural sustainability (Datta 2023).

## **CASE STUDIES FROM INDIA**

Empirical evidence gathered from various Indian settings provides crucial insights into the real-world impacts of agrochemical usage on both environmental health and human populations. The following case studies elucidate region-specific exposure patterns, associated health outcomes, and the systemic challenges present within regulatory structures and public education efforts (Cavalier, Trasande, and Porta 2023).

### **PUNJAB “CANCER BELT”**

The phrase "cancer belt" often comes up when discussing specific regions in Punjab, especially the Malwa area, where cancer diagnoses seem to be more prevalent than elsewhere. This troubling trend is closely connected to the widespread use of pesticides and fertilizers in the region's highly productive agricultural practices. Punjab, a key contributor to India's food grain output, has historically relied on high-input agricultural practices since the advent of the Green Revolution (Thakur *et al.* 2008).

Several epidemiological investigations have suggested a correlation between prolonged exposure to agrochemicals and an increase in cancer incidence, including malignancies affecting the liver, breast, and lymphatic system. The presence of pesticide residues and heavy metals in groundwater has been identified as a primary pathway of exposure.

Moreover, the widespread practice of growing a single crop, particularly wheat and rice, has led to the continuous and excessive use of chemicals, which has worsened environmental pollution. Although establishing direct causation is complex and involves numerous variables, the available evidence underscores the potential long-term health hazards associated with agriculture that is heavily reliant on agrochemicals (Kaur and Sharma 2017).

### **VIDARBHA REGION (MAHARASHTRA)**

Vidarbha, Maharashtra, is synonymous with sprawling cotton fields. However, it's also a revealing example of the health consequences tied to agrochemical use. The cultivation of cotton in this area relies significantly on the application of pesticides, primarily because of its susceptibility to pests like the bollworm. It is common for farmers to administer several applications of pesticides throughout a single growing season, often surpassing the suggested dosages. Farmers and agricultural workers in Vidarbha have been hit hard by several instances of acute pesticide poisoning (Koussé *et al.* 2023).

The primary causes of these cases include improper handling practices, insufficient protective gear, and a lack of understanding regarding chemical toxicity. Commonly reported symptoms encompass dizziness, nausea, respiratory distress, and, in severe instances, fatalities. The issue is exacerbated by socio-economic pressures, with numerous farmers facing financial limitations and restricted access to extension services. The enduring consequences of prolonged contact with pesticide mixtures extend beyond immediate health concerns, warranting greater attention (Jogie 2025).

Vidarbha serves as a troubling case study, where a combination of occupational hazards, economic hardships, and

insufficient governmental regulation has culminated in a significant public health crisis within rural India.

### **KERALA ENDOSULFAN TRAGEDY**

The Endosulfan disaster in Kerala highlights the devastating health and environmental impacts of agrochemicals in India. For over two decades, the organochlorine pesticide endosulfan was deployed by aerial spraying across cashew plantations in the Kasaragod district. Because of its lasting presence and tendency to build up in living things, endosulfan has contaminated soil, water, and the environment. As a result, prolonged exposure within affected communities has led to a variety of health problems, including birth defects, neurological issues, developmental delays, and reproductive disorders (Narayana Kurup and Mohanty 2017).

A considerable number of cases involving physical and cognitive disabilities have been recorded among children born in these regions, thereby drawing both national and international attention to the issue. Furthermore, the environmental consequences have manifested in the pollution of aquatic systems and adverse effects on regional biodiversity, encompassing the reduction of fish populations and the destabilization of local ecosystems that sustain diverse species. The gravity of the crisis precipitated legal proceedings and a nationwide prohibition of endosulfan.

This specific case highlights the imperative for robust regulatory structures, thorough environmental monitoring, and anticipatory approaches in the management of hazardous agricultural chemicals. The decision emphasizes the persistent and often permanent consequences stemming from the neglect of environmental and public health safeguards. The case studies provided elucidate the diverse and substantial impacts of agrochemical usage across different areas of India, thereby accentuating the imperative for the adoption of more sustainable and less harmful agricultural practices are needed (Sreekumar and Prathapan, n.d.).

### **REGULATORY FRAMEWORKS AND POLICY CHALLENGES**

Regulatory frameworks are essential for managing agrochemicals, which are crucial for their safe use and for reducing potential risks to human health and the environment. Globally, organizations like the World Health Organization and the Food and Agriculture Organization play a crucial role in this area. Guidelines and standards are created to manage agrochemicals (Ahmad *et al.* 2024b).

These frameworks aim to encourage the responsible use of pesticides and fertilizers, using scientific risk assessments and regulatory oversight. Global regulatory frameworks

require the registration and assessment of agrochemicals before they can be approved for use, ensuring that only substances meeting safety standards are allowed. In addition, Maximum Residue Limits (MRLs) are set to control the acceptable levels of pesticide residues in food, thus protecting consumer health. Global treaties and agreements have been crucial in banning or limiting the use of highly dangerous chemicals, particularly those known for their persistence, bioaccumulation, and toxicity. Despite these efforts, the success of such frameworks frequently hinges on the implementation and enforcement at the national level, which continues to vary significantly across different regions (Tarazona *et al.* 2024).

### **EXISTING REGULATIONS IN INDIA**

The regulation of agrochemicals in India is shaped by a combination of laws and the organizations that enforce them. The Insecticides Act of 1968 is the main law that governs the use of pesticides. The framework sets out guidelines for the registration, production, distribution, and application of insecticides. Its primary aim is to mitigate any potential risks to humans and animals.

The legislation requires that every pesticide be assessed for safety and effectiveness before receiving approval for commercial distribution. Another significant legal instrument is the Environmental Protection Act, 1986, which establishes a comprehensive framework for environmental protection, encompassing the regulation of hazardous substances. This legislation empowers the government to establish benchmarks for environmental quality, oversee emissions and discharges, and implement strategies to mitigate pollution stemming from the use of agrochemicals (Reddy, Reddy, and Mathur 2024b).

The Central Insecticides Board and Registration Committee (CIBRC) is another crucial player. It manages the approval process and keeps tabs on pesticide applications across India. Government agencies regularly evaluate the safety of chemicals that are registered. This process can lead to the limitation or outright banning of substances deemed dangerous. Nevertheless, the regulatory landscape is characterized by its inherent complexity. The complexity arises from overlapping jurisdictions and the different ways states implement regulations. Consequently, inconsistencies may arise in the application and enforcement of pesticide safety standards across the country.

### **KEY CHALLENGES**

Even with existing rules, several obstacles hinder their successful implementation. A major problem is the lack of strong enforcement. Regulatory bodies often face limitations in their infrastructure, technical capabilities, and available

staff. These limitations can hinder their ability to effectively monitor compliance and enforce existing laws. Consequently, instances of agrochemical misuse and disregard for safety protocols are quite prevalent. A significant concern involves the persistent existence and application of substances subject to prohibition or restriction. The continued illegal production, distribution, and sale of these substances in certain areas consistently undermines regulatory efforts. Sometimes, farmers might unintentionally use banned substances. This could be due to a lack of understanding of the rules, or it could be because product labels are misleading.

The problem is made worse by the lack of adequate training and extension services for farmers. Many farmers don't have access to reliable information about how to safely handle, use the right amounts of, and apply agrochemicals correctly. Insufficient training initiatives lead to the excessive application of materials, improper chemical combinations, and unsafe disposal practices, thereby amplifying the potential for environmental pollution and health complications (Singun 2025).

A significant obstacle stems from inadequate regulation concerning pesticide residues within both food and environmental settings. Although maximum residue limits are established, thorough monitoring and testing often fall short, particularly in rural and remote areas. As a result, this lack of oversight undermines food safety and hinders a comprehensive assessment of the risks linked to extended exposure. Moreover, current regulations have struggled to keep up with the rapid changes in agricultural chemicals, particularly nano-formulations and biopesticides. As a result, we need to take a fresh look at how we assess risks and the rules we have in place. The scarcity of extensive data concerning their long-term impacts further complicates the process of making informed regulatory decisions.

Although India has developed a well-organized regulatory framework that aligns with international standards, notable deficiencies in enforcement, monitoring, and awareness persist, hindering its overall effectiveness. To tackle these challenges, it is essential to bolster institutional capacity, elevate farmer education, refine surveillance systems, and embrace a more integrated and adaptive regulatory framework. Sustainable Alternatives and Mitigation Strategies (Nair *et al.* 2024; Dinçkol, Ozcan, and Zachariadis 2023).

## **SUSTAINABLE ALTERNATIVES AND MITIGATION STRATEGIES**

The detrimental environmental and health consequences stemming from excessive agrochemical application have spurred the creation and implementation of sustainable

agricultural methodologies. These practices are designed to diminish reliance on chemical inputs while simultaneously preserving crop yields and ecological equilibrium. Essential strategies encompass integrated pest management, organic farming, precision agriculture, and supportive policy measures.

### **Integrated Pest Management (IPM)**

Integrated Pest Management (IPM) constitutes a comprehensive strategy, integrating biological, cultural, mechanical, and chemical techniques to manage pest populations while ensuring economic and environmental viability. Integrated Pest Management (IPM) emphasizes the use of natural predators, crop rotation, resistant plant varieties, and habitat management to control pest populations, rather than relying solely on chemical pesticides. Using chemical pesticides should be a last resort, and they should be used carefully. This approach reduces environmental damage and lowers the risk to human health. IPM has been effectively adopted across diverse cropping systems in India, illustrating its capacity to decrease pesticide application without negatively impacting crop yields (Deguine *et al.* 2021).

### **Organic Farming**

Organic farming constitutes an alternative agricultural paradigm, distinguishing itself by its avoidance of synthetic fertilizers and pesticides. Instead, it employs natural inputs, including compost, green manure, and biological pest control methods. This methodology contributes to soil health by augmenting organic matter levels, fostering microbial activity, and facilitating nutrient cycling. Furthermore, it helps reduce environmental pollution and removes chemical residues from food. Despite the clear ecological and health benefits of organic farming, challenges related to consistent yields, certification processes, and market access must be addressed to encourage widespread adoption (Anim *et al.* 2025b).

### **Precision Agriculture**

Precision agriculture relies heavily on advanced technologies. Remote sensing, GIS, drones, and soil sensors – they're all players in this game. The goal is to make applying agrochemicals more efficient. This method facilitates targeted management of crops, ensuring that resources are utilized precisely when and where necessary, thereby decreasing unnecessary consumption and mitigating environmental impact. Precision agriculture significantly improves the efficiency of resource utilization while simultaneously reducing production costs and minimizing environmental impact. The adoption of this practice in India is steadily on the rise, especially among high-value crops; however, challenges such as substantial initial investment and a lack of technical

expertise persist, which can hinder the widespread implementation of precision agriculture techniques among smallholder farmers (Getahun, Kefale, and Gelaye 2024).

### **POLICY RECOMMENDATIONS**

To promote sustainable agricultural practices and reduce the risks associated with using agrochemicals, effective policy changes are essential. It is crucial to enhance regulatory enforcement to ensure the proper execution of current laws related to agrochemical registration, distribution, and usage. Enhanced monitoring systems and more stringent penalties for non-compliance may effectively mitigate the misuse of hazardous substances (Othman Said 2026).

Education and awareness initiatives for farmers are essential in promoting the adoption of safe and sustainable practices. Extension services ought to prioritize the distribution of information regarding appropriate agrochemical management, alternative strategies for pest control, and the maintenance of soil health. Training initiatives can enable farmers to make informed decisions and minimize unnecessary chemical inputs. Advancing innovation and progress in biopesticides and sustainable agricultural technologies is a crucial strategy. Investing in new ideas can help create safer and more effective alternatives to traditional agricultural chemicals. Furthermore, providing financial incentives, subsidies, and market support for sustainable farming methods can encourage their wider use, especially among small and marginal farmers (Lankinen *et al.* 2024).

### **CONCLUSION**

Undeniably, agrochemicals have significantly influenced Indian agriculture, fostered enhanced crop productivity and strengthened national food security. Conversely, the widespread and often unregulated use of these substances has precipitated substantial environmental and public health concerns. Significant ecological consequences include soil degradation, water pollution, air contamination, and a decline in biodiversity. At the same time, human populations, especially those involved in agriculture, children, and pregnant women, face both immediate and long-term health risks. Socioeconomic challenges, such as rising medical expenses and reliance on chemical inputs, intensify the vulnerabilities faced by smallholder farmers. This review highlights the importance of adopting a comprehensive strategy that emphasizes the significance of both productivity and sustainability. The implementation of sustainable agricultural practices—like integrated pest management, organic farming, and precision agriculture—has the potential to diminish dependence on harmful chemicals while ensuring crop productivity remains high. The safe use of agrochemicals requires strong regulations, better monitoring, and thorough

training for farmers. Moreover, research and development of biopesticides and environmentally friendly technologies offer viable alternatives to traditional agricultural methods. To promote sustainable agriculture in India, a comprehensive approach is essential, combining supportive policies, scientific progress, and active community participation. By promoting agricultural methods that are both sustainable and focused on health, we can protect ecosystems, improve human well-being, and ensure the long-term viability of farming

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**Ravi Verma** Formal analysis, Investigation, Original draft, Writing - review & editing.

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The authors have no conflicts of interest to declare that are relevant to the content of this article.

### **DATA AVAILABILITY STATEMENT**

The data that support the findings of this study are available on request from the corresponding author.

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The AI tool has been used only for drafting the body of this review work.

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