Pesticide Induced Environmental Toxicity in Indian Agriculture and Emerging Mitigation Strategies for Environmental Safety and Sustainable Food Security

Chandani Lakhani, Sandeep Bodkhe

Pesticides play an essential role in sustaining agricultural productivity; nevertheless, their prevalence and often indiscriminate use have resulted in significant concerns related to the environmental toxicity and human health hazards. This chapter presents a detailed examination of pesticide use patterns in Indian agriculture and examines the associated environmental toxicity through evidence drawn from peer-reviewed research, national surveys, and government reports. Data from regulatory and monitoring agencies, including the Ministry of Agriculture and Farmers Welfare, Central Pollution Control Board (CPCB), Directorate of Plant Protection, Quarantine and Storage (DPPQS), and Food Safety and Standards Authority of India (FSSAI), are synthesized to highlight trends in pesticide consumption, poisoning incidents, and regulatory enforcement. The chapter critically evaluates the fate and transport of pesticides in soil and water systems, as well as their ecotoxicological impacts on biodiversity. Policy frameworks such as the Insecticides Act, 1968, the proposed Pesticides Management Bill, and national Integrated Pest Management (IPM) programs are discussed to assess their effectiveness in mitigating environmental risks.

Keywords: *Pesticides, Indian Agriculture, Environmental Toxicity, Exposure Risks, Policy Frameworks, Sustainable Pest Management*

Chandani Lakhani, Sandeep Bodkhe*
Academy of Scientific and Innovative Research (AcSIR), Ghaziabad, India; Environmental Impact Assessment, Audit and Planning, CSIR-National Environmental Engineering Research Institute (CSIR-NEERI), Nehru Marg, Nagpur, India.

*Email: sandeep.bodkhe@csir.res.in

Publisher: Cornous Publications LLP., Puducherry, India.
Advanced Researches in Agricultural Sciences (Volume 2)
Editors: Dr. Ashim Midya, Dr. Selvakumar Gurunathan
ISBN: 978-81-986832-0-5
DOI: https://doi.org/10.37446/vol2book092025/29-40

Emerging alternative solutions, such as microbial and nano-enabled pesticides, precision application technologies, eco-friendly pest management protocols and sustainable pest management strategies, are also reviewed. By integrating scientific literature with government

policy and monitoring data, this chapter aims to provide a holistic understanding of pesticide-induced environmental toxicity in Indian agriculture and outlines future directions for environmentally sustainable and health-conscious pesticide management.

Introduction

The expansion of agricultural activities has led to the widespread use of pesticides, which has increased chemical burden on the natural environment (Mondal et al., 2026). The introduction of chemical pesticides in India began in 1948, with production starting in 1952. Annually, around 2 million tonnes of pesticides are used worldwide, leading to considerable biodiversity loss due to biomagnification and their persistence in ecosystems. Research indicates that merely around 0.1% of pesticides used effectively reach their specific targets, while the majority of them impact non-target organisms (Kumar et al., 2025). The consumption of pesticides worldwide has seen a substantial rise in recent decades, with an estimated total of around 3.73 million tonnes of active ingredients recorded in 2023 (Food and Agriculture Organization of the United Nations, 2025).

Approximately 15–25% of potential crop production is lost as a result of pests, weeds, and diseases (Yadav & Dutta, 2019). The predominant design and production of pesticides are based on the premise that they will primarily affect a single molecular site of action in the targeted organism. However, numerous compounds can trigger a series of secondary and tertiary effects beyond this initial target (Bhakar et al., 2023). Despite strict regulations established by international bodies such as the EPA and WHO, in India, organizations like the Central Insecticide Board and Registration Committee (CIBRC) and the FSSAI regulate production and use of pesticides. Nevertheless, it is observed that farmers frequently neglect the recommended dosage, timing, and frequency associated with pesticide application (Singh Brar et al., 2018). A variety of tools has been established to evaluate the effects of pesticides, including the Environmental Impact Quotient (EIQ), Ecotoxicological Risk Assessment (ERA), Life Cycle Assessment (LCA), Pesticide Risk Indicators (PRIs), Soil and Water Contamination Studies, Bioindicators and Biomonitoring, Residue Analysis in Food and Environment, modelling approaches like the Pesticide Root Zone Model for Groundwater (PRZM-GW) and Groundwater Loading Effects of Agricultural Management Systems (GLEAMS), and Biodiversity and Ecosystem Impact Assessments (Kukanur & Deshmukh, 2025). There is an urgent necessity to establish an integrated strategy among national and international organizations to ban the use of extremely hazardous pesticides and those identified as probable or possible carcinogens (Peshin et al., 2020). Furthermore, urgent changes in cropping patterns, farming practices, and knowledge about the types of pesticides utilized, their mode of action, persistence, and degradation in soil and agro-ecosystem are necessary to minimize the environmental impact of agriculture (Ghosh & Chakma, 2022). The existing literature reveals a lack of conclusive information concerning the reliable indicators necessary for comparing trends in pesticide use and its associated effects (Peshin et al., 2020). This chapter examines pesticide use and its associated environmental toxicity and sustainable mitigation strategies for environmental safety and ensuring food security within the context of Indian agriculture.

Pesticide uses in Indian agriculture

Patterns and trends of pesticide consumption: A case study

Yadav & Dutta (2019) reported that the majority of farmers agreed that they use pesticides in the cultivation of their crops in Tijara Tehsil, Rajasthan. The primary categories of pesticides utilized were 61.11% of insecticides, 22.22% of herbicides, and 11.11% of fungicides. The findings indicated that organophosphates were the most commonly utilized pesticides, followed by neonicotinoids and pyrethroids. Furthermore, it was noted that farmers possessed limited understanding of pest management and the implications of pesticide application in vegetable farming. Singh Brar et al. (2018) reported that the insecticides, fungicides, and acaricides most frequently applied to cauliflower and brinjal were malathion, mancozeb, and propargite, respectively, in Himachal Pradesh. Farmers were implementing crop protection measures based on recommendations from pesticide dealers instead of seeking guidance from agricultural extension officers or farm scientists. Additionally, they utilized pesticides that had not received approval from the CIBRC. According to Bhakar et al. (2023), each pesticide introduced into the agroecosystem will have an effect on one or more biotic components. The pesticide market in India is significant, projected to reach INR 342.3 billion by 2028. The observed market expansion highlights the necessity for robust surveillance and monitoring systems to address issues related to pesticide drift, contamination, and overuse (Kumar et al., 2025).

Figure 1 indicates that pesticide use is concentrated in a few agriculturally intensive states, particularly Uttar Pradesh, Maharashtra, Punjab, Telangana, and Haryana, whereas hilly and northeastern states show substantially lower consumption. This uneven distribution reflects variations in cropping intensity, dominant crop types, irrigation coverage, and the degree of reliance on chemical pesticides across different states of India.

Figure 1. Consumption of chemical pesticides in India by state as of October 31, 2025, for the year 2024-2025 in metric tonnes (Directorate of Plant Protection, 2026)

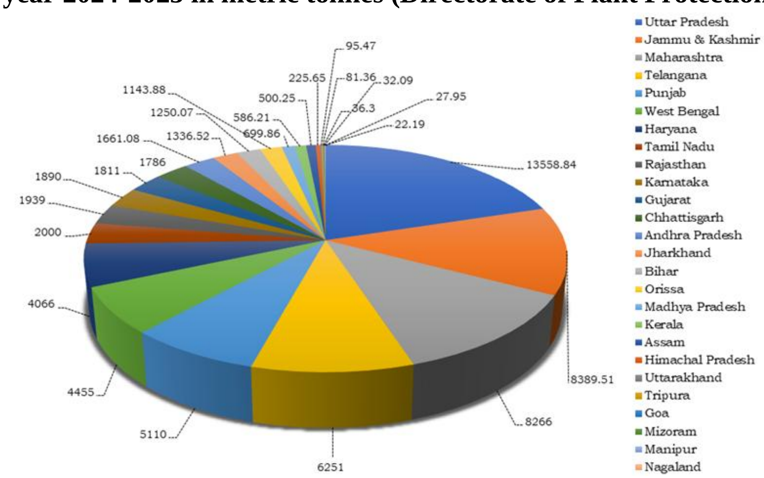

Figure 2. Consumption of pesticides (technical grade material) in thousand tonnes from 2001 to 2023 in India (Government of India, 2025)

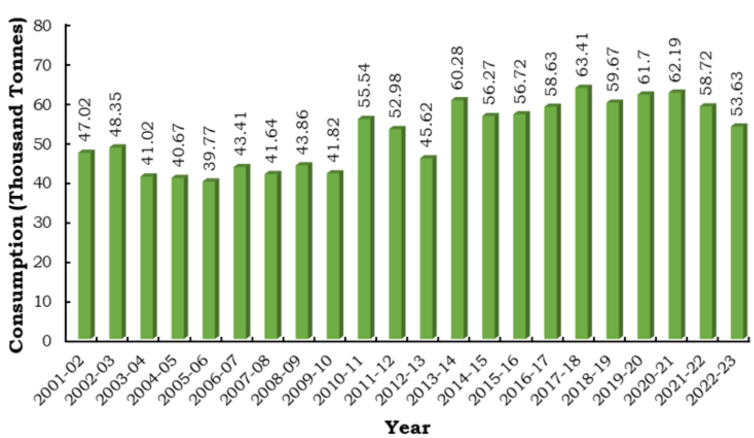

Figure 2 shows the consumption of pesticides (technical grade material) in thousand tonnes from 2001 to 2023 in India. The graph shows that pesticide consumption fluctuated between 2001–02 and 2012–13, followed by a general increasing trend with peaks around 2018–19 to 2020–21 and a slight decline in the most recent years (2021–22 and 2022–23).

Crop-wise and region-specific application practices

In Rajasthan, 93.27% of cotton was identified as the highest pesticide-consuming agricultural product, followed by 87.2% of vegetables, 66.4% of wheat, 52.6% of millet, and 12.6% of mustard (Yadav & Dutta, 2019). The findings indicated that the most frequently utilized insecticides, fungicides, and acaricides on cauliflower and brinjal were “malathion,” “mancozeb,” and “propargite,” respectively. The most effective pesticides identified were malathion, chlorpyrifos, cypermethrin, carbendazim, and mancozeb (Singh Brar et al., 2018). Peshin et al. (2020) reported that prophylactic pesticide applications in apple crops resulted in significant pesticide usage, totalling 25.2 kg of active ingredient (a.i.)/ha, with the application of high-risk carcinogenic pesticides at 9 kg of a.i./ha. The field use EIQ reached 620.4/ha, indicating that the Kashmir Valley is a notable area for pesticide application, followed by cotton and rice regions in Punjab and vegetable cultivation in Jammu.

Ghosh & Chakma (2022) reported that potatoes exhibit the highest toxicity potential at 13.78 kg 1,4-DBeq/ha, followed by paddy at 6.03 kg 1,4-DBeq/ha and vegetables at 5.40 kg 1,4-DBeq/ha, with pulses demonstrating the lowest levels. The primary factors contributing to agricultural unsustainability, particularly regarding toxicity potentials, are the increased specialization in the cultivation of potatoes and paddy, along with a deficiency in crop diversification. Figure 3 shows the crop-wise consumption of chemical and biopesticides across different commodity groups in India (2020–2025). Figure 3 shows that chemical pesticides consistently dominate total use across all crop groups particularly cereals and fruits while biopesticide consumption remains comparatively low.

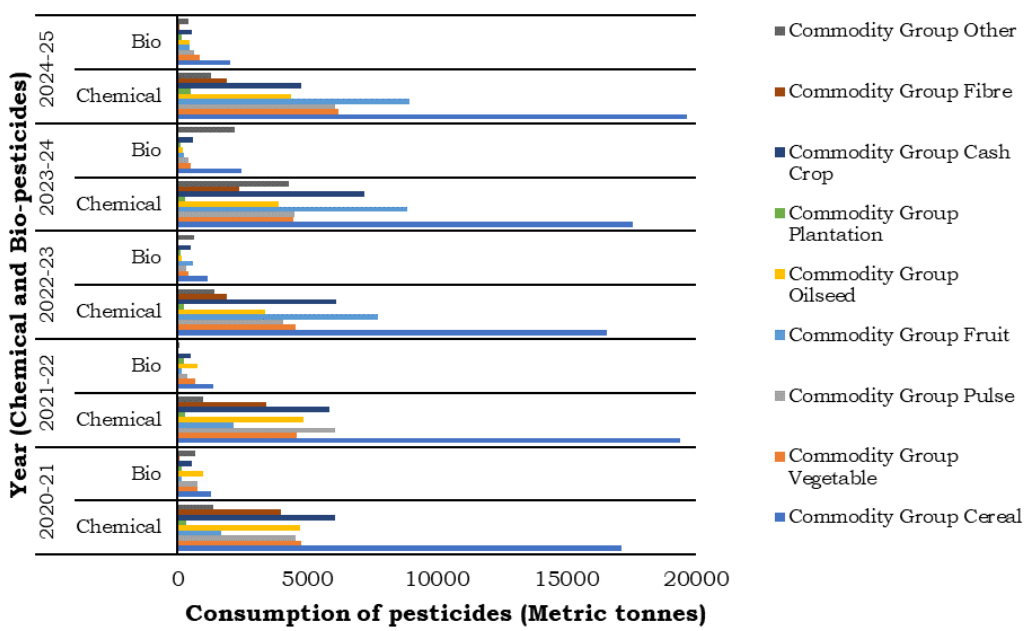

Figure 3. Crop-wise consumption of chemical and bio-pesticides across different commodity groups in India from 2020 to 2025 (Directorate of Plant Protection, 2026)

Environmental Toxicity of Pesticides

Pesticides are typically applied directly to plant parts, or the plant parts undergo pretreatment with pesticides. Nevertheless, merely 1% of the pesticide applied reaches the intended pest, while the remaining quantity integrates into various components of the environment, causing adverse impacts on biodiversity and non-target organisms. The aerial application of pesticides has the potential to contaminate surrounding areas. Based on the application method, existing weather conditions, and the changes that occur to the chemicals applied, a significant amount of the pesticide used is either redistributed or altered in the environment, failing to reach the desired target as anticipated (Bhakar et al., 2023). Fish and other aquatic organisms are exposed to pesticides primarily through three pathways: dermal absorption from contaminated water, branchial uptake via gills during respiration, and oral intake through ingestion of contaminated water or prey. Secondary exposure occurs through trophic transfer, where predators consume organisms previously contaminated with pesticides, such as insects or smaller aquatic fauna. Bioaccumulation and biomagnification of these compounds in aquatic food webs can result in acute toxicity or chronic physiological damage in fish. Consequently, the accumulation of pesticide residues in edible fish poses a potential health risk to human populations through dietary exposure (Soliman Sabra & El-Deeb Mehana, 2015).

Pesticides were found to exert predominantly negative effects on growth, reproduction, behavior, and physiological biomarkers of non-target plants, animals, and microorganisms across aquatic and terrestrial ecosystems, with stronger impacts in temperate regions, thereby raising concerns about the sustainability of current pesticide use and the adequacy of existing risk-assessment frameworks (Wan et al., 2025). The application of pesticides, whether as the primary strategy for crop protection or integrated within an IPM framework, accepts that with repeated exposure of pests to the same mode of action, Darwinian evolutionary principles and natural selection will prevail. In such scenarios, the resistance to mechanisms of action will emerge as a significant and evolving threat to agricultural yield (Smith et al., 2026). Figure 4 shows the pathways of pesticide entry into various ecosystems.

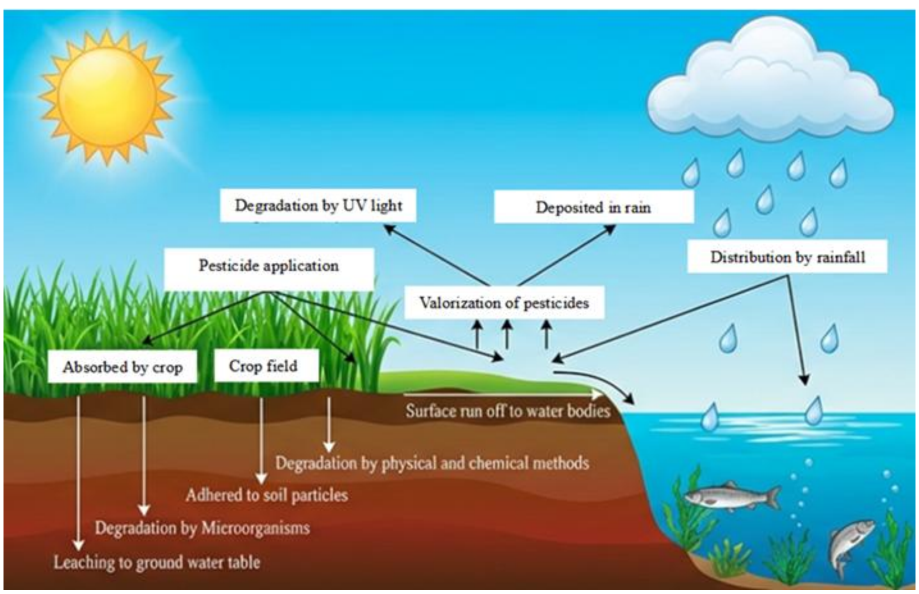

Figure 4. Pathways of pesticide entry into various ecosystems (Bhakar et al., 2023)

The WHO classifies pesticides based on their acute toxicity. This classification provides a standardized framework for assessing acute toxicity risks associated with pesticide exposure. Table 1 classifies pesticides into WHO hazard classes based on their acute toxicity, expressed as oral and dermal LD_{50} values for rats.

Table 1. Pesticide classification based on the WHO toxicity criteria in rats (mg/kg body weight) (Chaudhry, 2024)

WHO Class	LD_{50} (oral)	LD_{50} (dermal)
Extremely hazardous (Ia)	<5	<50
Highly hazardous (Ib)	5–50	50–200
Moderately hazardous (II)	50–2,000	200–2,000
Slightly hazardous (III)	Over 2,000	Over 2,000
Unlikely to present acute hazard (U)	5,000 or higher	5,000 or higher

Biodiversity implications of pesticide exposure

Pesticides have far-reaching effects on many ecosystem components. Specifically, these compounds have a substantial impact on soil, invertebrates, and birds. The utilization of insecticides and fungicides disrupts their enzymatic functions, leading to a reduction in earthworm biomass and population density (Kumar et al., 2025). The interruption of symbiotic nitrogen fixation, a vital mechanism for plant growth, eventually reduces crop yields and agricultural production. When pesticides are mishandled or misused, they contaminate ecosystems and enter the food chain, endangering aquatic life. Flooding, irrigation, and runoff can introduce chemicals into water bodies, contaminating rivers and groundwater, impairing water quality, and posing risks to human health through exposure and bioaccumulation in the food chain (Kukanur & Deshmukh, 2025). The overuse of pesticides can lead to the development of resistance in pest populations and result in considerable harm to biodiversity (Chaudhry, 2024). A retrospective study conducted at Telangana, India (2023–2024) analyzed 300 cases of acute pesticide poisoning reported that insecticides (53.6%) and herbicides (38.1%) were the most common poisoning agents, with organophosphate compounds being the most frequent. The incidence was higher in males than females (3:2). Paraquat poisoning showed the highest mortality (76.5%), followed by organophosphate poisoning (17.6%) (Bommineni et al., 2024). A toxicological case study on 18 Wistar rats demonstrated that exposure to Dichlorvos (1 ml/day for 7 days) caused significant cardiotoxicity, oxidative stress, and inflammation, indicated by increased LDH, CK, MDA, TNF-α, and IL-6 levels. These findings confirm the toxic effects of organophosphate pesticides on the cardiovascular system (Saka et al., 2025).

Integrated Pest Management strategies

Adoption of cost-effective protected technologies represents a viable strategy for diminishing reliance on pesticides. An exemplary method within this framework is the implementation of IPM that utilizes an integrative strategy incorporating biological, cultural, physical, and chemical strategies to effectively manage pest populations in a manner that is both economically viable and environmentally sustainable (Kumar et al., 2025). Utilizing an economic surplus model, the study estimates that the implementation of IPM for the control of *P. absoluta* could yield economic benefits amounting to USD 264 million in Bangladesh and India over a span of 20 years. Furthermore, the adoption of “insect-resistant varieties” is projected to result in economic gains exceeding USD 8.6 billion during the same timeframe (Depenbusch et al., 2025). IPM strategies encompass a multifaceted approach to achieve pest control objectives. This includes cultural control methods such as crop rotation and strategic planting dates to mitigate pest presence; host resistance through the utilization of pest-resistant plants and livestock; mechanical control techniques like uprooting, weed harvesting, clean cultivation, and insect trapping; biochemical control involving the introduction of grass carp for aquatic weed management; chemical control utilizing pesticides; and sanitation practices (Soliman Sabra & El-Deeb Mehana, 2015).

Alternative and emerging pest control approaches for Integrated Pest Management

Biopesticides are a good substitute for synthetic pesticides. Despite the substantial expansion of the biopesticide market in India and other countries, especially in the past ten years, biopesticides have not been able to effectively replace synthetic pesticides. Recent scientific research has identified several obstacles that Indian farmers face when using biopesticides instead of chemical pesticides, including reduced efficiency, limited shelf life, a challenging registration process, and low tenacity (Chaudhry, 2024). The biocontrol agents *T. viride, T. harzianum, P. fluorescens, B. bassiana, M. anisopliae*, and *B. subtilis* have established themselves as essential elements in the management of several pests and diseases in India (Singh, 2022). A recent study reported that nano-formulated insecticides significantly increased mortality in pyrethroid-resistant mosquito populations (Abbasi, 2026).

Management strategies for mitigating pesticide induced environmental toxicity

The implementation of surveillance and monitoring systems is essential for enhancing pesticide management practices and reducing risks to the environment and human health. The establishment of effective tracking mechanisms, displayed by the Pesticide Utilization Card for agricultural practitioners, serves to enable systematic observation of pesticide application trends, mitigate instances of misuse, and improve adherence to regulatory standards. Simultaneously, the mitigation of food wastage through the implementation of effective policy interventions has the potential to markedly decrease unnecessary pesticide inputs and the associated exposure throughout the food chain. Various remediation strategies, such as phytoremediation, bioremediation, and advanced oxidation processes, have shown significant efficacy in the removal of pesticide residues from contaminated soils and aquatic environments (Kumar et al., 2025). The EIQ serves as a critical framework for the evaluation of pesticide-related risks, facilitating informed decision-making among stakeholders regarding the selection of chemicals that pose minimal threats to environmental integrity and human health. The integration of EIQ assessments into agricultural decision-making processes enables policymakers and farmers to effectively mitigate pesticide-related risks (Kukanur & Deshmukh, 2025). The field study conducted on the capacity of *Aspergillus oryzae* AM2 and *Mucor circinelloides* 166, two fungal strains indigenous to Argentinean agricultural soils, to degrade glyphosate and aminomethylphosphonic acid in field conditions indicates that both exhibit significant potential for bioaugmentation applications in herbicide-contaminated environments (Carranza et al., 2025). A recent study indicated that low-cost bio-adsorbents, specifically sponge gourd (*Luffa cylindrica*), demonstrated efficacy in the removal of chlorpyrifos and cypermethrin from wastewater, achieving removal rates of 51.33% and 82.5%, respectively (Mondal et al., 2026).

Farmer perception and pesticide practices: Some case studies

A study conducted by Yadav & Dutta (2019) indicated that 78.2% of farmers possessed fundamental knowledge regarding the safe handling and application of pesticides, as well as the associated risks of pesticide exposure; however, they exhibited reluctance to change their attitudes towards pesticide practices. The 76.2% of respondents reported not engaging in the practice of reading labels on pesticide containers.

Only 19.4% of participants reported utilizing safety measures, such as masks, goggles, and gloves, to mitigate direct exposure to pesticides. Approximately 47% of participants reported mask usage, while 33.6% indicated a lack of safety measures. The field study revealed a prevalent habit among farmers of smoking and chewing tobacco concurrently with pesticide application. A total of 166 respondents, representing 33.2%, reported bathing immediately after pesticide application, while the remaining respondents washed their hands and continued with their daily activities. Singh Brar et al. (2018) reported that ~57% of participants primarily relied on pesticide dealers for advice, while 23.66% depended on relatives or friends, and 19.33% sought information from the public extension system or SAU personnel. Farmers lack familiarity with the guidelines of the CIBRC regarding the application of labelled and non-labelled pesticides. Furthermore, a significant proportion of farmers (57.33%) primarily rely on the recommendations of pesticide dealers for guidance.

Regulatory framework and monitoring of pesticides in India

The Insecticides Act (1968) and the Insecticides Rules (1971) represent the principal regulatory frameworks that oversee the importation, registration, production, sale, transportation, distribution, utilization, and disposal of pesticides in India. All pesticides are required to complete a stringent registration procedure with the CIBRC before they can be produced or sold. Upon validation, the CIBRC issues a registration number and certificate. The Central Insecticide Laboratory conducts testing of referral samples submitted by officers or agencies of the Central or State Governments (Reddy et al., 2024). The FSSAI is responsible for establishing and overseeing the “maximum residue limits” of pesticides in food items. The regulatory framework for pesticides in India, as established by the Insecticides Act (1968), lacks sufficient provisions for state-level regulation of pesticide application. Consequently, it is imperative for the central government to implement strategies aimed at mitigating the unregulated, unauthorized, and improper utilization of pesticides within the agricultural sector in India (Chaudhry, 2024). Additionally, national epidemiological studies and surveys should be conducted. IPM programs must be redefined to educate farmers on the safe handling and application of pesticides, particularly in areas identified as pesticide hotspots (Peshin et al., 2020).

Future perspectives and direction on sustainable pesticide use for environmental and ecological safety ensuring global food security

The Government of India must duly recognize regulatory responses that involve the gradual phasing out of pesticides classified as “extremely hazardous” and “highly hazardous” according to the WHO’s toxicity criterion. Additionally, the incorporation of the “polluter pays” and “precautionary principles” of environmental policy in relation to pesticide use is essential. The reduction of chemical pesticide application in agricultural practices may serve as a viable strategy to mitigate the risk of chronic diseases in premature populations in India (Chaudhry, 2024). For the production of next-generation goods with longer shelf life, recent research approaches on *Trichoderma*, in particular genomes, transcriptomics, proteomics, and metabolomics, can be employed (Singh, 2022). The implementation of telerobotic, target-specific pesticide applicators in greenhouse cultivation presents considerable opportunities for improving application efficiency, ensuring operator safety, and promoting environmental sustainability. The incorporation of sensor-driven activation systems has the potential to significantly reduce pesticide usage through the facilitation of precision spraying based on specific requirements (Naik et al., 2025). Insect trapping systems utilizing UV LED technology, combined with water-oil collection mechanisms, can facilitate automated and cyclic pest control in both protected and open-field agricultural settings (Madduri et al., 2025).

Utilization of AI-driven decision-support tools has demonstrated an enhancement in crop yield estimation, achieving predictive accuracies of nearly 92%. Concurrently, AI-driven pest identification systems facilitate the minimization of pesticide application through targeted interventions (Padhiary et al., 2025). Machine learning–based decision support systems can be integrated into pesticide management techniques to avoid unnecessary pesticide applications, ensuring need-based application of pesticides based on ETL and EIL after assessing Agro-Ecosystem Analysis (AESA). Post-application crop data, including spatial and physiological indications, can be examined using machine learning algorithms to identify specific zones that require a second pesticide application. This targeted application strategy has the potential to reduce recurrent pesticide use by at least 20% compared to standard blanket spraying practices, hence minimizing input costs, environmental contamination, and pesticide exposure risks and hazards to agro-ecosystem (Indu et al., 2022). Figure 5 shows the process for identifying crop areas requiring repeated pesticide application.

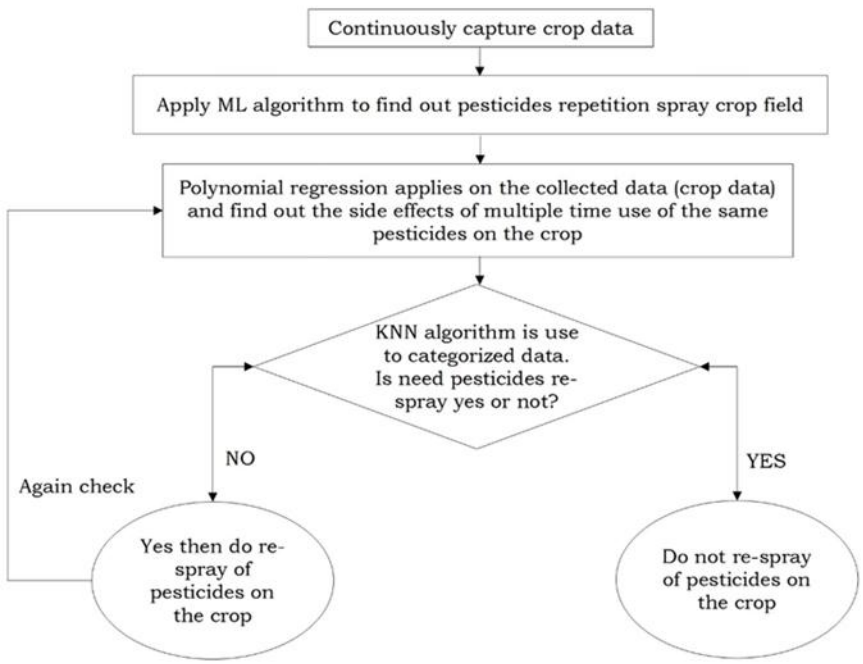

Figure. 5 Process for identifying crop areas requiring repeated pesticide application (Indu et al., 2022)

Conclusion

Pesticides are an integral part of modern agriculture, contributing to effective pest control and enhanced crop productivity. The effectiveness of pesticide application in Indian agriculture is notably low, with approximately 0.1–1% effectively targeting pests. Their environmental and health impacts and hazards are assessed using multiple established tools, including the EIQ, ERA, LCA, PRIs, soil and water contamination studies, bioindicators and biomonitoring, residue analysis in food and the environment, modelling approaches such as PRZM-GW and GLEAMS, and biodiversity and ecosystem impact assessments. The Indian pesticide market is substantial and is projected to reach INR 342.3 billion by 2028. Reportedly, pesticide consumption during 2024–2025 (as of October 31, 2025) is concentrated in a few agriculturally intensive states - namely, Uttar Pradesh, Maharashtra, Punjab, Telangana, and Haryana. In addition, crop-wise pesticide consumption patterns (2020–2025) highlight the dominance of chemical pesticides across all commodity groups, particularly cereals and fruits, whereas bio-pesticide use remains comparatively limited.

Research conducted across various agricultural regions in India reveals a prevalent dependence on pesticides, predominantly insecticides, with organophosphates leading, followed by neonicotinoids and pyrethroids. Data from Rajasthan and Himachal Pradesh underscores the frequent application of malathion, mancozeb, and propargite. The decision-making process appears to be predominantly influenced by pesticide vendors, with the utilization of certain products lacking approval from the CIBRC. Reportedly, pesticides significantly affect various biotic elements within agricultural ecosystems. Environmental redistribution, bioaccumulation, and biomagnification in aquatic food webs present significant risks to biodiversity and human health via contaminated food sources. The repeated application of pesticides contributes to the accelerated development of resistance in pest populations. IPM strategies encompass a multifaceted approach to achieve pest control objectives and should be adopted as the preferred pest management framework. In India, biocontrol agents such as *Trichoderma viride*, *Trichoderma harzianum*, *Pseudomonas fluorescens*, *Beauveria bassiana*, *Metarhizium anisopliae*, and *Bacillus subtilis* have been widely reported as effective and integral components of pest and disease management across diverse cropping systems.

Effective mitigation of pesticide-induced environmental toxicity requires integrated strategies encompassing surveillance and monitoring systems such as the Pesticide Utilization Card, reduction of food wastage exceeding 40% in India to curb unnecessary pesticide inputs, and the deployment of remediation technologies including phytoremediation, bioremediation, advanced oxidation processes, and low-cost bio-adsorbents. The application of standardized risk-assessment tools such as the EIQ, along with bioaugmentation approaches using indigenous fungal strains capable of degrading glyphosate, AMPA, chlorpyrifos, and cypermethrin. Field studies indicate that although a majority of Indian farmers possess basic awareness of pesticide risks, unsafe practices remain widespread, including failure to read labels, inadequate use of personal protective equipment, unsafe mixing methods, and poor post-application hygiene. Heavy reliance on pesticide dealers for advice, limited engagement with extension services, and low awareness of CIBRC guidelines highlight critical gaps in training, information dissemination, and behavioral change, illustrating the urgent need for targeted education, effective extension outreach, and strengthened regulatory communication to promote safer pesticide practices.

Recent advances in biocontrol research, particularly studies using modern “omics” tools on *Trichoderma*, ecological engineering, nanotechnology, host plant resistance, host induced plant volatiles, eco-friendly pest management packages, telerobotic and sensor-based applicators, UV LED–based pest trapping, and AI- and machine learning–driven decision-support systems, collectively demonstrate strong potential to enhance application precision, improve yield and water-use efficiency, reduce pesticide consumption by up to 20%, and minimize environmental contamination, thereby supporting safer, technology-enabled, and sustainable crop protection strategies. A sustainable transition in pesticide management in India requires a regulatory phase-out of WHO-classified extremely and highly hazardous pesticides, adoption of the polluter-pays and precautionary principles, and reduced chemical inputs to mitigate chronic health risks, and minimal pesticide load in agro-ecosystem and environment for ensuring pollution free sustainable agricultural production system.

Conflict of Interest Statement: The authors declare no conflict of interest.

Acknowledgments

This work is supported by the University Grants Commission (UGC). The authors are grateful to the director of CSIR-NEERI.

References

Abbasi, E. (2026). Nanotechnology-based innovations for overcoming insecticide resistance in disease vectors: An experimental approach. *Research Square*. https://doi.org/10.21203/rs.3.rs-8390384/v1

Bhakar, A., Singh, Y. V., Abhishek, & Tabassum, R. (2023). Pesticides in India in the twenty-first century and their impact on biodiversity. *Vegetos*, *36*(3), 768–778. https://doi.org/10.1007/s42535-022-00434-y

Bommineni, S. R., Alekhya, K., Chary, R. P., Reddy, S. B., & Sahithi, P. (2024). A study of acute pesticide poisoning in a tertiary care centre in South India. *International Journal of Research in Medical Sciences*, *12*(12), 4541–4544. https://doi.org/10.18203/2320-6012.ijrms20243703

Brar, G. S., Kumar Patyal, S., Dubey, J. K., & Singh, G. (2018). Survey on pesticide use pattern and farmers' perceptions in cauliflower and brinjal growing areas in three districts of Himachal Pradesh, India. *International Journal of Current Microbiology and Applied Sciences*, *7*(3), 2417–2423.

Carranza, C. S., Aluffi, M. E., Benito, N., Magnoli, K., De Gerónimo, E., Aparicio, V. C., Barberis, C. L., & Magnoli, C. E. (2025). Glyphosate and aminomethylphosphonic acid removal by fungal strains native to pesticide-exposed agricultural soil: A field study. *International Journal of Environmental Science and Technology, 22*(4), 2421–2430. https://doi.org/10.1007/s13762-024-05809-z

Chaudhry, D. (2024). Pesticide use in Indian agriculture: Policy alternatives for environmental health. *Journal of Development Policy and Practice, 9*(1), 133–161. https://doi.org/10.1177/24551333221121890

Depenbusch, L., Sequeros, T., Schreinemachers, P., Sharif, M., Mannamparambath, K., Uddin, N., & Hanson, P. (2025). Tomato pests and diseases in Bangladesh and India: Farmers' management and potential economic gains from insect-resistant varieties and integrated pest management. *International Journal of Pest Management*, *71*(4), 552–566. https://doi.org/10.1080/09670874.2023.2252760

Directorate of Plant Protection, Quarantine & Storage. (2026). *Statistical database*. https://ppqs.gov.in/en

Food and Agriculture Organization. (2025, July 15). *Pesticides use and trade: 1990–2023*. FAO Statistics Division. https://www.fao.org/statistics/highlights-archive/highlights-detail/pesticides-use-and-trade-1990-2023/en

Ghosh, B., & Chakma, N. (2022). Impact of agricultural pesticides on ecosystem and human health: A case study in lower Gangetic plain, India. *Arabian Journal of Geosciences*, *15*, 626.

Government of India. (2025). *Environment statistics of India*.

Indu, Baghel, A. S., Bhardwaj, A., & Ibrahim, W. (2022). Optimization of pesticide spray on crops in agriculture using machine learning. *Computational Intelligence and Neuroscience, 2022*, 408535.

Kukanur, V. S., & Deshmukh, S. S. (2025). Measuring what matters: Environmental impact assessment of pesticides in modern agriculture. *Indian Journal of Plant Protection, 53*(1), 1–12.

Kumar, A., Bhople, B. S., & Jeganathan, J. (2025). Balancing food security and environmental health: The dual challenge of pesticide use in India. *Environmental Science and Pollution Research, 32*(9), 4949–4956.

Madduri, K., Hiremath, S., Lokesh, J., Chiniwar, D. S., & Shrishail, M. H. (2025). Environment-friendly experimental solar-powered UV light pest trapping mechanism for open agricultural fields. *Environmental Research Communications, 7*(3), 035002. https://doi.org/10.1088/2515-7620/adb8a5

Mondal, S., Sardar, C., Das, A., Jana, H. K., & Mandal, T. K. (2026). A sustainable solution for environmental cleanup: Innovative bio-adsorbent method to remove pesticide residues from water samples. *Clean – Soil, Air, Water, 54*(1). https://doi.org/10.1002/clen.70099

Naik, M. A., Kumar, A., Kushwaha, D. K., Kushwaha, H. L., Gupta, S., Ramasubramanian, V., Singh, A. K., & Hasan, M. (2025). Development of a telerobotic target-specific pesticide applicator: An intervention for enhanced safety and efficiency. *Journal of Field Robotics, 42*(6), 2469–2491. https://doi.org/10.1002/rob.22524

Padhiary, M., Kumar, K., Hussain, N., Roy, D., Barbhuiya, J. A., & Roy, P. (2025). Artificial intelligence in farm management: Integrating smart systems for optimal agricultural practices. *International Journal of Smart Agriculture, 3*(1), 1–11. https://doi.org/10.54536/ijsa.v3i1.3674

Peshin, R., Hansra, B. S., Nanda, R., Singh, K., Sharma, R., Garg, L., Bajiya, M. R., Showkat, A., Kumar, R., & Yangsdon, S. (2020). Pesticide hazardous hotspots: Empirical evidences from North India. *Environmental Management, 66*(5), 899–915. https://doi.org/10.1007/s00267-020-01317-1

Reddy, A. A., Reddy, M., & Mathur, V. (2024). Pesticide use, regulation, and policies in Indian agriculture. *Sustainability, 16*(17). https://doi.org/10.3390/su16177839

Saka, W. A., Ayandele, O. A., Oladipo, O. O., Adeshina, O. S., & Kehinde, B. D. (2025). *Andrographis paniculata* aqueous extract exhibits cardioprotective effect against dichlorvos-induced toxicity, a commonly used organophosphate pesticide. *Toxicology Reports, 14*, 102038. https://doi.org/10.1016/j.toxrep.2025.102038

Singh, H. (2022). Current status and recent developments in microbial pesticide use in India. *Indian Journal of Plant Genetic Resources, 35*(3), 369–374. https://doi.org/10.5958/0976-1926.2022.00102.4

Smith, J., Martins, B. A. B., Beffa, R., Field, L. M., Goertz, A., Le Goupil, G., Mehl, A., Langewald, J., Martinelli, S., Rossi, C. V. S., & Wiles, J. A. (2026). Challenges facing the management of pesticide resistance in weeds, diseases and insect pests in European agriculture and the future of effective IPM implementation. *Pest Management Science*. https://doi.org/10.1002/ps.70522

Soliman Sabra, F., & El-Deeb Mehana, E.-S. (2015). Pesticides toxicity in fish with particular reference to insecticides. *Asian Journal of Agriculture and Food Sciences, 3*(1), 40–60.

Wan, N. F., Fu, L., Dainese, M., Kiær, L. P., Hu, Y. Q., Xin, F., Goulson, D., Woodcock, B. A., Vanbergen, A. J., Spurgeon, D. J., Shen, S., & Scherber, C. (2025). Pesticides have negative effects on non-target organisms. *Nature Communications, 16*(1), 1360. https://doi.org/10.1038/s41467-025-56732-x

Yadav, S., & Dutta, S. (2019). A study of pesticide consumption pattern and farmer's perceptions towards pesticides: A case of Tijara Tehsil, Alwar (Rajasthan). *International Journal of Current Microbiology and Applied Sciences, 8*(4), 96–104. https://doi.org/10.20546/ijcmas.2019.804.012.