REVIEW PAPER

Pesticide Exposure and Human Health Risks: Mechanisms, Toxicological Effects, and Preventive Strategies

Namita Saxena[1*], Jagdish Makhijani[2]

[1]*Department of Chemistry, Rustamji Institute of Technology, BSF Academy, Gwalior, Gwalior- MP -475005
Email: dr.namitasaxena@rjit.ac.in; namitagwl@gmail.com Contact: +91-9425341421

[2]Department of CSE, Rustamji Institute of Technology, BSF Academy, Gwalior, Gwalior- MP -475005
Email: drjagdish@rjit.ac.in

***Corresponding Author: Namita Saxena**
Department of Chemistry Rustamji Institute of Technology BSF Academy Gwalior Gwalior- MP -475005
Email: dr.namitasaxena@rjit.ac.in; namitagwl@gmail.com Contact: +91-9425341421

Abstract

Pesticides are extensively used in modern agriculture to enhance crop productivity and control pest infestations; however, their widespread and often indiscriminate application has raised significant concerns regarding human health. This review synthesizes current evidence on human exposure pathways, including occupational, environmental, and dietary routes, and evaluates associated acute and chronic health outcomes. Acute pesticide exposure, predominantly affecting agricultural workers and applicators, is commonly associated with cholinesterase inhibition leading to neurological, respiratory, dermatological, and gastrointestinal symptoms. Long-term exposure to low-dose pesticide mixtures has been increasingly linked to chronic diseases, including neurodegenerative disorders, cancers, endocrine disruption, reproductive toxicity, and multi-organ damage involving hepatic, renal, and immune systems.

Mechanistically, pesticide toxicity is primarily mediated through oxidative stress, mitochondrial dysfunction, endocrine interference, and genotoxic effects. Particular emphasis is placed on organophosphate, organochlorine, and pyrethroid compounds due to their persistence and widespread use. Evidence from global and Indian studies highlights elevated risk among agricultural populations, with additional concerns arising from environmental contamination of soil, water, and food chains.

Given the growing burden of pesticide-related health risks, this review underscores the urgent need for strengthened regulatory frameworks, promotion of integrated pest management strategies, and improved occupational safety measures. Transition toward sustainable and less hazardous pest control alternatives is essential to mitigate long-term public health impacts.

Keywords: Chronic diseases, Endocrine disruption, Environmental contamination, Neurotoxicity, Pesticides, occupational exposure.

How to cite this article: Saxena N, Makhijani J. Pesticide Exposure and Human Health Risks: Mechanisms, Toxicological Effects, and Preventive Strategies. Int J Drug Deliv Technol. 2026;16(54s): 358-367. DOI: 10.25258/ijddt.16.54s.31

1. Introduction

Pesticides have become an integral component of modern agriculture, contributing significantly to enhanced crop productivity and global food security. Their widespread use has expanded rapidly over the past few decades in response to increasing food demand driven by population growth. However, this intensive reliance on pesticides has raised serious concerns regarding their potential impact on human health and the environment. Globally, human exposure to pesticides occurs through multiple pathways, including occupational contact, environmental contamination, and dietary intake via food and water. Studies have shown that pesticide residues are commonly detected in air, soil, and water, making exposure pervasive and often unavoidable (Fagundes TR, 2025). A growing body of epidemiological and toxicological evidence indicates that pesticide exposure is associated with a wide range of adverse health outcomes. These include acute poisoning as well as chronic diseases such as cancer, neurodegenerative disorders, respiratory illnesses, endocrine disruption, and reproductive abnormalities. Particularly concerning is the impact on vulnerable populations such as agricultural workers, pregnant women, and children, who are more susceptible due to higher exposure levels and physiological sensitivity. Furthermore, recent research emphasizes the risks associated with long-term, low-dose exposure and the combined effects of multiple pesticide residues, which remain insufficiently understood (Shekhar C,2024). Thus, while pesticides play a crucial role in sustaining agricultural productivity, their extensive global use presents a significant public health challenge that necessitates improved monitoring, regulation, and safer alternatives.

India, being an agrarian economy, relies heavily on pesticides to ensure crop protection and food security for its large and growing population. The intensification of agriculture, particularly since the Green Revolution, has led to increased use of agrochemicals, including

*Author for Correspondence: namitagwl@gmail.com

pesticides (Kashyap U,2024).Although pesticide consumption in India is lower compared to some developed and developing countries, its usage has increased substantially over time, with production and application rising significantly in recent decades (Soman S,2024).One of the major concerns in India is the indiscriminate and unregulated use of pesticides, often without adequate awareness, training, or protective measures. As a result, pesticide residues have been detected in soil, surface water, groundwater, and food products, sometimes exceeding permissible safety limits set by national and international agencies (Kashyap U,2024). Occupational exposure among farmers and pesticide applicators is particularly significant. Studies conducted in rural regions of India have reported various health issues among pesticide sprayers, including respiratory problems, neurological symptoms, and biochemical alterations due to prolonged exposure (Mathew P,2015). In addition, indirect exposure through contaminated food and water further increases the risk to the general population. The lack of proper regulation, inadequate enforcement of safety standards, and limited awareness among users exacerbate the problem.

Given these challenges, pesticide exposure represents a critical public health issue in India, highlighting the urgent need for stricter regulatory frameworks, improved farmer education, and the promotion of sustainable agricultural practices.

2. Routes of Human Exposure

Humans are exposed to pesticides through multiple pathways (Figure 1)

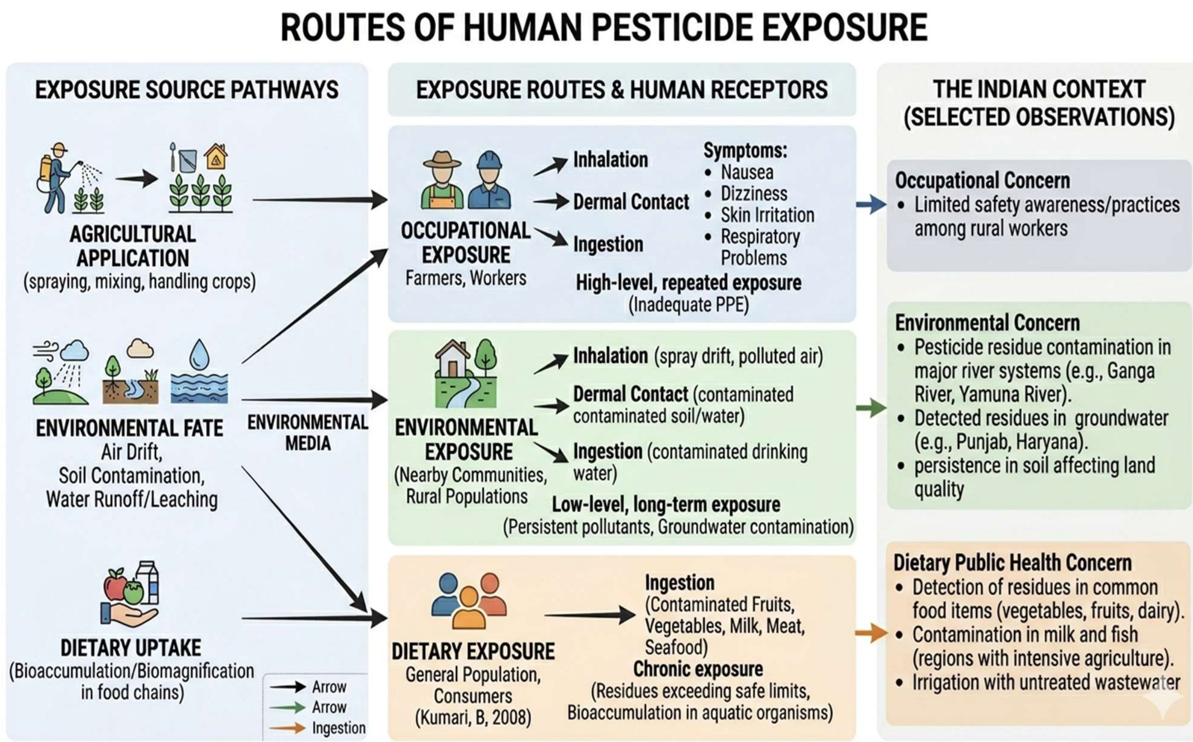

Figure 1: Routes of Human Exposure to Pesticides

2.1. Occupational Exposure

Humans are exposed to pesticides through multiple pathways, with occupational exposure being one of the most significant. Farmers and agricultural workers experience the highest levels of exposure due to direct handling, mixing, and spraying of pesticides, as well as frequent contact with treated crops. In many cases, inadequate use of personal protective equipment further increases the risk. Repeated exposure can lead to the accumulation of toxic substances in the body. Studies have reported that pesticide concentrations are significantly higher among farmers compared to the general population, resulting in symptoms such as nausea, dizziness, skin irritation, and respiratory problems (Tadsual, M.K., 2025). In the Indian context, occupational exposure is particularly concerning due to limited awareness and safety practices among rural workers.

2.2. Environmental Exposure

Environmental exposure to pesticides occurs when chemical residues contaminate natural resources such as air, soil, and water. These contaminants may arise from agricultural runoff, improper disposal, and atmospheric drift during pesticide spraying, allowing chemicals to spread far beyond the target area. Spray drift, in particular, exposes nearby communities and ecosystems, even those not directly involved in agricultural activities. Over time, many pesticides persist in the environment and undergo processes such as bioaccumulation and biomagnification, leading to their concentration in food chains. As a result, humans may be indirectly exposed through drinking contaminated water, consuming affected crops, or inhaling polluted air. According to Hongoeb, J. (2025), pesticide residues can remain in environmental matrices for extended periods, increasing long-term exposure risks.

In the Indian context, environmental exposure is a growing concern due to intensive agricultural practices and inadequate regulation in some regions. Studies have reported pesticide contamination in major river systems such as the Ganga River and Yamuna River, largely due to agricultural runoff and industrial discharge. Additionally, groundwater in agriculturally intensive states like Punjab and Haryana has shown detectable levels of pesticide residues. Rural populations relying on these water sources are therefore at increased risk of chronic exposure. Furthermore, the persistence of certain chemicals in soil reduces land quality and facilitates their entry into crops, thereby affecting food safety. These findings highlight the need for stricter environmental monitoring and sustainable pesticide management practices in India (Kumari, B,2008).

2.3. Dietary Exposure

Dietary exposure is one of the most common pathways through which humans come into contact with pesticides, primarily through the consumption of contaminated food products. Fruits, vegetables, cereals, milk, and meat may contain pesticide residues due to their direct application on crops or indirect contamination from soil and water. In many cases, improper application practices and failure to observe recommended waiting periods before harvest result in residue levels exceeding safe limits. Additionally, pesticides present in water bodies are absorbed by aquatic organisms, leading to bioaccumulation in fish and other seafood. These contaminants are further transferred to humans through the food chain, posing significant health risks. According to Adokiya, M.N. (2025), aquatic organisms can act as reservoirs of pesticide residues, increasing the likelihood of chronic dietary exposure in human populations.

In the Indian context, dietary exposure is a major public health concern due to widespread pesticide use and challenges in monitoring food safety. Several studies have reported the presence of pesticide residues in commonly consumed food items, including vegetables, fruits, and dairy products. For instance, research by Kumari B. et al. (2006) detected significant levels of pesticide residues in vegetables and fruits from local markets in India. Similarly, contamination has been observed in milk and fish, particularly in regions with intensive agriculture and polluted water bodies. The use of untreated wastewater for irrigation in some areas further increases the risk of contamination in food crops. These findings indicate that a large section of the population may be chronically exposed to low levels of pesticides through diet, emphasizing the need for strict regulation, regular monitoring, and public awareness regarding safe food practices (Kumari, B,2006). Different classes of pesticides exert toxicity through distinct biochemical mechanisms and are associated with diverse acute and chronic health effects. A summary of major pesticide classes, their mechanisms of toxicity, and associated human health outcomes is presented in Table 1.

Table:1 Major classes of pesticides, mechanisms of toxicity, and associated human health effects.

Pesticide Class	**Examples**	**Toxicity Mechanism**	**Acute Health Effects**	**Chronic Health Effects**	**Key Target Organs/Systems**
Organophosphates	Chlorpyrifos, Malathion, Parathion, Diazinon	Inhibition of acetylcholinesterase causing accumulation of acetylcholine	Headache, dizziness, nausea, muscle twitching, respiratory distress, excessive salivation	Neurodegenerative disorders, cognitive impairment, endocrine disruption, reproductive toxicity	Nervous system, respiratory system, reproductive system
Carbamates	Carbaryl, Aldicarb, Carbofuran	Reversible inhibition of acetylcholinesterase	Sweating, abdominal pain, blurred vision, weakness	Neurological dysfunction, liver toxicity	Nervous system, liver
Organochlorines	DDT, Endosulfan, Lindane	Persistent bioaccumulation, endocrine interference, oxidative stress	Tremors, seizures, skin irritation	Cancer, endocrine disruption, infertility, developmental abnormalities	Endocrine system, reproductive organs, liver

Pesticide Class	**Examples**	**Toxicity Mechanism**	**Acute Health Effects**	**Chronic Health Effects**	**Key Target Organs/Systems**
Pyrethroids	Cypermethrin, Permethrin, Deltamethrin	Alteration of sodium channel function in neurons	Skin irritation, paresthesia, eye irritation, headache	Neurotoxicity, hormonal imbalance, immune dysfunction	Nervous system, immune system
Herbicides	Glyphosate, Paraquat, Atrazine	Oxidative stress, mitochondrial dysfunction	Skin burns, nausea, breathing difficulty	Kidney damage, endocrine disruption, carcinogenic potential	Kidneys, lungs, endocrine system
Fungicides	Mancozeb, Carbendazim, Captan	Cellular oxidative damage, endocrine effects	Skin and eye irritation, gastrointestinal symptoms	Thyroid dysfunction, reproductive toxicity,liver damage	Thyroid gland, liver, reproductive system
Neonicotinoids	Imidacloprid, Thiamethoxam, Clothianidin	Interaction with nicotinic acetylcholine receptors	Dizziness, fatigue, nausea	Neurobehavioral changes, developmental toxicity	Nervous system
Rodenticides	Warfarin, Brodifacoum	Anticoagulant activity leading to impaired blood clotting	Bleeding, weakness, abdominal pain	Liver toxicity, coagulopathy	Blood system, liver
Bipyridyl Compounds	Paraquat, Diquat	Generation of reactive oxygen species (ROS)	Severe lung injury, vomiting, renal failure	Pulmonary fibrosis, chronic kidney disease	Lungs, kidneys
Persistent Organic Pollutants (POPs)	Aldrin, Dieldrin, Heptachlor	Bioaccumulation and endocrine disruption	Neurological symptoms, skin irritation	Cancer, immunotoxicity, metabolic disorders	Immune system, endocrine system, liver

3. Acute Health Effects of Pesticide Exposure

Acute pesticide exposure refers to the short-term adverse health effects that occur within hours to a few days (typically within 48h) after contact with pesticides through inhalation, ingestion, or dermal absorption. These effects are primarily observed among agricultural workers, pesticide applicators, and populations living near treated fields, especially in developing countries where safety practices are often inadequate (Boedeker, W,2020). These effects are primarily observed among agricultural workers, pesticide applicators, and populations living near treated fields, especially in developing countries where safety practices are often inadequate. Many commonly used pesticides, particularly organophosphates and carbamates, exert toxicity by inhibiting the enzyme acetylcholinesterase, leading to accumulation of acetylcholine in the nervous system. This results in overstimulation of nerve receptors and causes a range of neurological and systemic symptoms. Symptoms may vary depending on the type, dose, and duration of exposure. The most commonly reported symptoms include: Neurological effects: headache, dizziness, confusion, weakness, fatigue; Respiratory effects: cough, breathlessness, chest tightness; Dermatological effects: skin irritation, redness, itching; Ocular effects: burning eyes, blurred vision; Gastrointestinal symptoms: nausea, vomiting, abdominal pain; Systemic effects: excessive sweating, salivation, and fatigue (Figure 2).

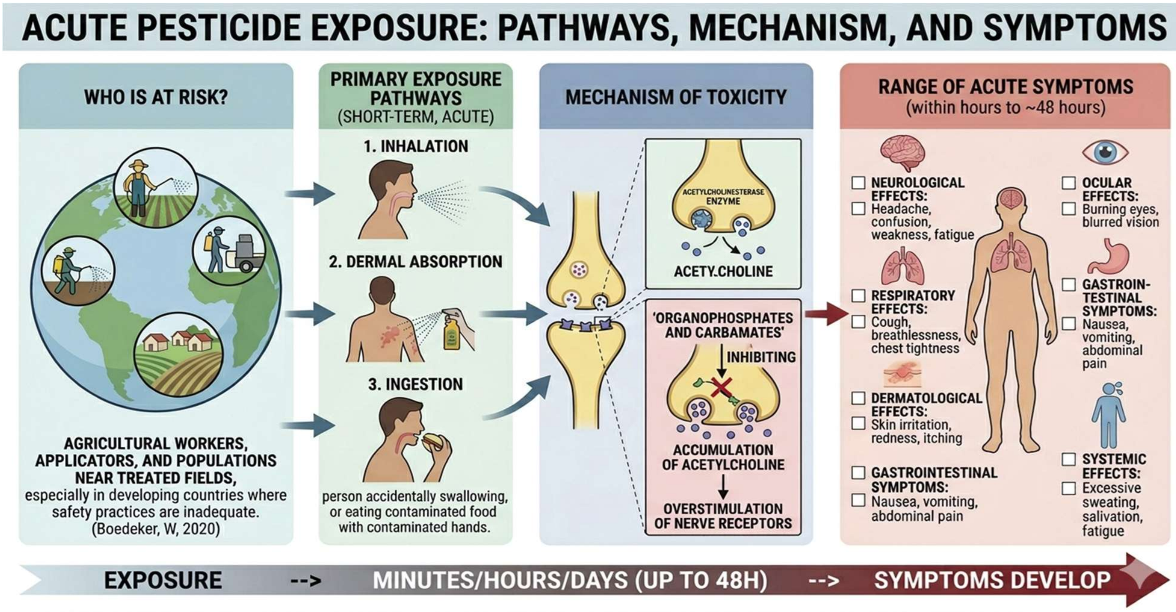

Figure 2. Pathways, mechanisms, and symptoms associated with acute pesticide exposure.

Several studies highlight the high burden of acute pesticide toxicity in India.A study in Kashmir Valley reported symptoms such as weakness (60%), dizziness (44%), headache (38%), and cough (58.7%) among pesticide sprayers (Sobia Nisar, 2021). Research from Odisha (2025) found that 63.4% of farmers experienced illness after insecticide exposure, with skin irritation being the most common symptom (Kumar N, 2025). A study in Bhopal reported acute symptoms including eye irritation (18%), blurred vision (23%), skin problems (50%), and breathing difficulty (34%) (Choudhary A,2014). Field surveys from Maharashtra (Yavatmal) showed that nearly 29% of farmers reported acute symptoms such as nausea, headaches, and respiratory distress (A joint field survey by PAN Asia Pacific and PAN India conducted in December 2024). These findings indicate that occupational exposure combined with poor use of protective equipment is a major driver of acute toxicity in India.

4. Chronic Health Effects of Pesticide Exposure

Chronic exposure to pesticides refers to long-term, repeated exposure to low or moderate doses over months or years. Unlike acute toxicity, chronic effects develop gradually and are often irreversible. A growing body of global and Indian research demonstrates that prolonged pesticide exposure is strongly associated with non-communicable diseases, including neurological disorders, cancers, endocrine disruption, reproductive toxicity, and organ damage (Shekhar C,2024) Figure 3.

4.1. Neurological Disorders

Long-term pesticide exposure has been widely linked to neurotoxicity and neurodegenerative diseases, such as Parkinson's disease, Alzheimer's disease, Cognitive decline and memory impairment. Mechanistically, pesticides induce Oxidative stress, Mitochondrial dysfunction, Neuronal cell damage. Studies on agricultural workers in India report neurochemical and behavioural dysfunctions, including impaired cognition and neurological symptoms due to chronic exposure. A recent biomonitoring study from Telangana found reduced acetylcholinesterase levels, indicating long-term neurological risk among exposed workers (Kumar Dt et al ,2024 & Kori RK et al ,2018)

4.2. Cancer

Chronic pesticide exposure has been associated with increased risk of several cancers. Epidemiological links include Breast cancer, Leukemia,Brain tumors mainly caused by DNA damage (genotoxicity), oxidative stress and disruption of cell signalling pathways. In India, several epidemiological observations indicate a higher incidence of cancer in agriculturally intensive regions, particularly those with heavy pesticide usage. One of the most frequently cited examples is the Malwa region of Punjab, often referred to as the *"cancer belt"*. This region has reported an unusually high number of cancer cases, which has been linked in multiple studies to long-term exposure to pesticides and environmental contaminants (Thakur et al., 2008; Mittal et al., 2014).

Environmental monitoring studies have demonstrated the presence of pesticide residues in groundwater, soil, and food commodities in Punjab. These residues are largely attributed to indiscriminate pesticide application, overuse of agrochemicals, and lack of adherence to safety guidelines (Kaur et al., 2012). Chronic exposure occurs not only among farmers but also in the general population through contaminated drinking water and food chains, leading to cumulative toxic effects.

A widely recognized public health concern is the so-called *"cancer train"* running from Punjab to Bikaner, where many patients travel for cancer treatment. While this phenomenon is not definitive evidence of causation, it reflects the perceived clustering of cancer cases in high-exposure areas and has drawn national and international attention to the issue (Kaur et al., 2012).

Epidemiological studies in India have suggested associations between pesticide exposure and various cancers, including breast cancer, gastrointestinal cancers, and haematological malignancies such as leukemia (Mathur et al., 2002; Thakur et al., 2008). Biomonitoring studies have further reported elevated levels of organochlorine pesticide residues in human blood and tissues, supporting the hypothesis of chronic internal exposure (Mittal et al., 2014). Organochlorine pesticides, known for their persistence in the environment, may act as carcinogens and endocrine disruptors, thereby contributing to cancer development.

4.3. Endocrine Disruption

Many pesticides are recognized as endocrine-disrupting chemicals (EDCs), capable of interfering with the normal functioning of the hormonal system. These compounds disrupt endocrine signaling through multiple mechanisms, including mimicking endogenous hormones, antagonizing hormone receptors, and altering hormone synthesis, transport, and metabolism (Gore et al., 2015; Mnif et al., 2011). Such disruptions can lead to long-term physiological and developmental consequences even at low levels of exposure.At the molecular level, several pesticides particularly organochlorines such as dichlorodiphenyltrichloroethane (DDT) have been shown to exhibit estrogenic or anti-androgenic activity, thereby disturbing hormonal balance. Additionally, pesticides may interfere with thyroid hormone homeostasis by affecting hormone synthesis and receptor binding, leading to altered circulating levels of triiodothyronine (T3) and thyroxine (T4) (Boas et al., 2006). The health outcomes associated with endocrine disruption are diverse and affect multiple organ systems. Reported effects include thyroid dysfunction, hormonal imbalance, metabolic disorders such as obesity and diabetes, and developmental abnormalities, particularly in children exposed during critical windows of growth (Gore et al., 2015). Disruption of thyroid hormones is of particular concern, as these hormones play a crucial role in brain development, metabolism, and growth regulation.A substantial body of global research supports the endocrine-disrupting potential of pesticides. For instance, studies have demonstrated that exposure to organochlorine pesticides, including DDT and its metabolites, is associated with altered thyroid hormone levels and impaired neurodevelopment (Boas et al., 2006; Mnif et al., 2011). Furthermore, longitudinal studies have linked chronic exposure to EDCs with increased risk of metabolic syndrome, reproductive disorders, and developmental impairments (Gore et al., 2015). In India, the issue of endocrine disruption due to pesticide exposure is particularly relevant in agricultural communities, where prolonged and unregulated pesticide use is common. Biomonitoring and field-based studies have reported hormonal disturbances and altered biochemical parameters among pesticide-exposed workers (Kaur et al., 2012). Additionally, research indicates that rural populations exposed to pesticide residues through food and water sources may experience metabolic disorders and endocrine imbalances, although large-scale longitudinal data remain limited.Given the widespread use of pesticides and the persistence of certain compounds in the environment, the potential for endocrine disruption represents a significant public health concern in India, warranting further investigation, stricter regulation, and increased awareness.

4.4. Reproductive and Developmental Effects

Chronic exposure to pesticides has been increasingly associated with adverse reproductive outcomes and developmental abnormalities in both males and females. Many pesticides, particularly organophosphates, organochlorines, and pyrethroids, are known to exert reprotoxic and teratogenic effects, either directly or through endocrine disruption pathways (Mnif et al., 2011; Bretveld et al., 2008). These compounds can interfere with hormonal regulation, gametogenesis, and fetal development, especially during critical windows of exposure.In males, pesticide exposure has been linked to reduced sperm count, impaired sperm motility, altered morphology, and decreased fertility. Studies suggest that oxidative stress and endocrine disruption are key mechanisms underlying these effects (Agarwal et al., 2014). In females, chronic exposure has been associated with menstrual irregularities, hormonal imbalance, reduced fertility, and increased risk of spontaneous abortion (Bretveld et al., 2008).

Developmental toxicity is a major concern, particularly for prenatal and early-life exposure. Pesticides can cross the placental barrier and affect fetal growth and organ development. Reported outcomes include low birth weight, preterm birth, congenital anomalies, and neurodevelopmental deficits (García et al., 2017). Early-life exposure has also been linked to long-term health consequences, including impaired cognitive development and behavioral disorders.A substantial body of global research supports the association between pesticide exposure and reproductive health risks. Epidemiological studies have shown that populations exposed to pesticides have a higher prevalence of infertility and adverse pregnancy outcomes (Bretveld et al., 2008). Additionally, research has demonstrated that exposure to pesticide mixtures can have synergistic effects, increasing the risk of developmental abnormalities (Mnif et al., 2011). Longitudinal cohort studies further indicate that prenatal exposure to pesticides is associated with delayed neurodevelopment and reduced birth outcomes (García et al., 2017). In India, where pesticide use is widespread in agriculture, several studies have highlighted reproductive and developmental health concerns among exposed populations. Research conducted in agricultural regions has reported increased incidence of infertility, adverse pregnancy outcomes, and developmental abnormalities in communities with high pesticide exposure (Pathak et al., 2010). Biomonitoring studies have also detected pesticide residues in maternal blood and breast milk, indicating direct exposure of infants (Kashyap et al., 2014). Furthermore, the use of multiple pesticides and unsafe handling practices in rural areas increases cumulative exposure, thereby elevating the risk of reproductive toxicity. Despite growing evidence, large-scale epidemiological data in India remain limited, underscoring the need for systematic surveillance, improved regulatory measures, and public health interventions.

5.Organ Toxicity

Chronic exposure to pesticides has been strongly associated with multi-organ toxicity, affecting vital organs such as the liver, kidneys, and immune system. These toxic effects are primarily mediated through mechanisms including oxidative stress, mitochondrial dysfunction, bioaccumulation, and disruption of cellular signalling pathways (Mostafalou & Abdollahi, 2017). Due to their persistent nature and lipophilicity, many pesticides accumulate in biological tissues over time, leading to progressive organ damage.

5.1. Hepatotoxicity (Liver Damage)

The liver is a primary target organ for pesticide toxicity due to its central role in metabolism and detoxification. Chronic exposure has been associated with elevated liver enzymes (ALT, AST) , hepatocellular degeneration and fatty liver changes and fibrosis. Experimental and epidemiological studies have shown that pesticides induce oxidative stress and lipid peroxidation in hepatocytes, resulting in structural and functional liver impairment (Kim et al., 2017).

5.2. Nephrotoxicity (Kidney Dysfunction)

The kidneys are particularly vulnerable to pesticide toxicity because of their role in filtration and excretion of toxic substances. Long-term exposure has been linked to reduced glomerular filtration rate (GFR), tubular damage and increased risk of chronic kidney disease (CKD). Available evidence indicates that pesticide exposure is a contributing factor to chronic kidney disease of unknown ethology (CKDu) observed in agricultural communities (Mostafalou & Abdollahi, 2017).

5.3. Immunotoxicity (Immune System Suppression)

Pesticides can also adversely affect the immune system, leading to suppressed immune responses, increased susceptibility to infections and altered cytokine production. Chronic exposure may result in immune dysregulation, increasing the risk of inflammatory disorders and reducing the body's ability to respond to pathogens (Corsini et al., 2013).

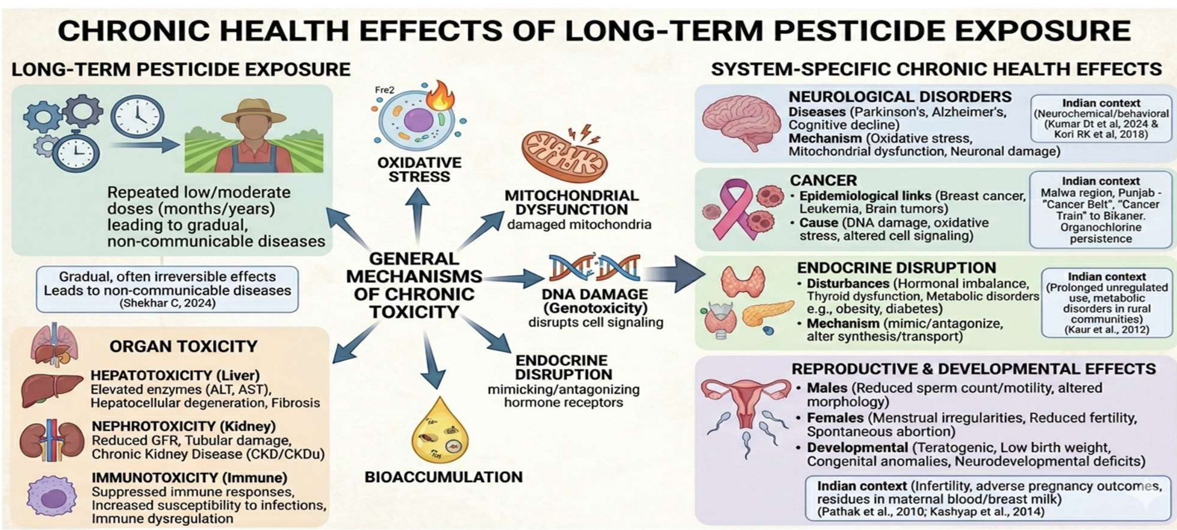

Figure 3: Chronic health effects associated with long-term pesticide exposure.

6. Mitigation and Prevention Strategies

Mitigating the adverse health effects of pesticide exposure requires a comprehensive, multi-sectoral approach integrating regulatory control, sustainable agricultural practices, occupational safety, environmental protection, and public health interventions. Given the widespread use of pesticides globally and particularly in developing countries, targeted strategies are essential to reduce both acute and chronic exposure risks. At the policy level, strengthening regulatory frameworks is fundamental. This includes rigorous evaluation and registration of pesticides based on toxicity, enforcement of maximum residue limits (MRLs) in food and water, and gradual phasing out of highly hazardous pesticides (HHPs). International organizations such as the World Health Organization and Food and Agriculture Organization advocate stricter control measures and global harmonization of pesticide regulations (WHO, 2020; FAO, 2018). In India, improved enforcement and monitoring under national regulatory authorities remain critical to ensure compliance and minimize misuse. The promotion of Integrated Pest Management (IPM) is a key sustainable strategy to reduce reliance on chemical pesticides. IPM combines biological control agents, crop rotation, resistant crop varieties, and mechanical methods to manage pests with minimal environmental impact. Evidence suggests that IPM adoption significantly reduces pesticide usage while maintaining agricultural productivity (FAO, 2018). Expanding IPM practices in high-use regions can substantially lower exposure risks among farmers and surrounding communities.

Occupational safety measures are equally important, as agricultural workers represent the most vulnerable group. The use of personal protective equipment (PPE) including gloves, masks, protective clothing, and eye protection can significantly reduce dermal and inhalation exposure. Training programs focused on safe handling, proper mixing, application techniques, and storage practices are essential. Studies indicate that appropriate PPE use and training can reduce pesticide exposure levels by up to 90% (Damalas & Koutroubas, 2016). Environmental management strategies play a crucial role in preventing indirect exposure. Measures such as safe disposal of pesticide containers, prevention of agricultural runoff, establishment of buffer zones, and protection of water sources can limit environmental contamination. Regular monitoring of soil, air, and water quality is necessary to detect and control pesticide residues, particularly in agriculturally intensive regions. Reducing dietary exposure is also a critical component of prevention. Consumers can lower risk through washing, peeling, and proper cooking of food, while regulatory bodies must ensure routine surveillance of pesticide residues in food products. Encouraging organic farming and low-input agricultural systems further contributes to minimizing pesticide contamination in the food chain.

Public awareness and health surveillance are essential to sustain long-term risk reduction. Educational initiatives targeting farmers and rural communities can improve understanding of pesticide hazards and promote safer alternatives. Additionally, establishing biomonitoring programs and health surveillance systems for exposed populations can facilitate early detection of adverse effects and guide policy interventions.

In conclusion, effective mitigation of pesticide exposure requires coordinated efforts across policy, agriculture, environment, and public health sectors. Transitioning toward safer pest control methods, strengthening regulations, and enhancing awareness are crucial steps to reduce the global and Indian burden of pesticide-related health risks (Figure 4).

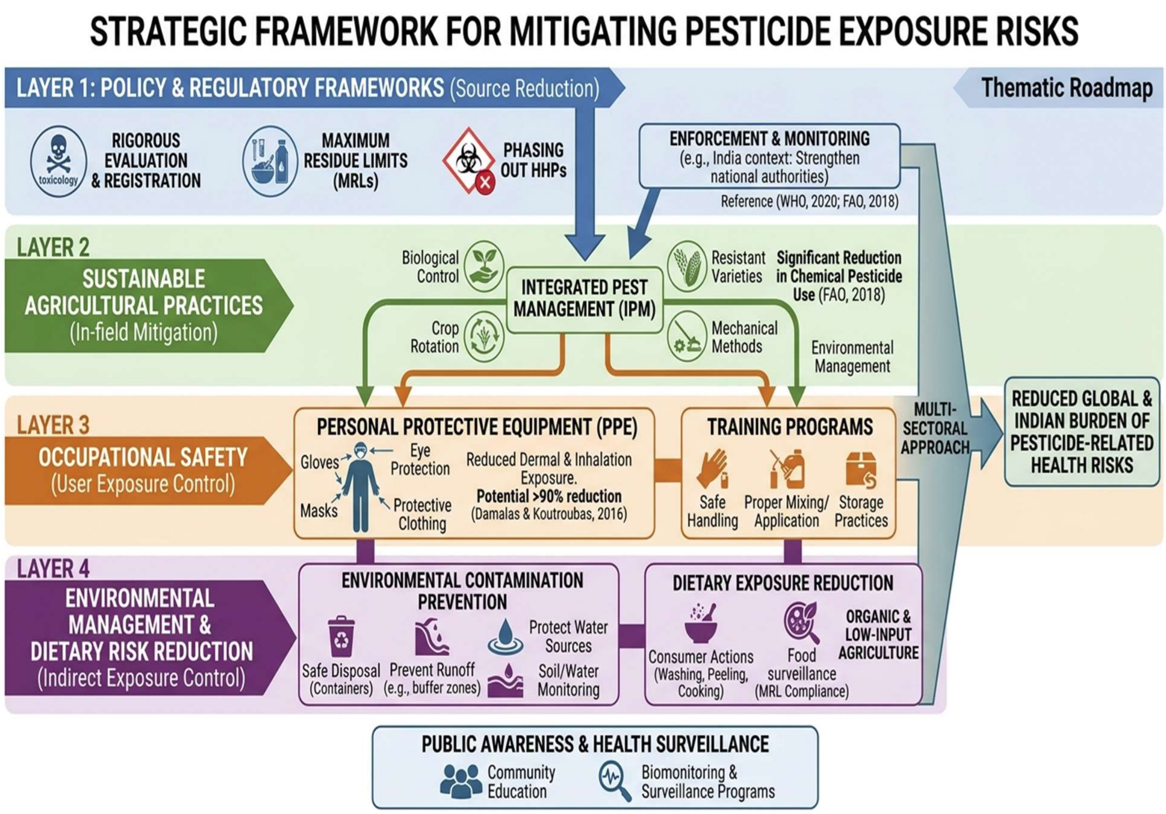

Figure 4: Framework for mitigation of pesticide exposure

7. Future Perspectives

Despite extensive evidence linking pesticide exposure to adverse human health outcomes, several critical knowledge gaps remain that limit effective risk assessment and regulation. First, most existing studies focus on single-pesticide exposures, whereas real-world exposure occurs as complex mixtures. The combined and synergistic toxicological effects of pesticide cocktails remain poorly understood and require systematic investigation using advanced exosomes and mixture toxicity models.

Second, there is a need for long-term longitudinal cohort studies, particularly in developing countries such as India, to better establish causal relationships between chronic low-dose pesticide exposure and diseases such as cancer, neurodegenerative disorders, and endocrinerelated metabolic dysfunctions. Current evidence is largely cross-sectional, limiting causal inference.

Third, biomonitoring data in occupationally exposed populations remain insufficient. The development of standardized biomarkers of exposure and effect, including oxidative stress markers, endocrine disruption indicators, and neurotoxicity biomarkers, is essential for early detection and prevention.

Fourth, emerging technologies such as machine learning-based exposure modelling, high-throughput toxicogenomic, and *in silico* toxicology should be integrated into pesticide risk assessment frameworks to improve predictive accuracy and reduce reliance on traditional animal models.

Finally, policy-level interventions must prioritize the phase-out of highly hazardous pesticides, strengthen enforcement of maximum residue limits, and promote widespread adoption of Integrated Pest Management (IPM) practices. Farmer education programs and community-level awareness campaigns are also critical to reduce occupational and dietary exposure risks.

Collectively, a multidisciplinary approach combining toxicology, environmental monitoring, epidemiology, and policy reform is essential to mitigate the long-term public health burden of pesticide exposure.

8.Conclusion

This review highlights that pesticide exposure remains a significant global and public health concern due to its widespread use, environmental persistence, and ability to affect multiple exposure pathways, including occupational, environmental, and dietary routes. Evidence from epidemiological and toxicological studies consistently demonstrates that both acute and chronic exposure to pesticides is associated with a broad spectrum of adverse health outcomes.

Acute exposure is primarily characterized by cholinesterase inhibition leading to neurological, respiratory, dermatological, and gastrointestinal effects, particularly among agricultural workers. In contrast, chronic low-dose exposure has been strongly associated with neurodegenerative diseases, cancers, endocrine disruption, reproductive toxicity, and multi-organ dysfunction involving hepatic, renal, and immune systems. These effects are largely mediated through oxidative stress, mitochondrial dysfunction, endocrine interference, and genotoxic mechanisms.

The Indian context further emphasizes the severity of the issue, where intensive agricultural practices, inadequate regulatory enforcement, and limited awareness contribute to widespread environmental contamination and human exposure. Detection of pesticide residues in soil, water, air, and food products highlights the pervasive nature of exposure risks.

In conclusion, mitigating pesticide-related health risks requires urgent implementation of integrated strategies, including strict regulatory control, promotion of sustainable agricultural practices, enhanced occupational safety measures, and strengthened environmental monitoring systems. Transitioning toward safer pest management alternatives and increasing public awareness are essential to reduce the long-term burden of pesticide-induced diseases.

CRediT authorship contribution statement

Namita Saxena, Jagdish Makhijani: Writing-review & editing

Funding

This research received no specific grant from any funding agency, commercial, or not-for-profit sector.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement:

The figure was generated with the assistance of AI tools and refined by the author.

References:

1. Fagundes TR, Coradi C, Vacario BGL, de Morais Valentim JMB, Panis C. Global evidence on monitoring human pesticide exposure. Journal of Xenobiotics. 2025;15(6):187. doi:10.3390/jox15060187.
2. Shekhar C, Khosya R, Thakur K, Mahajan D, Kumar R, Kumar S, Sharma AK. A systematic review of pesticide exposure, associated risks, and long-term human health impacts. Toxicology Reports. 2024;13:101840. doi:10.1016/j.toxrep.2024.101840.
3. Kashyap U, Garg S, Arora P. Pesticide pollution in India: Environmental and health risks, and policy challenges. Toxicology Reports. 2024;13:101801. doi:10.1016/j.toxrep.2024.101801.
4. Soman S, Christiansen A, Florinski R, Bharat G, Steindal EH, Nizzetto L, Chakraborty P. An updated status of currently used pesticides in India: Human dietary exposure from an Indian food basket. Environmental Research. 2024;242:117543. doi:10.1016/j.envres.2023.117543.
5. Mathew P, Jose A, Alex RG, Mohan VR. Chronic pesticide exposure: Health effects among pesticide sprayers in Southern India. Indian Journal of Occupational and Environmental Medicine. 2015;19(2):95-101. doi:10.4103/0019-5278.165334.
6. Hongoeb J, Tantimongcolwat T, Ayimbila F, Ruankham W, Phopin K. Herbicide-related health risks: Key mechanisms and a guide to mitigation strategies. Journal of Occupational Medicine and Toxicology. 2025;20(1):6. doi:10.1186/s12995-025-00448-7.
7. Kumari B, Madan VK, Kathpal TS. Status of insecticide contamination of soil and water in Haryana, India. Environmental Monitoring and Assessment. 2008;136:239-244. doi:10.1007/s10661-007-9679-1.

8. Adokiya MN, Orou-Seko A, Agbohessi PT, et al. Pesticide contamination and associated health risks in fish from Libga and Builpela reservoirs, Northern Ghana. BMC Environmental Science. 2025;2:5. doi:10.1186/s44329-025-00020-y.
9. Kumari B, Madan VK, Kathpal TS. Monitoring of pesticide residues in fruits. Environmental Monitoring and Assessment. 2006;123:407-412. doi:10.1007/s10661-006-1493-7.
10. Boedeker W, Watts M, Clausing P, Marquez E. The global distribution of acute unintentional pesticide poisoning: Estimations based on a systematic review. BMC Public Health. 2020;20:1875. doi:10.1186/s12889-020-09939-0.
11. Sobia N, Muzaffer U, Kareem O, Rashid A, Khan K, Ahmed RN. Acute health effects of pesticide exposure among farmers directly involved with spraying: A cross-sectional pilot study from Kashmir Valley. International Journal of Health Sciences and Research. 2021;11. doi:10.52403/ijhsr.20210527.
12. Kumar N, Nie V, Palaniappan K, Bohatko-Naismith J. Insecticide exposure and associated acute health effects in farmers in a rice growing district of India. International Journal of Environmental Health Research. 2025;35(5):1143-1155. doi:10.1080/09603123.2024.2382305.
13. Choudhary A, Ali AS, Ali SA. Adverse health effects of organophosphate pesticides among occupationally exposed farm sprayers: A case study of Bhopal, Madhya Pradesh, India. Asian Journal of Biomedical and Pharmaceutical Sciences. 2014;4(35). doi:10.15272/ajbps.v4i35.565.
14. Kumar D, Sinha SN. Chronic exposures to cholinesterase-inhibiting pesticides adversely affects the health of agricultural workers in India. Environmental Research. 2024;252(Pt 2):118961. doi:10.1016/j.envres.2024.118961.
15. Kori RK, Singh MK, Jain AK, Yadav RS. Neurochemical and behavioral dysfunctions in pesticide exposed farm workers: A clinical outcome. Indian Journal of Clinical Biochemistry. 2018;33(4):372-381. doi:10.1007/s12291-018-0791-5.
16. Kaur P, Radotra BD, Minhas SS, Gill KD. Impaired mitochondrial function in pesticide-exposed workers of Punjab. Environmental Toxicology and Pharmacology. 2012;33(3):364-372.
17. Mathur V, Bhatnagar P, Sharma RG, Acharya V, Saxena R. Breast cancer incidence and exposure to pesticides among women in rural India. Indian Journal of Medical Research. 2002;116:35-45.
18. Mittal S, Kaur G, Vishwakarma GS. Effects of environmental pesticides on the health of rural communities in the Malwa region of Punjab. Human and Experimental Toxicology. 2014;33(9):973-979.
19. Thakur JS, Prinja S, Singh D, Rajwanshi A, Prasad R. Cancer risk in rural agricultural communities of Punjab, India. Indian Journal of Cancer. 2008;45(2):52-57.
20. Boas M, Feldt-Rasmussen U, Main KM. Thyroid effects of endocrine disrupting chemicals. Molecular and Cellular Endocrinology. 2006;355(2):240-248.
21. Gore AC, Chappell VA, Fenton SE, et al. EDC-2: The Endocrine Society's second scientific statement on endocrine-disrupting chemicals. Endocrine Reviews. 2015;36(6):E1-E150.
22. Mnif W, Hassine AIH, Bouaziz A, et al. Effect of endocrine disruptor pesticides: A review. International Journal of Environmental Research and Public Health. 2011;8(6):2265-2303.
23. Agarwal A, Aponte-Mellado A, Premkumar BJ, Shaman A, Gupta S. The effects of oxidative stress on female reproduction: A review. Reproductive Biology and Endocrinology. 2010;8:49.
24. Bretveld RW, Thomas CMG, Scheepers PTJ, Zielhuis GA, Roeleveld N. Pesticide exposure: The hormonal function of the female reproductive system disrupted? Reproductive Biology and Endocrinology. 2008;6:79.
25. García AM, Benavides FG, Fletcher T. Pesticide exposure and health outcomes in agricultural workers. Environmental Health Perspectives. 2017;125(8):086001.
26. Kashyap R, et al. Pesticide residues in human breast milk samples from India. Environmental Research. 2014;132:177-183.
27. Pathak R, et al. Adverse reproductive outcomes among women exposed to pesticides in India. Indian Journal of Occupational and Environmental Medicine. 2010;14(2):63-67.
28. Corsini E, Sokooti M, Galli CL, Moretto A, Colosio C. Pesticide induced immunotoxicity in humans: A comprehensive review. Toxicology. 2013;307:123-135.
29. Damalas CA, Koutroubas SD. Farmers' exposure to pesticides: Toxicity types and ways of prevention. Toxics. 2016;4(1):1. doi:10.3390/toxics4010001.
30. Food and Agriculture Organization. Integrated pest management: Guidelines for sustainable agriculture. Rome: FAO; 2018.
31. World Health Organization. Public health impact of pesticides used in agriculture. Geneva: WHO; 2020.
32. Pretty J, Bharucha ZP. Integrated pest management for sustainable intensification of agriculture. Agricultural Systems. 2015;135:92-99.