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REVIEW PAPER

Pesticide Usage in India: Trends, Regional Consumption, Toxicological Impact, and Analytical Approaches

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ABSTRACT

Pesticides are vital tools in modern agriculture and public health, but their extensive use has raised serious ecological and health concerns. This review comprehensively examines the classification, environmental behavior, and health impacts of major pesticide groups including organochlorines, organophosphates, carbamates, and pyrethroids. Drawing from extensive literature and national data, we highlight pesticide usage patterns in India, residue levels in food crops, and associated chronic health effects such as cancer, neurotoxicity, endocrine disruption, and respiratory illnesses. Special attention is given to residue detection in vegetables across Indian states and the carcinogenic mechanisms triggered by prolonged pesticide exposure. The review also explores regulatory measures and sustainable pest control alternatives like biopesticides and Integrated Pest Management (IPM). Our findings underscore the urgency for policy reforms, improved farmer awareness, and environmentally safer pest control technologies to balance agricultural productivity with public and environmental health.

HIGHLIGHTS

- Insecticides dominate national consumption, with regional variations showing higher usage in states like Maharashtra, Uttar Pradesh, Punjab, and Madhya Pradesh, while northeastern states report lower dependence due to agro-climatic condition.
- Multi-state studies reveal pesticide residues in vegetables, soil, and water, with some exceeding maximum residue limits—posing risks of neurotoxicity, endocrine disruption, cancer, and respiratory illnesses, especially among vulnerable populations.
- National efforts emphasize Integrated Pest Management (IPM), biopesticides, and stricter legislation (e.g., Pesticide Management Bill, 2020) to balance agricultural productivity with environmental safety and public health.

Keywords: Pesticides, Human Health, Pesticide Residues, India, Environmental Impact, Integrated Pest Management

Pesticides are indispensable tools in contemporary agriculture and public health frameworks, encompassing a wide spectrum of chemical and biological substances formulated to deter, suppress, or eradicate pests that jeopardize crop yields, livestock health, human wellbeing, and built environments. They act as frontline defenses against a broad array of threats—including insects, fungi, weeds, rodents, and microbial agents—thus playing a pivotal role in safeguarding food security and curbing the transmission of vector-borne diseases.

These substances are categorized based on both the nature of their target organisms and their biochemical modes of action. Insecticides are tailored to eliminate insect pests, herbicides focus on controlling invasive or undesirable plant species, fungicides inhibit or destroy pathogenic

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fungi, rodenticides are directed against rodent populations, and bactericides aim to neutralize bacterial threats. Each of these categories includes numerous compounds engineered for optimal pest specificity, with the intent to reduce collateral damage to non-target species and the broader environment.

The evolution of pesticide use is deeply rooted in human history, with ancient societies employing botanical extracts (such as neem and chrysanthemum derivatives) and mineral-based substances (like sulfur and arsenic) for pest control. The emergence of synthetic chemical pesticides in the 20th century, notably after the introduction of DDT during World War II, marked a paradigm shift in pest management strategies—contributing significantly to increased agricultural productivity and a substantial reduction in pest-borne diseases (Whalon *et al.* 2012; Aktar *et al.* 2009).

Despite these advantages, the extensive reliance on pesticides has generated considerable ecological and health-related concerns. The environmental ramifications of pesticide usage are particularly contentious, as these chemicals can adversely affect soil microbiota, leach into water systems, and disrupt aquatic ecosystems. Runoff from treated agricultural fields is a major source of surface and groundwater contamination, potentially affecting drinking water quality and leading to the bioaccumulation of toxic substances in aquatic organisms (Stehle & Schulz, 2015). Additionally, the persistence of certain pesticides in soil and water can instigate long-lasting ecological changes and contribute to the development of pest resistance—an evolutionary response that diminishes the efficacy of chemical control methods and necessitates the use of more potent or alternative compounds (Gould *et al.* 2018).

The implications for human health are equally significant. Chronic exposure to pesticides, whether through occupational handling or the ingestion of residues in food products, has been linked to a spectrum of health disorders. These range from acute symptoms such as dermal and respiratory irritation to chronic effects, including endocrine disruption, neurotoxicity, carcinogenesis, and reproductive health issues (Mostafalou & Abdollahi, 2013). Certain demographics—especially agricultural workers, pregnant women, and children—are particularly vulnerable to the toxic effects of pesticide exposure, underscoring the need for stringent regulatory oversight and the adoption of safer pest control alternatives.

Regulatory agencies across the globe enforce rigorous standards and permissible exposure limits to govern the use of pesticides, striving to strike a balance between maximizing the efficacy of pest control and minimizing the attendant health and environmental risks. Organizations such as the U.S. Environmental Protection Agency (EPA), the European Food Safety Authority (EFSA), and the Central Insecticides Board and Registration Committee (CIBRC) in India play pivotal roles in evaluating pesticide safety, approving new formulations, and monitoring residues in food and the environment (EPA, 2023; EFSA, 2022).

In alignment with sustainable agricultural practices, Integrated Pest Management (IPM**)** has emerged as a comprehensive and adaptive strategy that promotes the judicious use of pesticides. IPM combines a spectrum of control techniques—including biological controls (e.g., beneficial insects, microbial agents), cultural practices (e.g., crop rotation, resistant crop varieties), mechanical methods (e.g., traps, barriers), and chemical inputs—as a last resort. This approach is designed to reduce the ecological footprint of pest control, slow the evolution of pesticide resistance, and protect non-target organisms (Kogan, 1998; Ehler, 2006).

Advancements in pesticide science continue to focus on creating next-generation formulations that exhibit high selectivity, reduced toxicity, and minimal environmental persistence. Innovations include biopesticides derived from natural organisms such as *Bacillus thuringiensis*, entomopathogenic fungi, and plant-derived compounds, which offer targeted action with fewer side effects (Copping & Menn, 2000). Concurrently, the integration of precision agriculture technologies—such as drone-assisted spraying, sensor-based field mapping, and AI-guided application systems—enhances the accuracy and efficiency of pesticide deployment, minimizing overuse and off-target exposure (Zhang *et al.* 2020).

Despite these advances, the overarching challenge remains: achieving a sustainable equilibrium that supports agricultural productivity while safeguarding environmental integrity and public health. As the global demand for food intensifies due to population growth and climate change pressures, the importance of evolving pesticide practices within a framework of sustainability becomes increasingly critical (Goulson, 2013). This necessitates ongoing research, policy refinement, and the proactive participation of stakeholders at all levels of the agricultural ecosystem.

Insecticides are broadly divided into three categories:

1. Organochlorines
2. Organophosphorus compounds and carbamates
3. Pyrethrins and Pyrethroids

1. Organochlorine Pesticides

Organochlorine (OC) pesticides are a class of synthetic chemical agents extensively utilized worldwide, particularly in agriculture and various sectors of the chemical industry. They are categorized under chlorinated hydrocarbon derivatives and are characterized by their chemical stability, lipophilicity, and persistence in the environment. OCs, including compounds such as DDT, aldrin, dieldrin, and lindane, have historically played a significant role in pest control due to their effectiveness against a broad spectrum of pests (ATSDR, 2002).

However, these compounds are also notorious for their high toxicity, environmental persistence, and strong tendency to bioaccumulate in the fatty tissues of living organisms. Their resistance to natural degradation processes leads to prolonged presence in soil, water bodies, and biota, contributing to widespread ecological contamination (Li and Macdonald, 2005). Despite the banning or severe restriction of many OC pesticides in several developed nations through conventions such as the Stockholm Convention on Persistent Organic Pollutants (UNEP, 2009), reports suggest that misuse and unauthorized application continue globally, particularly in developing regions where regulatory enforcement is weaker (Jayaraj *et al.* 2016).

Classification of Organochlorine pesticides is as follows:—

(a) Organochlorines

Organochlorines (OCs) are a category of chlorinated chemical compounds extensively employed as pesticides. These substances are classified under persistent organic pollutants (POPs) due to their remarkable environmental stability and resistance to degradation. Historically, OC insecticides proved highly effective in combating diseases such as malaria and typhus; however, they have been prohibited in the majority of developed nations (Aktar *et al.* 2009). Statistical reviews regarding pesticide usage indicate that organochlorines account for approximately 40% of the total pesticides applied globally (Gupta, 2004; FAO, 2005). Despite regulatory restrictions elsewhere, their affordability and continued necessity for pest management have sustained the widespread use of organochlorine pesticides—including DDT, hexachlorocyclohexane (HCH), aldrin, and dieldrin—particularly across developing regions in Asia (FAO, 2005; Gupta, 2004; Lallas, 2001).

(b) Dichlorodiphenylethanes (e.g., DDT, DDE, DDD)

This group includes DDT and its major environmental degradation products DDE and DDD. DDT was historically used in malaria control and agriculture but is now banned or restricted in most countries due to its persistence and endocrine-disrupting effects. These compounds are known for their high bioaccumulation in the food chain and long-range atmospheric transport.

(c) Hexachlorocyclohexanes (e.g., Lindane, α-HCH, β-HCH)

HCHs are composed of several isomers, with γ-HCH (lindane) being the most biologically active and widely used. Lindane was used for insect control in agriculture and pharmaceuticals. Due to its toxicity and persistence, its use has been phased out in many countries.

(d) Cyclodiene Pesticides (e.g., Aldrin, Dieldrin, Endrin, Chlordane, Heptachlor, Endosulfan)

Cyclodienes are highly neurotoxic and environmentally stable pesticides. They act by disrupting ion transport in the nervous system. Though effective in pest control, their high persistence and toxicity led to widespread bans. Endosulfan, once widely used in Asia, has now been listed under the Stockholm Convention.

(e) Chlorinated Camphenes (e.g., Toxaphene)

Toxaphene is a complex mixture of over 670 chlorinated camphenes and was used extensively on cotton and grain crops. It is extremely persistent and bioaccumulative, with strong evidence of toxicity to aquatic life and potential carcinogenicity in humans.

1. Organophosphorus compounds and carbamates

Organophosphorus (OP) pesticides are widely used insecticides that act by irreversibly inhibiting acetylcholinesterase (AChE), leading to toxic accumulation of acetylcholine in synapses (Costa, 2006). Common OPs include chlorpyrifos, malathion, and diazinon, frequently applied in agriculture and vector control. Though less persistent than organochlorines, OPs are associated with acute neurotoxicity, endocrine disruption, and potential reproductive effects, especially among farm workers (Jaga & Dharmani, 2003; Kwong, 2002). Regulatory agencies have classified several OPs as Highly Hazardous Pesticides, calling for their restriction or phased elimination (FAO & WHO, 2020).

Carbamates, such as carbaryl, aldicarb, and methomyl, also inhibit acetylcholinesterase but do so reversibly, resulting in a shorter duration of action and generally lower mammalian toxicity (Fukuto, 1990). They are widely used for controlling a variety of insect pests in crops, animals, and public health. While less persistent in the environment than OPs, carbamates can still pose risks to non-target species, including bees and aquatic life (Ecobichon, 2001). Due to their acute toxicity and ecological concerns, several carbamates have been banned or restricted under international guidelines (UNEP, 2021).

Classification of Organophosphate Pesticides:

(i) Phosphates: Phosphate OPs, such as *malathion* and *parathion*, are characterized by a phosphorus atom double-bonded to oxygen (P=O). These pesticides inhibit acetylcholinesterase, leading to neurotoxicity and death in pests. They are commonly used in agriculture, but their persistence in the environment and toxicity to non-target organisms are significant concerns (Kwong, 2002; Costa, 2006).

(ii) Phosphorothioates: Phosphorothioates, including **chlorpyrifos** and **diazinon**, have a sulfur atom in place of one of the oxygen atoms in the P=O group (P=S). These pesticides are more toxic than phosphates and require bioactivation in the body. They are widely used for insect control in agriculture, but their use has raised concerns due to environmental persistence and resistance in pest populations (Eaton *et al.* 2008).

(iii) Phosphonates: Phosphonates, such as *glyphosate*, are primarily used as herbicides and contain a carbon-phosphorus bond (P-C). While these pesticides are less toxic to mammals, they can persist in the environment and pose a risk to aquatic ecosystems. They are widely used for weed control, but their impact on non-target species remains a subject of concern (Tomlin, 2009).

(iv) Diphosphates: Diphosphates, like *tetraethyl pyrophosphate*, contain two phosphate groups linked by an oxygen atom. They are highly toxic and primarily used in research or specific pest control situations. Their use is limited due to their toxicity to both pests and humans (Eaton *et al.* 2008).

Classification of Carbamates

(i) Aryl Carbamates: Aryl carbamates, such as *carbaryl*, are widely used as insecticides. They inhibit acetylcholinesterase, leading to the accumulation of acetylcholine in the nervous system of pests. These carbamates have moderate toxicity, and their effects are reversible. They are commonly used in both agricultural and household pest control (Ecobichon, 2001).

(ii) Oxime Carbamates: Oxime carbamates, including *aldicarb* and *methomyl*, are fast-acting, systemic insecticides. They inhibit acetylcholinesterase and are highly toxic to pests. Due to their toxicity and the potential for groundwater contamination, their use is heavily regulated in many countries (Fukuto, 1990).

(iii) Phenyl Carbamates: Phenyl carbamates, such as *phenylphenol*, are less common and are primarily used for fungicidal and herbicidal purposes. These compounds are generally less toxic to humans and animals compared to other carbamates. They are selective in their action and have specific applications for controlling fungal diseases and certain weed species (Tomlin, 2009).

(iv) N-Methyl Carbamates: N-methyl carbamates, such as *carbofuran*, are another subclass used as insecticides and nematicides. These pesticides are particularly effective in controlling soil pests but are highly toxic to mammals and birds. Their use is restricted in many regions due to their environmental impact and toxicity (Ecobichon, 2001).

Pesticides Usage in India

India is among the world's largest producers and consumers of pesticides, with agriculture contributing significantly to its GDP and employing more than 50% of the workforce. The country's diverse agro-climatic zones and high pest pressure across staple crops like rice, wheat, cotton, and vegetables necessitate extensive pesticide use. Over the past two decades, the pattern of pesticide consumption in India has shown a dynamic shift both in volume and composition, influenced by policy, awareness, environmental concerns, and technological developments.

Historically, India's pesticide use has been dominated by insecticides, accounting for nearly 60% of total usage, followed by fungicides and herbicides (Sharma *et al.* 2020). This is in contrast to global trends where herbicides lead consumption due to mechanized monoculture farming. In India, the predominant use of insecticides is closely associated with cotton and rice cultivation in northern and central regions, particularly in Punjab, Maharashtra, and Madhya Pradesh (Saha *et al.* 2021).

From 2000 to 2024, pesticide usage in India fluctuated between 40,000 to 60,000 metric tons (technical grade), with a gradual decline in per hectare usage from 0.6 kg/ha to around 0.3 kg/ha in 2023 (PPQS, 2024). The decreasing trend in unit-area usage is attributed to increasing adoption of integrated pest management (IPM), organic farming initiatives, and government-imposed restrictions on hazardous pesticides. Nevertheless, localized overuse remains a concern in regions where extension services are weak and pesticide regulation is inconsistently enforced (Mandal *et al.* 2022).

The type of pesticides used has also shifted significantly. Organochlorines such as DDT and HCH, once dominant in Indian agriculture, have been phased out due to their long persistence and bioaccumulation effects. These have been replaced by organophosphates, carbamates, synthetic pyrethroids, and more recently, neonicotinoids and biopesticides (Yadav *et al.* 2019). There is also a growing interest in plant-based and microbial biopesticides, though their current market share remains below 10% of total pesticide use (Kumar & Singh, 2022).

Pesticide consumption is not uniform across India. States like Maharashtra, Uttar Pradesh, Punjab, and Madhya Pradesh collectively contribute over 40% of national usage due to extensive cash crop cultivation and pest incidence. Conversely, northeastern states and regions with high rainfall typically use less pesticide due to natural pest suppression and different cropping patterns (PPQS, 2024).

Recent government efforts to reduce pesticide dependence include the Sub-Mission on Plant Protection and Plant Quarantine, support for IPM practices, and digital advisory services to farmers. Additionally, the draft Pesticide Management Bill, 2020, seeks to regulate manufacturing, usage, and labeling more stringently (MoAFW, 2021). Yet, the lack of real-time monitoring and uneven enforcement at the local level continues to undermine these efforts.

Despite moderate national pesticide use per hectare compared to global averages (India: ~0.3 kg/ha; World average: ~2.5 kg/ha), the misuse and overuse in certain districts raise serious environmental and public health issues. Residue levels in food crops, contamination of water bodies, and pesticide poisoning cases among farmers have been widely reported (Rao *et al.* 2020). The challenge lies in promoting sustainable pest management while ensuring food security and farm profitability.

Consumption of pesticides in some of the major countries is as follows:

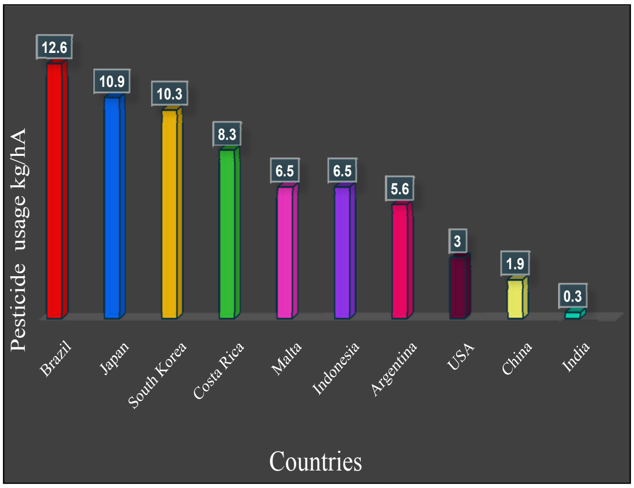

Fig. 1

Consumption of pesticides in India in Metric Tons (Tech. Grade)

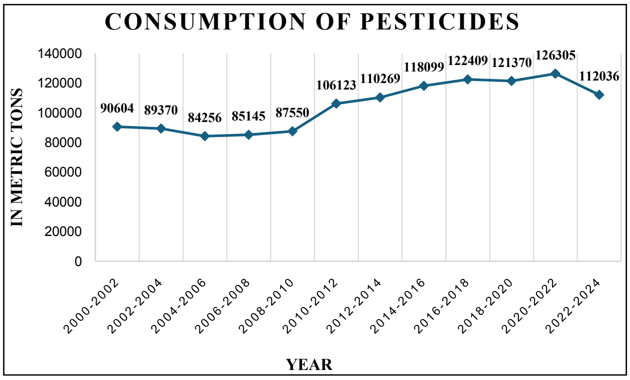

Fig. 2

Consumption of pesticides in Madhya Pradesh during 2015 to 2022

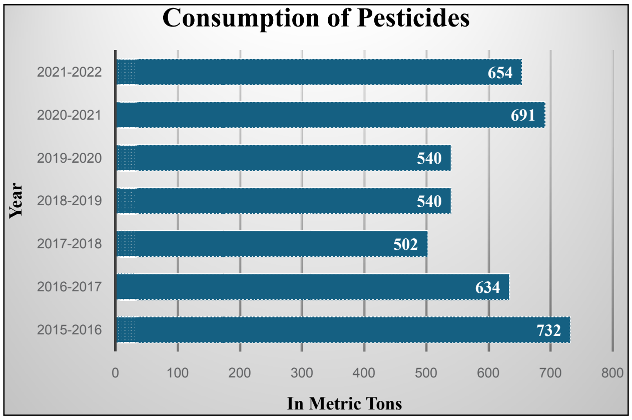

Fig. 3

Pesticide overuse has led to pest resistance and harmful environmental effects like food contamination and bioaccumulation (Karanth, 2002). Vegetable growers heavily use insecticides—13–14% of total pesticide use on just 2.6% of cropped area—often spraying even at fruiting stages without observing safe intervals, causing residue buildup in food (Kumari, 2008). Insecticides, toxic even in small amounts, are classified into organochlorines, organophosphates/carbamates, and pyrethroids (Swaminathan, 1999).

MATERIALS AND METHODS

Monitoring of pesticide residues in vegetables collected from supervised trials, markets and farmer's fields

A comprehensive study analyzed 966 samples of cabbage, green chili, and okra from North and North-Western India to detect residues of 155 pesticides. Using modified QuEChERS extraction and advanced chromatographic techniques, the study found that 94.4% of cabbage, 34.5% of green chili, and 61% of okra samples were free from detectable residues. Detected pesticides, such as acetamiprid, cypermethrin, imidacloprid, metalaxyl, and profenofos, were within safe consumption limits, indicating no significant dietary risk to consumers (Banerjee *et al.* 2021).

In Haryana, a study evaluated 198 samples comprising vegetables, soil, and water for 161 pesticides. Findings revealed pesticide residues in 30.39% of vegetable samples, 95.65% of soil samples, and 68% of water samples. Chlorpyrifos, cypermethrin, pendimethalin, and butachlor were frequently detected. Health risk indices for triazophos and chlorpyrifos in vegetables ranged from 1.16 to 2.76 mg/kg, indicating potential health concerns (Kumar *et al.* 2023).

A study in Gujarat analyzed 120 samples of cauliflower, green chili, cucumber, grapes, bananas, and mangoes for 61 pesticide residues. Using UHPLC-q-TOF-MS and GC-MS/MS, 29 residues were detected in 107 samples, with 68 samples showing multiple residues. Pesticides such as dimethoate, λ-cyhalothrin, fenvalerate, bifenthrin, and cyfluthrin were frequently detected. Hazard Index values indicated marginal risk in green chili and banana samples, emphasizing the need for proper application and continuous monitoring (Patel *et al.* 2023).

In the Kinnaur district of Himachal Pradesh, a study assessed pesticide residues in vegetables using GC-MS/MS. Results indicated varying concentrations of pesticide residues, with farm samples more contaminated than market samples. Chronic health hazard predictions suggested that organophosphorus pesticides like methyl parathion and triazophos posed health risks to children in the study area (Sharma *et al.* 2019).

In Karnataka's Tumakuru district, 50 vegetable samples, including beans, brinjal, cabbage, and carrot, were analyzed for 20 pesticide residues using gas liquid chromatography. All samples were found to be contaminated, with organochlorines (97%) dominating, followed by organophosphates (83%)

and pyrethroids (60%). Notably, 58% of the samples contained residues above their respective maximum residue limits (Reddy *et al.* 2020).

A study in Ranchi, Jharkhand, monitored 39 market samples of seasonal vegetables, including cauliflower, brinjal, and okra, for endosulfan residues. All samples were found to be contaminated with endosulfan (0.002–2.47 ppm), with six samples exceeding the maximum residue limit of 2.0 ppm (Shahi *et al.* 2005).

A comparative study evaluated pesticide residue patterns in vegetables grown using Integrated Pest Management (IPM) and conventional practices. Vegetables grown under IPM practices were safer to consume at harvest, with pesticide residues mostly in trace amounts (<0.01 ppm), except for methomyl and monocrotophos in cabbage, which showed slightly higher levels (Sharma *et al.* 2009).

The All India Network Project on Pesticide Residues (AINP-PR) analyzed over 1.30 lakh samples from 2018 to 2023. Pesticide residues were detected in 28% of samples, with 3.5% exceeding the maximum residue limits. The data highlighted the presence of banned pesticide residues in 0.25% of samples, emphasizing the need for promoting safe and judicious use of pesticides among farmers (Majumder *et al.* 2024).

In Bengaluru, a study evaluated pesticide residues in commonly used fruits and vegetables using GC-MS and LC-MS. While most samples were found to be contaminated with pesticide residues, they were under maximum residue limits after washing with salted water. However, some samples with residues above MRLs may pose health hazards to consumers, highlighting the need for farmer awareness regarding application doses and methods (Devi *et al.* 2017).

In Jasra block of Allahabad district, Uttar Pradesh, a study analyzed 120 vegetable samples, including brinjal, ladyfinger, tomato, chili, and cabbage, using GC-MS. Samples were contaminated with organophosphorus pesticides like chlorpyrifos and carbamates such as carbaryl. Residue levels exceeded the maximum residue limits recommended by FSSAI and FAO/WHO, indicating potential health risks due to over-spraying practices by farmers (Singh *et al.* 2021).

Effects of Pesticides on Human Health

Pesticides can enter the human body directly or indirectly. When pesticides are used on crops, people are directly exposed to them, which can harm their skin, eyes, mouths, and respiratory systems. Acute responses can result, including headaches, irritation, vomiting, sneezing, and skin rashes. The duration and dosage of exposure determine how harmful certain insecticides are to people. Excretion is the usual way that pesticides leave the body (urinary, biliary, and secretory gland). Consuming fruits and vegetables that have been grown in soil and water contaminated by pesticides over an extended period of time increases the concentration of toxins inside the body's organs and can lead to chronic illnesses like diabetes, cancer, neurotoxicity, asthma, heart disease, and reproductive disorders. (Kalyabina *et al.* 2021). Although their chemical mechanism is yet unknown, quaternary nitrogen compounds, including paraquat, are linked to neurodegenerative illnesses like Parkinson's (Franco *et al.* 2010). Analogously, the carbamate pesticide group is utilised as a neurotoxicity biomarker because it inhibits the action of acetylcholinesterase (AChE) (Gupta *et al.* 2016). Pesticides of all kinds are the root cause of the cancer epidemic, but of all cancer types, breast cancer is the most prevalent and is linked to organophosphorus, which interferes with cellular development and division. Similarly, organophosphorus has been linked to asthma through autoinhibitory M2 muscarinic receptors on parasympathetic neurons that innervate airway smooth muscle (Calaf, 2021). By altering endocrine hormone activity, timing of release, and imitation, it also lowers fertility and causes genital tract malformations in both males and females. Numerous studies indicate that organophosphorus raises the risk of coronary artery disease and decreases paraoxonase function (Kabir *et al.* 2015). Undernourishment and hunger are the biggest issues in a number of African countries.

Role of Pesticides in Cancer

Several studies, both epidemiological and molecular, have underscored a strong link between prolonged exposure to pesticides and heightened risks of various health conditions, including neurodegenerative diseases, disruptions in the endocrine system, respiratory issues, reproductive disorders, and birth abnormalities (García *et al.* 2017; Larsen *et al.* 2017; Addissie *et al.* 2020; Bast *et al.* 2021; Bhadauriya *et al.* 2021; Witczak *et al.* 2021; Gea *et al.* 2022; Iteire *et al.* 2022). Additionally, these compounds, known for their carcinogenic, teratogenic, and mutagenic properties, are believed to significantly contribute to the development of cancer in humans.

Direct exposure to pesticides has been observed to substantially increase the susceptibility to various types of cancers, encompassing those affecting the head, neck, breast, thyroid, brain, colorectal system, pancreas, lungs, leukemia, prostate, non-Hodgkin lymphoma, and ovarian areas (Obiri *et al.* 2013; Pardo *et al.* 2020; Leonel *et al.* 2021; Lerro *et al.* 2021). While multiple pathways have been identified, the primary molecular mechanism behind pesticideinduced carcinogenesis appears to involve oxidative stress, genetic and epigenetic alterations, as well as disruptions in the endocrine system. For example, the excessive generation of reactive oxygen species (ROS) due to pesticide exposure can disrupt the delicate balance between pro- and anti-oxidant molecules within cells, resulting in oxidative stress that damages macromolecules. This, in turn, disrupts fundamental cellular processes and may stimulate the initiation, growth, progression, metastasis, and resistance to chemotherapy in cancer development (Pardo *et al.* 2020; Leonel *et al.* 2021; Lerro *et al.* 2021).

Želježić *et al.* (2018) demonstrated that exposure to the herbicide terbuthylazine led to the creation of reactive terbuthylazine by-products, causing DNA cross-links in both lab-based and live systems. Thakur *et al.* (2018) found that oxidative DNA damage caused by widely used organophosphate pesticides, monocrotophos and chlorpyrifos, altered the AP endonuclease 1- dependent base excision repair pathway, potentially promoting lung cancer proliferation. Similarly, exposure to neonicotinoid insecticides (dinotefuran, nitenpyram, and acetamiprid) resulted in amino acid metabolism disturbance, lipid accumulation, and heightened oxidative stress in ICR mice by lowering glutathione (GSH) levels and increasing superoxide dismutase (SOD) levels (Yan *et al.* 2020). While polymorphisms in oxidative stress-related genes (catalase, glutathione peroxidase, glutathione-S-transferases, manganese superoxide dismutase, and paraoxonase) might not directly cause cancer, they could render individuals 11 more vulnerable to pesticide-triggered oxidative stress (Kaur *et al.* 2018; Moradi *et al.* 2018; Costa *et al.* 2019; Mbah Ntepe *et al.* 2020).

Endocrine-disrupting chemicals (EDCs) interfere with the natural function of the body's hormone systems, affecting hormone synthesis, release, binding, and activity. These disruptions, caused by pesticides, lead to reduced fertility, neurological issues, thyroid irregularities, immune suppression, and cancer (Kori *et al.* 2018; Pizzorno, 2018; Requena *et al.* 2019; Brandt *et al.* 2020; Montes-Grajales and Olivero-Verbel, 2020). Pesticides often act as agonists, activating hormone receptors like androgen receptors, estrogen receptors, pregnane X receptors, nuclear hormone receptors, and aryl hydrocarbon receptors (Eve *et al.* 2020; Lacouture *et al.* 2022). Low doses of phenolic EDCs stimulate aromatase signaling, encouraging breast cancer cell proliferation (Williams and Darbre, 2019). Thiacloprid and imidacloprid exposure boost estrogen production similar to hormone-dependent breast cancer (Caron-Beaudoin *et al.* 2018). Some pesticides like cypermethrin inhibit androgen receptor interaction, while others exhibit anti-mineralocorticoid activity promoting liver cancer (Zhen *et al.* 2020; Zhang *et al.* 2018). Fungicides like Prochloraz and vinclozolin compete with the androgen receptor, inhibiting cell apoptosis in prostate cancer (Thomas and Dong, 2019). Glyphosate, imidacloprid, and thiacloprid were found to interfere with aromatase and estrogen receptors, impacting cancer-related cell signaling (Zhang C. *et al.* 2020). Overall, pesticides can alter cellular metabolism in various ways to increase cancer risks, especially when coupled with genetic susceptibilities in those with direct or occupational exposure.

Cause of Allergies and Asthma

Pesticides, while advantageous for modern agriculture and crop yield improvement, pose severe health risks due to their persistent nature and ability to magnify in biological systems (Sharma *et al.* 2019). Their vapors infiltrate water, soil, and air, eventually entering the food chain, posing a significant threat to human health (Sharma *et al.* 2017c). The toxicity of pesticide-contaminated food surpasses that of contaminated water or air, leading to disrupted hormonal balance, weakened immunity, cancer, and reproductive issues (Yadav *et al.* 2015). Individuals chronically or acutely exposed to pesticides, such as farmworkers, pest control or agricultural industry workers, and those living near agricultural areas, face heightened risks of developing respiratory conditions like asthma or allergic rhinitis (Ernst, 2002; Ndlovu *et al.* 2011). Studies across various countries like the United States, Canada, France, and Australia have documented increased asthmatic conditions among farmers, their families, and pesticide 12 applicators (Baldi *et al.* 2014). Exposure to these chemicals can decrease forced expiratory volume, exacerbate asthma, affect autonomic functions, and alter immune responses (Osteen and Fernandez-Cornejo, 2013; Henneberger *et al.* 2014). Household pesticide exposure, especially to insecticides, significantly contributes to asthma and asthma-like symptoms, especially in regions with high cockroach sensitization, like the United States (Garthwaite *et al.* 2012).

Research on farm operators found a notable link between current asthma and lifetime allergic rhinitis due to specific pesticides like carbaryl and 2,4-dichlorophenoxyacetic acid (Patel *et al.* 2018). Synthetic insecticides used for mosquito control, such as pyrethroids, can trigger asthma attacks, while substances like permethrin and Sumithrin contribute to various health issues, including headaches, tremors, and even fatal conditions (EPA *et al.* 2009; Amaral, 2014). Although the specific pesticides responsible for allergic or asthmatic reactions remain uncertain, organophosphates and carbamates have been identified as significant contributors to asthmatic conditions in studies from Canada, Spain, India, and South Africa (Hernández, 2015). These studies often involve lung function tests but lack primary inhalation challenge testing.

CONCLUSION

This review reveals a dynamic and evolving pattern driven by agricultural demands, regional cropping systems, and pest resistance challenges. While the deployment of pesticides—particularly organochlorines, organophosphates, and carbamates has significantly contributed to improving crop yields, it has simultaneously raised concerns regarding ecological integrity and public health safety. The data analyzed, especially from Madhya Pradesh and other major agricultural regions, reflects both the reliance on chemical control and the urgency to monitor residue accumulation.

Despite technological advancements in analytical detection methods (e.g., HPLC, GC-MS), a clear gap persists in the uniform implementation of monitoring frameworks and in accessible data for recent years. There remains limited surveillance of chronic low-dose exposures and their cumulative health outcomes in vulnerable populations.

Current debates in the field focus on the balance between food security and pesticide regulation, the phasing out of persistent pollutants, and the viability of alternatives like biopesticides and precision pest control systems. Moving forward, emphasis should be placed on strengthening Integrated Pest Management (IPM), investing in residue monitoring infrastructure, and enforcing region-specific regulatory compliance.

Pesticide management in India demands a science-led, multidisciplinary approach that incorporates toxicological insights, real-time consumption data, and sustainable pest control practices. Future research should focus on long-term exposure assessments, regional usage impact studies, and the development of safer, low-residue pesticide formulations. Such efforts are crucial for aligning agricultural productivity with environmental and public health priorities.

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