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ORIGINAL ARTICLE

Pesticide Contamination in Indian Agricultural and Residential Areas: A Comparative Assessment of Health Risks and Environmental Impacts

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ABSTRACT

The extensive use of pesticides in India, particularly in agriculturally intensive regions, has raised significant concerns regarding environmental contamination and associated human health risks. This review synthesizes recent evidence on pesticide residue occurrence in water, milk, vegetables, and soil, with special emphasis on high-risk agricultural districts of Chhattisgarh and comparable regions. Data were compiled from government databases, peer-reviewed literature, and empirical field-based analytical studies employing standardized protocols (APHA, AOAC) and advanced instrumental techniques such as GC–MS, GC–MS/MS, HPLC-PDA, AAS, ICP–MS, and HPTLC. Findings indicate widespread detection of organophosphates, organochlorines, and pyrethroids—including carbaryl, chlorpyrifos, malathion, diazinon, deltamethrin, quinalphos, and 4,4′-DDT—in environmental and food matrices. Several studies reported exceedance of acceptable daily intake (ADI) and acute reference dose (ARfD) values, particularly among children, highlighting elevated vulnerability. Health risk assessments utilizing Hazard Quotient (HQ), Hazard Index (HI), Target Hazard Quotient (THQ), and Lifetime Cancer Risk (LCR) models revealed potential non-carcinogenic and carcinogenic risks in areas proximal to pesticide application sites.These compounds exert toxicity primarily through mechanisms such as

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acetylcholinesterase inhibition, endocrine disruption, oxidative stress induction, and bioaccumulation, contributing to both acute and chronic health effects. Spatial analyses further demonstrated contamination hotspots near agricultural spraying zones, while seasonal variation influenced physicochemical water quality and pollutant persistence.

Despite regulatory efforts, critical research gaps remain, including limited longitudinal monitoring, inadequate evaluation of cumulative and mixture toxicity, insufficient exploration of non-agricultural contamination sources, and weak implementation strategies for sustainable alternatives.The review underscores the urgent need for integrated surveillance systems, farmer education on safe pesticide handling, improved regulatory enforcement, and adoption of sustainable pest management strategies. Strengthening evidence-based policymaking is essential to safeguard environmental integrity, public health, and long-term agricultural sustainability.

KEYWORDS

• Pesticide residues • Toxicokinetics • Neurotoxicity • Endocrine disruption • Forensic toxicology • Food safety • Sustainable agriculture • GC–MS • HPLC • Heavy metals • Spatial analysis • Integrated pest management

INTRODUCTION

Over the past several decades, pesticide use in India has surged, driven by the need to enhance agricultural productivity to support a growing population (FAO, 2022; Government of India, 2023). India ranks among the world's leading producers and consumers of pesticides, with insecticides dominating the market **(Sharma *et al.*, 2019).** The introduction of chemical pesticides during the Green Revolution in the 1960s significantly increased crop yields **(Pingali, 2012).** However, excessive and indiscriminate use has raised concerns regarding environmental contamination, human health risks, and pesticide resistance **(Aktar *et al.*, 2009; Pimentel & Burgess, 2014).** Small-scale farmers often lack adequate training in safe pesticide handling, increasing exposure risks **(Matthews, 2008).** Regulatory efforts by the Government of India and agencies such as the Food and Agriculture Organization aim to promote responsible pesticide use, yet enforcement challenges persist **(FAO & WHO, 2014).**

Understanding pesticide contamination is critical due to its significant public health implications. Residues in food and water may cause chronic health conditions, including cancer, endocrine disruption, and neurotoxicity **(Kim *et al.*, 2017; Mostafalou & Abdollahi, 2013).** Reports by the World Health Organization highlight the burden of pesticide-related illnesses in developing nations **(WHO, 2020).** Studying contamination patterns helps establish safe exposure limits and maximum residue levels (MRLs) **(EFSA, 2021).**

Environmental consequences are equally concerning. Pesticides contaminate soil, groundwater, and surface water, affecting non-target organisms such as pollinators, aquatic species, and soil microbiota **(Stehle & Schulz, 2015; Sánchez-Bayo & Wyckhuys, 2019).** The United Nations Environment Programme emphasizes the ecological risks associated with persistent pesticide residues **(UNEP, 2019).** Disruption of biodiversity and ecosystem services threatens long-term agricultural sustainability **(Tilman *et al.*, 2002).**

Economically, pesticide contamination can result in export rejections, trade losses, and increased healthcare expenditures **(Wilson & Tisdell, 2001).** Establishing evidence-based regulatory frameworks is therefore essential. Research on pesticide persistence, toxicology, and exposure pathways informs policymaking and supports regulatory authorities such as the Ministry of Agriculture and Farmers Welfare in developing safer agricultural strategies **(Government of India, 2023).**From a toxicological perspective, pesticide exposure involves complex interactions at molecular and cellular levels. Organophosphates inhibit acetylcholinesterase, leading to accumulation of acetylcholine and subsequent neurotoxicity, while organochlorines such as DDT exhibit lipophilicity and bioaccumulate in adipose tissues, causing endocrine disruption and potential carcinogenicity. Understanding these mechanisms is essential for interpreting both clinical and forensic manifestations of pesticide exposure.Collectively, these perspectives underscore the multifaceted importance of pesticide contamination research, reinforcing the need for sustained scientific investigation and strengthened regulatory systems to safeguard human health, environmental integrity, and economic stability.

METHODOLOGY

This review synthesizes data from a diverse range of credible sources to assess contamination levels in environmental matrices and their associated health risks. The methodology follows a systematic approach involving data collection, evaluation, and synthesis of findings from government records, academic studies, and experimental analyses.

1. Data Collection Methods

To ensure comprehensive coverage and methodological reliability, this review synthesizes evidence from multiple credible sources.

Government Databases: National environmental and agricultural datasets were obtained from official repositories, including the Ministry of Agriculture and Farmers Welfare, Central Pollution Control Board, and Indian Council of Medical Research. These sources provided baseline statistics on pesticide and heavy metal usage, environmental contamination indices, permissible exposure limits, and region-specific environmental assessments.

Academic and Research Literature: Peer-reviewed journal articles, theses, and institutional reports were systematically retrieved from databases such as PubMed, Scopus, and Google Scholar using keywords including “soil contamination,” “pesticide residues,” “groundwater pollution,” “pesticide residues,” “toxicology,” “organophosphate poisoning,” “human health risk assessment.” Studies published within the last 10–15 years were prioritized to ensure contemporary relevance, with preference given to those employing robust experimental designs and extensive field-based sampling.

Field Surveys and Laboratory Analyses: Empirical investigations involving environmental and agricultural sampling were also reviewed. Standardized protocols such as American Public Health Association (APHA) guidelines for water analysis and AOAC International methods for food and pesticide residue analysis were commonly adopted. Instrumental techniques frequently reported included GC–MS, HPLC, AAS, and ICP–MS for accurate pollutant quantification.

2. Analytical Approaches for Contamination and Health Risk Assessment

To contextualize contamination levels and evaluate associated public health implications, multiple analytical frameworks reported in the literature were examined.

Contamination Indices: Standardized indices such as the Contamination Factor (CF), Geo-accumulation Index (Igeo), and Pollution Load Index (PLI) were utilized to compare pollutant concentrations against background values and assess environmental risk levels.

Human Health Risk Assessment (HHRA): Many studies adopted the risk assessment framework developed by the United States Environmental Protection Agency. Key parameters included Hazard Quotient (HQ), Hazard Index (HI), and Lifetime Cancer Risk (LCR), calculated using exposure factors such as ingestion rate, exposure frequency, body weight, and toxicity reference values.

Spatial and Statistical Analysis: Geographic Information Systems (GIS) were employed in several studies to map contamination hotspots and identify spatial trends. Additionally, multivariate statistical tools such as Principal Component Analysis (PCA) and cluster analysis were applied to determine pollutant sources and correlations among environmental variables.

3. Inclusion Criteria and Review Scope

Studies were included based on methodological transparency, validated analytical techniques, and direct relevance to the Indian environmental context. The review emphasizes research investigating pesticide residues, heavy metals, and agrochemical pollutants in soil, water, and food systems, particularly in high-intensity agricultural regions. Only studies presenting clearly defined sampling strategies, standardized analytical procedures, and interpretable risk assessment outcomes were considered.

Title	Date of Publication	Methodology	Findings	Limitation
Occurrence of Carbaryl, DDT and Deltamethrin Residues in Bovine milk in Chhattisgarh, India and Risk Assessment to Human Health	2020	• **Sample Analysis:** A total of 200 milk samples were analysed using HPLC-PDA for pesticide residue detection. • **Target Pesticides:** Carbaryl, 4,4′-DDT, and deltamethrin were assessed. • **Spatial Distribution:** Residue prevalence was evaluated across the study area, with carbaryl showing widespread occurrence. • **Milk Type Comparison:** Residual levels were compared between cow and buffalo milk samples.	• **Occurrence:** Carbaryl was detected in 27.5% of samples, while 4,4′-DDT and deltamethrin were found in 11% and 5%, respectively. • **Spatial Distribution:** Carbaryl showed widespread distribution across the study area. • **Milk Type Comparison:** No significant difference in mean residue levels was observed between cow and buffalo milk. • **Health Risk Assessment:** EADDI values were below ADI limits (mean and 95th percentile UB) for adults and children; however, children showed relatively higher risk.	• The study does not identify specific contamination sources in Chhattisgarh, limiting targeted mitigation. • The effectiveness of proposed management strategies and farmer-focused educational interventions was not evaluated. • Additionally, the assessment emphasized carcinogenic risk, overlooking other potential health effects, indicating the need for a more comprehensive evaluation.
Assessment of knowledge and practice of safety measures by the agricultural workers using pesticide in Loharsi Gram Panchayat of Durg District, Chhattisgarh: One-year pilot study	2020	• A cross-sectional, questionnaire-based pilot study was conducted over one year in Loharsi village, Chhattisgarh. • Data were collected from the target population using a specially designed questionnaire.	• The study identified poor awareness among agricultural workers regarding PPE use. • It emphasizes the urgent need for targeted training and awareness programs to prevent avoidable fatalities from improper pesticide handling.	
Spectrophotometric Determination of Phenthoate in Vegetables and Fruit Samples of Kabirdham (Chhattisgarh)	2020	• The study developed a rapid spectrophotometric method for detecting phenthoate based on an azo-coupling reaction. • After diazotization, phenthoate reacts with 4-aminoazobenzene to form an orange dye with λmax at 480 nm. The method follows Beer's law in the range of 5–40 µg/25 mL.	• The method demonstrated high sensitivity and specificity for phenthoate detection in vegetable, fruit, water, and soil samples. • It showed a molar absorptivity of 1.083×10^{7} L mol^{-1} cm^{-1} and Sandell's sensitivity of 0.99×10^{-5} µg cm^{-2}. Low SD (±0.003) and RSD (0.89%) confirmed good reproducibility, with no interference from other pesticides or ions, ensuring accurate determination in agricultural samples.	• Although promising, the spectrophotometric method has a limited detection range and may be affected by variability in sample preparation. • Potential matrix interferences in complex samples remain a concern despite claims of minimal interference. • Its applicability to diverse crops and matrices is unclear, and further refinement is required to enhance accuracy and broader utility
HPTLC Determination of Diazinon and Malathion Residues in Water Sample of Northern Bastar Area of Chhattisgarh	2022	• **Technique:** HPTLC was employed to assess malathion and diazinon contamination in drinking water in Northern Bastar, Chhattisgarh. • **Sampling:** Water samples were collected from four stations at intervals of 1 day, 1 week, 2 weeks, 1 month, 2 months, and 3 months post-spraying. • **Extraction & Detection:** Organophosphorus insecticides were extracted using acetone and methylene chloride, and residues were quantified using HPTLC.	• **Residue Trends:** Malathion and diazinon levels decreased with increasing distance and time from spraying sites. • **Proximity Effect:** Stations nearer to spraying areas (1 and 2) showed higher residues, exceeding permissible limits up to 1–2 months post-spraying. • **Temporal Variation:** At distant stations (3 and 4), residues were detectable only within 1 day and 1 month, respectively. • **Risk Assessment:** While widespread contamination was unlikely, populations near spraying sites may face chronic toxicity risks through contaminated water and agricultural produce.	

Title	Date of Publication	Methodology	Findings	Limitation
A Study on Pesticide Contamination and Assessment of Health Effects Using Health Effect Model in Some Vegetables of Durg District, Chhattisgarh State, India	2022	• **Sample Collection:** Vegetable samples were collected from various locations in Durg district, Chhattisgarh. • **Pesticide Analysis:** Samples were examined for Malathion, Chlorpyrifos, Endosulfan, Deltamethrin, and Butachlor using chromatographic/ spectrometric techniques for detection and quantification.	• **Pesticide Occurrence:** Five pesticides were detected in vegetable samples from Durg district. Malathion (57.14%) was most prevalent, followed by Chlorpyrifos (48.98%), Butachlor (24.49%), and Deltamethrin (16.33%); Endosulfan was not detected. • **ADI Exceedance:** Approximately 50% of samples exceeded ADI limits, indicating potential health risks. • **Health Risk Assessment:** Chlorpyrifos showed a high Health Risk Index (HRI = 1.67), suggesting significant consumer risk. • **EFSA-PRIMo2.0 Analysis:** Highest ARfD exceedance was observed in cauliflower, with 26% (adults) and 54.2% (children) for Chlorpyrifos, and 9.9% (adults) and 20.7% (children) for Malathion.	
A Study on Pesticide Contamination and Assessment of Health Effects Using Health Effect Model in Some Vegetables of Durg District, Chhattisgarh State, India	2022	• **Sample Collection:** Vegetable samples were collected from various locations in Durg district, Chhattisgarh. • **Pesticide Analysis:** Samples were examined for Malathion, Chlorpyrifos, Endosulfan, Deltamethrin, and Butachlor using chromatographic/ spectrometric techniques for detection and quantification.	• **Pesticide Occurrence:** Five pesticides were detected in vegetable samples from Durg district. Malathion (57.14%) was most prevalent, followed by Chlorpyrifos (48.98%), Butachlor (24.49%), and Deltamethrin (16.33%); Endosulfan was not detected. • **ADI Exceedance:** Approximately 50% of samples exceeded ADI limits, indicating potential health risks. • **Health Risk Assessment:** Chlorpyrifos showed a high Health Risk Index (HRI = 1.67), suggesting significant consumer risk. • **EFSA-PRIMo2.0 Analysis:** Highest ARfD exceedance was observed in cauliflower, with 26% (adults) and 54.2% (children) for Chlorpyrifos, and 9.9% (adults) and 20.7% (children) for Malathion.	• The study does not evaluate cumulative or combined pesticide risks and lacks longitudinal monitoring to assess regulatory impact over time. • Limited vegetable coverage restricts broader contamination insights. Additionally, the specific health implications of Chlorpyrifos exposure are insufficiently detailed, warranting further investigation.
Study on the effect of pesticides in labeo rohita from some water reservoirs of raipur chhattisgarh	2023	• **Sample Collection:** A total of 100 water samples were collected (August 2020–September 2021) from five selected ponds/spots in Raipur district, Chhattisgarh. Samples were divided for physicochemical analysis and assessment of heavy metal effects on fish populations. • **Analysis:** Fresh samples were analyzed using GC–MS and AAS for detailed chemical evaluation.	• Physicochemical parameters showed clear seasonal variations in water quality. • During the pre-monsoon period, 41% of samples met BIS permissible limits for drinking water. Water quality, influenced by physicochemical and biological factors, was critical for fish survival and development. • Acute pesticide toxicity was observed, affecting fish behavior and opercular movements.	

Title	Date of Publication	Methodology	Findings	Limitation
Analysis of factors influencing preferences for sources and brands of pesticides in Bemetara district of Chhattisgarh (Direct Sample)	2023	• The study in Bemetara district, Chhattisgarh, assessed pesticide usage patterns through surveys and interviews with farmers, retailers, and company representatives. • Collected data were analyzed using statistical methods to derive conclusions.	• **Purchase Drivers:** Product effectiveness was the main factor influencing pesticide purchase, followed by product quality. • **Application Practices:** All farmers used chemical control methods, alongside physical control, soil testing, and IPM practices. • **Information Sources:** Retailers were the primary information source, followed by company representatives and fellow farmers. • **Promotional Influence:** Dealers most strongly influenced company promotional strategies. • **Company Ranking:** Based on promotional strategies, UPL ranked first, followed by BASF and IT sector companies.	• The study provides insights into pesticide procurement and marketing influences but lacks evaluation of the effectiveness of alternative management practices. • It does not assess the quality of information provided by retailers or examine specific marketing strategies and mechanisms of dealer influence. • Although UPL ranked highest in promotional strategies, the study does not detail these strategies or compare their effectiveness, indicating the need for further investigation.
Health Risk Assessment of Pesticide Residues in Drinking Water of Upper Jhelum Region in Kashmir Valley-India by GC-MS/MS	2023	• **Sampling Sites:** Fifteen locations were selected along the upper Jhelum basin to represent diverse water sources. • **Sample Collection:** A total of 60 water samples were collected for analysis. • **Pesticide Analysis:** Residues were determined using GC–MS/MS.	• **Pesticide Detection:** Ten of the 26 commonly used pesticides were detected in water samples. • **Highest Concentration:** Difenoconazole showed the highest mean concentration (0.412 ± 0.424 µg/L; range: 0.0–0.8196 µg/L). • **Health Risk Assessment:** THQ analysis indicated non-carcinogenic risk, with Chlorpyrifos and Quinalphos exceeding the safety threshold (>1) at sites RWS3, RWS4, RWS14, and RWS15, suggesting potential health concerns.	• The study assessed pesticide residues only during spring and summer, limiting understanding of seasonal variation. • Although 26 pesticides from 13 chemical families were screened, residues were detected from only five families, potentially underestimating overall exposure risk. • The focus on agricultural and horticultural sources excluded other contributors such as industrial runoff and urban applications. • Health risk evaluation relied mainly on THQ, which may not comprehensively reflect total health impacts.

RESULTS

1. Occurrence of Pesticide Residues in Environmental and Food Matrices

Across the reviewed studies, pesticide residues were frequently detected in milk, vegetables, groundwater, and surface water samples. Organophosphates (e.g., chlorpyrifos, malathion, diazinon, quinalphos), organochlorines (e.g., 4,4′-DDT), and pyrethroids (e.g., deltamethrin) were the most commonly reported contaminants. Carbaryl and chlorpyrifos demonstrated relatively higher prevalence rates in food and water matrices, while certain compounds exceeded permissible limits in specific locations.

Several studies reported residue concentrations surpassing Acceptable Daily Intake (ADI) or Acute Reference Dose (ARfD) thresholds, particularly in vegetable samples. Health Risk Index (HRI), Target Hazard Quotient (THQ), and Hazard Quotient (HQ) values above unity were observed in high-exposure regions, indicating potential non-carcinogenic health risks. Children were consistently identified as a more vulnerable population group due to lower body weight and higher intake-to-body-mass ratios **(Kim** ***et al.*****, 2017; Mostafalou & Abdollahi, 2013).**

2. Spatial and Seasonal Variations

Spatial analysis revealed higher contamination levels in areas proximal to pesticide spraying zones, with residue concentrations decreasing over time and distance from application sites. Seasonal variations were also evident, particularly in water quality parameters during pre-monsoon and post-monsoon periods. These findings align with previous reports highlighting agricultural runoff and spray drift as major contamination pathways **(Stehle & Schulz, 2015; Yadav** ***et al.*****, 2015).**

3. Environmental Implications

The persistence of pesticide residues in soil and water ecosystems poses risks to non-target organisms, including aquatic species and beneficial insects. Declines in biodiversity and ecosystem functioning have been associated with chronic pesticide exposure **(Sánchez-Bayo & Wyckhuys, 2019).** Contamination of surface water beyond safety thresholds further threatens freshwater ecosystems and agricultural sustainability **(Tilman** ***et al.*****, 2002).**

4. Toxicological Interpretation

The frequent detection of organophosphates and organochlorines is toxicologically significant due to their known mechanisms of neurotoxicity and persistence. Chronic low-dose exposure, even below acute toxicity thresholds, may result in cumulative biochemical alterations including enzyme inhibition and oxidative stress.

5. Toxicological Mechanisms of Major Pesticides

Pesticides exert their toxic effects through diverse biochemical mechanisms depending on their chemical class. Organophosphates such as chlorpyrifos and malathion act by inhibiting acetylcholinesterase, leading to accumulation of acetylcholine at synapses and neuromuscular junctions, resulting in continuous nerve impulse transmission and neurotoxicity.Organochlorines such as DDT are highly lipophilic and resistant to degradation, leading to bioaccumulation in adipose tissues and biomagnification along the food chain. These compounds interfere with endocrine function and have been associated with reproductive toxicity and carcinogenicity. Pyrethroids, although considered less persistent, act on voltage-gated sodium channels, prolonging neuronal excitation and leading to neurobehavioral effects.These mechanisms highlight the importance of integrating toxicological understanding with environmental monitoring data to better assess long-term health risks.

6. Toxicokinetics of Pesticides

The toxicokinetics of pesticides involves their absorption, distribution, metabolism, and excretion. Exposure occurs primarily through ingestion of contaminated food and water, inhalation of aerosols during spraying, and dermal contact.Once absorbed, lipophilic pesticides such as organochlorines accumulate in fatty tissues, whereas organophosphates are rapidly distributed and metabolized in the liver. Biotransformation processes may either detoxify compounds or generate more toxic metabolites. Excretion occurs through urine, feces, or, in some cases, breast milk, contributing to secondary exposure.Understanding toxicokinetic behavior is essential in both clinical toxicology and forensic investigations, particularly in interpreting biological sample analysis.

Pesticide poisoning represents a significant concern in forensic investigations, particularly in cases of accidental exposure, occupational hazards, and intentional self-harm. Toxicological analysis of biological samples such as blood, urine, and viscera is essential for confirming exposure.Analytical techniques such as GC–MS and HPLC are routinely employed in forensic laboratories for the detection and quantification of pesticide residues. Biomarkers such as reduced acetylcholinesterase activity are commonly used in cases of organophosphate poisoning.The integration of environmental contamination data with forensic toxicology enhances the ability to establish exposure pathways and support medico-legal conclusions.

7. Human Health Risk Assessment

Human Health Risk Assessment (HHRA) models, primarily based on the United States Environmental Protection Agency framework, were widely employed. Metrics such as Hazard

Index (HI) and Lifetime Cancer Risk (LCR) suggested potential carcinogenic and non-carcinogenic risks in populations consuming contaminated water and food products. Chronic exposure to pesticide residues has been linked to neurological disorders, endocrine disruption, and carcinogenic outcomes **(Aktar *et al.*, 2009; Kim *et al.*, 2017).**The findings confirm that pesticide contamination remains a significant environmental and public health concern in agriculturally intensive regions. The dominance of organophosphates and synthetic pyrethroids reflects current pesticide usage trends in India **(Sharma *et al.*, 2019).** Despite regulatory frameworks implemented by the Ministry of Agriculture and Farmers Welfare, monitoring and enforcement gaps persist.

Elevated HQ and THQ values in specific regions indicate localized exposure risks, particularly for children. Similar conclusions have been reported by the World Health Organization, emphasizing the disproportionate burden of pesticide exposure in developing **countries (WHO, 2020).** While indices such as HQ and THQ provide quantitative estimates of risk, they do not fully capture underlying toxicodynamic processes. For instance, organophosphate exposure leads to inhibition of acetylcholinesterase activity, which can be clinically correlated with symptoms such as muscle twitching, respiratory distress, and neurological impairment. Similarly, chronic exposure to organochlorines may result in endocrine disruption and carcinogenic outcomes due to their persistence and bioaccumulation.Spatial clustering of contamination near spraying sites suggests the need for buffer zones, improved application techniques, and farmer education programs. Evidence indicates that improper handling practices and lack of personal protective equipment significantly contribute to occupational and environmental exposure **(Matthews, 2008)** Although some studies recommend sustainable alternatives such as Integrated Pest Management (IPM) and bio-pesticides, implementation strategies remain insufficiently developed. Strengthening surveillance systems, conducting longitudinal monitoring, and incorporating cumulative risk assessment models are essential for comprehensive evaluation. Furthermore, future research should integrate mixture toxicity and multi-pathway exposure assessment to better reflect real-world scenarios.

The reviewed studies collectively indicate significant variability in pesticide contamination levels across regions, influenced by factors such as agricultural intensity, pesticide type, climatic conditions, and regulatory enforcement. While several studies report concentrations exceeding ADI and ARfD limits, the absence of cumulative and mixture toxicity assessment remains a critical limitation. Toxicologically, combined exposure to multiple pesticide classes may produce synergistic or additive effects, which are not adequately captured by conventional risk indices such as HQ and THQ. This highlights the need for integrated toxicological models that account for real-world exposure scenarios. Future research should prioritize toxicological evaluations including dose-response relationships, mixture toxicity, and biomarker-based assessments to better understand the long-term health implications of pesticide exposure. Integrating environmental monitoring with forensic toxicology will be critical in strengthening public health surveillance and medico-legal investigations.

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