Jurnal Kesehatan
Vol. 19, No. 2, September 2026, pp. 184~198
p-ISSN: 1979-7621, e-ISSN: 2620-7761, DOI: 10.23917/jk.v19i2.17418

Toxicological Literature Review of Organophosphate Pesticides Regarding Environmental and Human Health in Lampung

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How to Cite: Fitryah, U. (2026). Toxicological Literature Review of Organophosphate Pesticides Regarding Environmental and Human Health in Lampung. Jurnal Kesehatan, 19(2), 184–198. https://doi.org/10.23917/jk.v19i2.17418

Article Information

Article History:
Submission: 8 May 2026
Revision: 4 September 2026
Receipt: 4 September 2026

Keywords: Biomonitoring, cholinesterase, environmental health, Lampung, organophosphate pesticides

ABSTRACT

Introduction: The use of organophosphate (OP) pesticides in the agricultural sector poses serious threats to environmental and human health. This literature review article aims to examine the toxicological effects of OP exposure, evaluate the effectiveness of control methods that have been implemented, identify research gaps, and assess their relevance to agricultural management conditions in Lampung Province. **Method:** The review was conducted through a literature review of 15 scientific articles published between 2021 and 2026, obtained from relevant scientific sources. **Results:** The findings indicate that OP exposure is associated with decreased cholinesterase enzyme activity in farmers, gut microbiome disturbances, neurotoxic effects, and contamination of soil and groundwater. Control methods, such as the use of personal protective equipment (PPE) and washing of food products, have not been fully effective due to low compliance and the presence of OP transformation products in the environment that remain toxic. Research gaps include limited longitudinal data on chronic low-dose exposure and a lack of studies on OP transformation products at the local level. **Conclusion:** These findings are relevant to Lampung Province because OP residues have still been detected in local agricultural products, highlighting the need for improved education on pesticide poisoning management. Therefore, routine pesticide residue monitoring and biomonitoring should be strengthened to support safer and more sustainable pesticide management. However, the interpretation of conditions in Lampung remains limited because most of the reviewed literature originated from outside Lampung, emphasizing the need for multisite studies with broader geographical coverage.

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INTRODUCTION

Agriculture is a vital sector for maintaining food security; however, agricultural intensification has driven the widespread use of pesticides (Purba et al., 2025; Nining et al., 2019). Organophosphate (OP) pesticides are among the most widely used due to their high efficacy, broad spectrum of pest control, and relatively affordable cost (Perry et al., 2020). Nevertheless, the use of OPs affects not only target organisms but also leaves environmental residues that can harm non-target organisms, disrupt ecosystem balance, and potentially pose public health risks (Saad et al., 2025; Deviyani et al., 2026).

Human exposure to organophosphate (OP) pesticides can occur via inhalation, ingestion, or dermal contact, affecting both high-risk groups—such as farmers—and consumers through agricultural products (Saad et al., 2025; Purba et al., 2025). Mechanistically, OPs function by inhibiting the enzyme acetylcholinesterase (AChE), leading to an accumulation of acetylcholine in the synaptic cleft; this can result in central nervous system disorders and even death (Wicaksono et al., 2023; Saad et al., 2025). OP exposure also presents a potential public health issue due to its implications for food safety and the health of agricultural workers. This issue is particularly critical in agrarian regions like Lampung, where the detection of OP residues in vegetables circulating in Bandar Lampung indicates that contamination extends beyond the production stage to reach consumers (Hartami et al., 2024). Although extensive research on organophosphate pesticides has been conducted, most studies have focused on acute effects and have yet to comprehensively integrate human toxicology, ecological impacts, and risk management—especially within the context of agrarian regions like Lampung. Therefore, a more comprehensive assessment of the toxicological risks associated with organophosphates (OPs)—along with the identification of research gaps and management strategies—is required to inform the formulation of safer and more sustainable policies.

Previous research indicates that the use of organophosphate (OP) pesticides impacts not only pest control efficacy but also human health, food safety, and the environment. OPs are widely used in agriculture; however, their residues persist in the environment, contaminating soil and water and entering the food chain, thereby potentially increasing human exposure (Leskovac & Petrović, 2023; Yao et al., 2023). Regarding human health, research indicates that while OP toxicity is primarily linked to acetylcholinesterase inhibition, chronic low-dose exposure may also involve other neurotoxic mechanisms that do not necessarily depend on the inhibition of this enzyme (Aroniadou-Anderjaska et al., 2023). These findings reflect a shift in research focus from acute toxicity assessment toward a broader understanding of the effects of chronic exposure and the mechanisms of OP toxicity.

Regarding environmental aspects, research on organophosphate (OP) residues has evolved from merely identifying the presence of pesticides to assessing their distribution and associated risks across various environmental compartments. Studies on agricultural land indicate that OP residues are detectable in soil and exhibit distribution patterns linked to agricultural activities, thereby posing potential ecological and human health risks through the migration of residues into the environment and the food chain (Yao et al., 2023). Furthermore, concerns regarding food safety have driven the development of strategies to reduce pesticide residues, including biotic and abiotic degradation approaches (Leskovac & Petrović, 2023). Consequently, recent research increasingly frames OP management within a perspective that links pesticide use, environmental residue presence, human exposure, and risk reduction efforts.

This evolution is also evident in the adoption of increasingly advanced analytical approaches for assessing pesticide toxicity. New Approach Methodologies (NAM) and machine learning are being developed to support neurotoxicity assessments and enhance the ability to predict the toxic characteristics of pesticides (Karaboga et al., 2024; Wang et al., 2025). These approaches demonstrate that the current state of OP research has moved beyond the mere identification of pesticide presence or the measurement of acute toxic effects; instead, it is shifting toward comprehensive risk assessments that consider chronic exposure, biological changes, transformation products, and the use of modern analytical and predictive methods.

Despite the extensive research conducted on organophosphate pesticides, several research gaps remain. Existing studies generally address specific aspects in isolation—such as measuring cholinesterase activity in farmers, detecting pesticide residues in food, assessing environmental contamination, or examining specific biological effects. Research on human OP exposure also tends to rely on specific indicators and has yet to fully integrate the correlations between exposure sources, exposure pathways, environmental conditions, and health impacts within a single study. Furthermore, data regarding chronic low-dose exposure and its long-term effects remain limited (Wang et al., 2025; Lopez et al., 2024).

Gaps also exist regarding environmental aspects, particularly concerning the presence and characteristics of organophosphate (OP) transformation products. While some studies indicate that pesticides undergo chemical or biological transformations in the environment, information regarding the toxicity of these transformation products and their contribution to overall risk requires further development (Saad et al., 2025; Wang et al., 2025). Furthermore, research on microbial community changes resulting from OP exposure reveals ecological impacts, yet the links to human health risks and comprehensive pesticide management strategies remain under-explored (Rakhmawati et al., 2023).

These gaps are particularly significant for Lampung Province, a region with intensive agricultural activity. The detection of OP residues in vegetables circulating in Bandar Lampung suggests a potential risk of consumer exposure (Hartami et al., 2024). However, research specifically integrating evidence on human toxicity, environmental contamination, exposure pathways, control effectiveness, and relevance to local agricultural conditions in Lampung remains limited. Information regarding the effectiveness of Personal Protective Equipment (PPE) use, biomonitoring, residue monitoring, and education on pesticide poisoning management also requires further study as part of risk management.

Therefore, a study is needed that not only summarizes the toxicological impacts of OPs but also integrates evidence regarding human health and environmental effects, implemented control methods, and existing research gaps. Such an approach is expected to provide a more comprehensive overview of the risks associated with organophosphate pesticide use and serve as a foundation for understanding the need for safer, more sustainable pesticide management, particularly in Lampung Province. Based on this context, a comprehensive study addressing OP toxicological risks—along with the identification of research and management gaps—is essential to inform the formulation of safer and more sustainable policies.

LITERATURE REVIEW

The toxicity of organophosphate (OP) pesticides is closely linked to their chemical structure, which contains a phosphate ester bond, enabling irreversible binding to the serine residue at the active site of the cholinesterase enzyme (Saad et al., 2025; Karaboga et al., 2024). This mechanism causes not only acute effects, such as cholinergic syndrome, but also long-term consequences. Chronic OP exposure has been linked to cognitive impairment, reduced lung function, reproductive system disorders, and increased susceptibility to infections, including SARS-CoV-2 (Wang et al., 2025; Lopez et al., 2024). Furthermore, recent findings indicate that OPs can disrupt the balance of the gut microbiome, which plays a crucial role in regulating human metabolism and the immune system (Zhang et al., 2024).

In an ecological context, OP pesticides readily enter water bodies—both surface water and groundwater—via agricultural runoff and affect the structure and function of the soil microbiome (Deviyani et al., 2026; Rakhmawati et al., 2023). These compounds tend to be persistent and can undergo transformation through hydrolysis or microbial activity (Wang et al., 2025; Saad et al., 2025). In some instances, the resulting transformation products exhibit toxicity levels equal to or even higher than those of the parent compounds (Wang et al., 2025). This situation drives the development of advanced analytical approaches, such as New Approach Methodologies (NAM) and machine learning, to improve the accuracy of neurotoxicity assessments and support more effective management and restriction of pesticide use (Karaboga et al., 2024; Wang et al., 2025).

Conceptually, the toxicological risk of pesticides can be understood through the relationship between hazard and exposure. Hazard refers to the intrinsic property of a compound capable of causing adverse effects on humans or non-target organisms (Adam et al., 2024; Shekhar et al., 2024). Meanwhile, exposure signifies contact between a pesticide and an organism under specific conditions and via particular pathways. Consequently, the presence of a toxic pesticide does not directly indicate the magnitude of risk, as risk is also influenced by the level and characteristics of exposure (Adam et al., 2024). This risk assessment concept is crucial in pesticide studies because it links a compound's toxic properties, the likelihood of exposure, and the potential impacts on human health and the environment (Saad et al., 2025).

Human exposure to pesticides can occur via several routes: inhalation, ingestion, and dermal absorption (Shekhar et al., 2024). Agricultural workers constitute a group potentially at higher risk of exposure due to their direct involvement in mixing, spraying, and handling crops treated with pesticides (Shekhar et al., 2024; Hua & Liu, 2024). The general public can also be exposed through the consumption of food containing pesticide residues (Beyuo et al., 2024). The level of risk an individual faces can be influenced by the route, intensity, frequency, and duration of exposure (Adam et al., 2024). Therefore, pesticide risk assessment must consider exposure characteristics in addition to the toxic properties of the compounds used.

In an environmental context, applied pesticides can migrate from the site of application to various environmental compartments. This migration can occur through drift, volatilization, surface runoff, or leaching, allowing residues to reach soil and water bodies (Saad et al., 2025). The presence of residues in various environmental media can subsequently create exposure pathways for humans and non-target organisms (Adam et al., 2024). Consequently, monitoring environmental residues is a crucial component of pesticide risk assessment and environmental health protection (Hua & Liu, 2024).

Pesticide use is also linked to food safety, as residues remaining on agricultural produce can serve as a source of exposure for consumers (Beyuo et al., 2024). Monitoring residues in food products is necessary to determine contamination levels and support health risk assessments regarding dietary exposure (Hua & Liu, 2024). Residue management efforts can be implemented through various approaches, including reducing pesticide use and employing biotic or abiotic residue degradation strategies (Leskovac & Petrović, 2023).

Based on this concept, the toxicological risk of OP pesticides can be understood as a sequence spanning from pesticide application, environmental dispersal and residue persistence, and exposure, to the resulting impacts on humans and the environment. The toxicological risk assessment framework positions hazard, exposure, response or impact, and risk control as interconnected components (Adam et al., 2024). In the study of OP pesticides, this concept serves as a foundation for integrating research findings on human and environmental toxicity, evaluating implemented control strategies, and identifying research gaps, particularly within the context of Lampung Province.

METHOD

This study employs a narrative literature review method with a qualitative descriptive approach to analyze the toxicological risks of organophosphate (OP) pesticides to human health and the environment. The review integrates and describes relevant research findings thematically, focusing on OP toxicological impacts, exposure pathways, environmental effects, biomonitoring, and control strategies. Literature searches were conducted using scientific databases and academic search engines, namely Google Scholar, PubMed, and Scopus. Keywords included "organophosphate pesticides," "toxicology," "environmental health," "cholinesterase," "biomonitoring," and "Lampung." To broaden and refine search results, keywords were combined using Boolean operators (AND, OR), with search strategies such as ("organophosphate pesticides" OR "organophosphate pesticide") AND (toxicology OR "environmental health" OR cholinesterase OR biomonitoring) AND (Lampung OR Indonesia). The literature search was carried out between April 6 and April 19, 2026, covering publications from 2021 to 2026.

Selected literature consisted of scientific publications available in full-text format. Inclusion criteria encompassed research and review articles addressing the toxicological impacts of organophosphate pesticides on human health and the environment, as well as biomonitoring and pesticide risk management. Articles irrelevant to the topic, unavailable in full text, or not peer-reviewed were excluded. The selection process was conducted in stages: initially screening titles and abstracts from the search results, followed by a full-text review of articles deemed relevant. Articles meeting all inclusion criteria were selected as primary sources, resulting in a final set of 15 articles for analysis.

Data from the selected articles were extracted using a matrix developed by the authors. The extraction process involved a thorough reading of the articles and the systematic recording of relevant information. The extracted data included the research title, authors, publication year, study type, study location, research subjects or objects, analysis methods, focus of exposure, and key findings regarding the impacts of organophosphate pesticides on biological systems, ecology, farmer behavior, and control strategies.

Article quality assessment was conducted descriptively, considering the clarity of research objectives, the alignment of the study design with those objectives, the clarity of methods, the relevance of the variables or outcomes examined, and the completeness of result reporting. This assessment served to evaluate the strength and limitations of the evidence presented in each analyzed article. As this study employed a narrative literature review approach, the assessment of risk of bias was not conducted using a specific, formal risk-of-bias instrument.

Next, the data was analyzed using narrative synthesis and thematic analysis. The research results from 15 articles were compared and grouped based on similar topics and study objectives. The synthesis was conducted by identifying consistent and divergent patterns of findings across studies and then grouping them into key themes: risks to human health, pollution and environmental impacts, exposure pathways and characteristics, and risk control strategies for organophosphate pesticides. The synthesis results were then used to evaluate the toxicological risks of organophosphate pesticides, assess implemented control strategies, and identify research gaps, particularly those related to the conditions in Lampung Province.

The article identification and selection process was conducted manually by the authors. No specialized software for statistical analysis or meta-analysis was used because the data were analyzed descriptively and narratively. PRISMA flow diagrams were not used because this study employed a narrative literature review design, not a systematic review. This study utilized secondary data from publicly available scientific publications and did not involve direct data collection from humans, animals, or the environment, therefore, it did not require ethical clearance.

RESULTS AND DISCUSSION

Impact of Organophosphate Pesticides on Human Health

A synthesis of the literature indicates that the toxicity of organophosphate (OP) pesticides affects not only the environment but also has broad impacts on human biological systems. Various studies have reported the inhibition of cholinesterase enzyme activity resulting from OP exposure—particularly among agricultural workers—a phenomenon influenced by the duration of exposure, poor hygiene practices, and non-compliance with the use of personal protective equipment (Wicaksono et al., 2023; Mayaserli et al., 2022; Aulia et al., 2024). The toxicological impact is becoming increasingly complex, with recent findings showing that OPs can alter the composition of the human gut microbiome and affect metabolic processes as well as the body's defense mechanisms against pathogens (Zhang et al., 2024). Furthermore, chronic OP exposure, especially starting in childhood, has been linked to increased susceptibility to viral infections, including SARS-CoV-2 (Lopez et al., 2024).

Ecological Impact of Organophosphate Pesticides

In an ecological context, exposure to organophosphates (OPs) has been shown to disrupt environmental balance by altering soil bacterial diversity and contaminating groundwater in agricultural areas. Research indicates the presence of chlorpyrifos residues in groundwater at Hazard Quotient (HQ) levels exceeding safety thresholds, particularly for children (Rakhmawati et al., 2023; Deviyani et al., 2026). These findings demonstrate that the toxicological impact of OPs is not limited to the individual level but also has the potential to affect environmental quality and public health on a broader scale.

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Table 1. Results from Selected Articles for the Literature Review

No.	Title	Authors	Who/What Was Studied	Location	Study Design/Type	Exposure Focus	Outcome	Main Findings
1	*Overview of Organophosphate Pesticide Residues in Cabbage (Brassica oleracea) Served as Fresh Vegetables by Vendors*	Hartami et al. (2024)	Cabbage sold as fresh vegetables by vendors	Bandar Lampung	Descriptive quantitative observational study	OP pesticide residues in cabbage	OP residue levels before and after washing	Dimethoate, diazinon, fenthion, chlorpyrifos, and profenofos were detected. The highest fenthion residue was 0.8607 mg/kg. Washing reduced the residue levels.
2	*Biomonitoring of Organophosphate Pesticide Exposure among Agricultural Workers*	Liem (2021)	Agricultural workers and biomarkers of OP exposure	–	*Literature review*	OP exposure among agricultural workers	AChE and BChE activity	AChE and BChE can be used to assess OP exposure but cannot specifically identify the type of OP compound.
3	*Pesticide Poisoning Antidote Counseling and Education*	Muslim et al. (2024)	Students of STIT Darul Fattah	Bandar Lampung, Lampung	Community service program with a *pre-post test*	Education on pesticide poisoning and antidotes	Participants' knowledge level	Education and counseling improved participants' knowledge regarding the management of pesticide poisoning.
4	*Literature Review: Impact of Organophosphate Pesticide Exposure on Cholinesterase Enzyme Activity and Associated Risk Factors for Poisoning, 2017–2020*	Wicaksono et al. (2023)	Farmers/individuals exposed to OP pesticides in the reviewed studies	–	*Systematic literature review*	OP pesticide exposure	Cholinesterase enzyme activity and risk factors for poisoning	OP exposure was associated with decreased cholinesterase activity. Contributing factors included age, knowledge, PPE use, and duration of spraying.
5	*The Presence of Organochlorine and Organophosphate Pesticide Residues in Groundwater at the Upper Citarum Watershed*	Deviyani et al. (2026)	Groundwater	Upper Citarum Watershed, West Java	Quantitative sampling and GC-MS analysis	OP pesticide residues in groundwater	Residue concentrations and Hazard Quotient (HQ)	Chlorpyrifos was detected in groundwater at concentrations of 0.0116–0.2469 mg/L. HQ values indicated potential health risks, particularly among children.
6	*Assessing Soil Bacterial Community Response to Organophosphate Pesticides in Agricultural Field of Yogyakarta, Java, Indonesia*	Rakhmawati et al. (2023)	Soil bacterial communities in agricultural fields	Yogyakarta, Java	Analytical observational study using 16S rRNA sequencing	OP exposure in agricultural soil	Bacterial community composition and structure	Bacterial communities were dominated by Proteobacteria, Actinobacteria, and Firmicutes. Differences in bacterial communities were observed across agricultural zones.

Table 1. Results from Selected Articles for the Literature Review

No.	Title	Authors	Who/What Was Studied	Location	Study Design/Type	Exposure Focus	Outcome	Main Findings
7	*Types and Toxicity Levels of Pesticides: A Study of an Agricultural Area in Brebes Regency*	Budiyono et al. (2023)	166 respondents from 1,017 households in two agricultural villages	Brebes Regency, Central Java	Cross-sectional	Pesticide types, use, packaging, and pesticide residues in households	Types and toxicity levels of pesticides	Various pesticides with toxicity levels ranging from U to Ib were identified, along with the presence of pesticide residues in household environments.
8	*Relationship between Organophosphate Exposure Risk Factors and Decreased Cholinesterase Levels among Members of the At-Tanwir Farmers' Group*	Aulia et al. (2024)	Members of the At-Tanwir farmers' group	Lembah Gumanti, Solok, West Sumatra	Analytical observational cross-sectional study	OP exposure and occupational/behavioral risk factors	Cholinesterase levels	Decreased cholinesterase levels were associated with several exposure factors, including length of employment, knowledge, hygiene, spraying frequency, and compliance with PPE use.
9	*Environmental Health Risk Assessment of Consumption of Foodstuffs Containing Organophosphate Residues among Farmers*	Purba et al. (2025)	117 farmers and red chili and tomato samples	North Dempo District, Pagar Alam City, South Sumatra	Environmental Health Risk Assessment with a cross-sectional approach	Consumption of food containing OP residues	Residue concentrations and Risk Quotient (RQ)	Chlorpyrifos and profenofos were detected in red chili and tomatoes. Profenofos in tomatoes had an RQ of 2.92, indicating a potential non-carcinogenic health risk.
10	*Effect of Organophosphate Pesticide Exposure Duration on Blood Cholinesterase Levels Using the Comparator Method*	Mayaserli et al. (2022)	Farmers/agricultural workers	West Sumatra	Experimental/ descriptive study	Duration of OP exposure	Blood cholinesterase levels	Longer pesticide exposure was associated with changes/decreases in cholinesterase levels.
11	*Ambient Long-Term Exposure to Organophosphorus Pesticides and the Human Gut Microbiome: An Observational Study*	Zhang et al. (2024)	190 participants from a Parkinson's disease epidemiological study	California, United States	*Observational study*	Long-term environmental OP exposure	Gut microbiome composition and metabolic pathways	Long-term exposure was not associated with overall alpha/beta diversity but was associated with changes in several bacterial families, genera, and predicted metabolic pathways.
12	*Organophosphate Pesticide Exposure and Risk of SARS-CoV-2 Infection*	Lopez et al. (2024)	Population with biomarker data on OP exposure	California, United States	Longitudinal cohort study	OP exposure	SARS-CoV-2 infection and immune response	OP exposure was examined in relation to the risk of SARS-CoV-2 infection and immune response.

Table 1. Results from Selected Articles for the Literature Review

No.	Title	Authors	Who/What Was Studied	Location	Study Design/Type	Exposure Focus	Outcome	Main Findings
13	*Organophosphate Pesticides: A Review on Classification, Synthesis, Toxicity, Remediation and Analysis*	Saad et al. (2025)	OP pesticides, toxicity, residues, and remediation/analysis methods	–	*Review article*	Toxicity, contamination, remediation, and analysis of OP pesticides	Synthesis of toxicological and OP management information	OP pesticides inhibit AChE, can contaminate the environment, and require effective remediation strategies and sensitive detection methods.
14	*Organophosphate Toxicity Patterns: A New Approach for Assessing Organophosphate Neurotoxicity*	Karaboga et al. (2024)	42 OP compounds and their neurotoxicity patterns	–	NAM, computational, and experimental approaches	Compound structure and OP neurotoxicity	Neurotoxicity profiles	Classification based on structural characteristics revealed distinct patterns of neurotoxicity among OP compounds.
15	*Organophosphorus Pesticides Management Strategies: Prohibition and Restriction Multi-Category Multi-Class Models, Environmental Transformation Risks, and Special Attention List*	Wang et al. (2025)	OP compounds and their transformation risks	China	*Machine learning modeling*	OP restrictions and transformation-product risks	Restriction categories and transformation risks	Machine learning models were used to predict restriction categories. Pesticide transformation products also require attention because they may have toxicity equal to or greater than that of the parent compounds.

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Based on the characteristics and key results of the 15 selected articles, the research findings were analyzed and categorized into several major themes aligned with the study's objectives: impacts on human health, environmental impacts, factors influencing exposure, control strategies, and research gaps. A thematic synthesis of these findings is presented in Table 2.

Table 2. Thematic Synthesis of Research Findings

Theme/Finding	Number of Articles	Key Findings	Consistent Evidence Across Articles
Impact on human health	6	OP exposure is associated with decreased cholinesterase activity, alterations in the gut microbiome, neurotoxic effects, and increased susceptibility to certain health problems.	Wicaksono et al. (2023), Mayaserli et al. (2022), Aulia et al. (2024), Zhang et al. (2024), Lopez et al. (2024), Liem (2021)
Environmental contamination and impacts	4	OP pesticides have been detected in food, groundwater, and agricultural soil and may affect soil microbial communities.	Hartami et al. (2024), Deviyani et al. (2026), Rakhmawati et al. (2023), Saad et al. (2025)
Dietary exposure and health risks	2	OP residues in food commodities can serve as a source of consumer exposure and may pose non-carcinogenic health risks.	Hartami et al. (2024), Purba et al. (2025)
Factors influencing exposure	4	Exposure duration, spraying frequency, knowledge, personal hygiene, and compliance with PPE use are associated with the risk of OP exposure.	Wicaksono et al. (2023), Mayaserli et al. (2022), Aulia et al. (2024), Budiyono et al. (2023)
Risk control and management strategies	5	PPE use, food washing, education, biomonitoring, remediation, and restrictions on pesticide use are approaches used to reduce OP-related risks.	Hartami et al. (2024), Muslim et al. (2024), Liem (2021), Saad et al. (2025), Wang et al. (2025)
Research gaps	4	Longitudinal studies on chronic low-dose exposure, OP transformation products, and the application of biomonitoring and predictive methods at the local level remain limited.	Liem (2021), Zhang et al. (2024), Wang et al. (2025), Karaboga et al. (2024)

***Note**: A single article may fall under more than one theme; therefore, the number of articles for each theme is not cumulative.

Control Effectiveness and Research Gaps

Despite the implementation of various control measures, their effectiveness remains limited. Conventional approaches—such as the use of personal protective equipment (PPE) and the washing of produce—can reduce exposure levels but fail to control risks comprehensively. For instance, washing vegetables only partially reduces pesticide residues on cabbage in Bandar Lampung (Hartami et al., 2024). High exposure levels in rural communities are also driven by unsafe pesticide storage practices and low farmer compliance regarding PPE use (Budiyono et al., 2023). From a regulatory perspective, policies restricting organophosphates (OPs) in developing countries are progressing slowly and have yet to account for the toxicity of pesticide transformation products in the environment. This is despite the fact that modern approaches—such as New Approach Methodologies (NAM) and machine learning—have demonstrated potential for improving the accuracy of toxicological risk assessments, even though their local application remains limited (Karaboga et al., 2024; Wang et al., 2025).

Beyond control limitations, several research gaps require attention. Most studies focus on acute exposure, while the long-term impacts of low-dose chronic exposure on the human nervous and metabolic systems remain under-researched. Existing studies also tend to emphasize parent OP compounds, overlooking the fact that environmental transformation products can exhibit toxicity levels equal to or higher than the parent compounds—a shortcoming in current monitoring systems (Wang et al., 2025). Another gap lies in the suboptimal implementation of biomonitoring based on specific biomarkers—such as urinary metabolites and genetic variations in specific enzymes—particularly among high-risk populations (Liem, 2021).

Risks associated with organophosphate pesticides are also linked to post-application pesticide migration, as residues can spread from the site of application to various environmental compartments—including air, soil, surface water, groundwater, and crops or food products. This process can create exposure pathways for humans and non-target organisms through direct contact, inhalation, or the consumption of contaminated materials. Consequently, pesticide management must consider the entire sequence of events—ranging from application, environmental dispersal, and exposure to the resulting impacts and the implementation of control measures. This sequence is illustrated simply in Figure 1 (Ore et al., 2023; Boonupara et al., 2023).

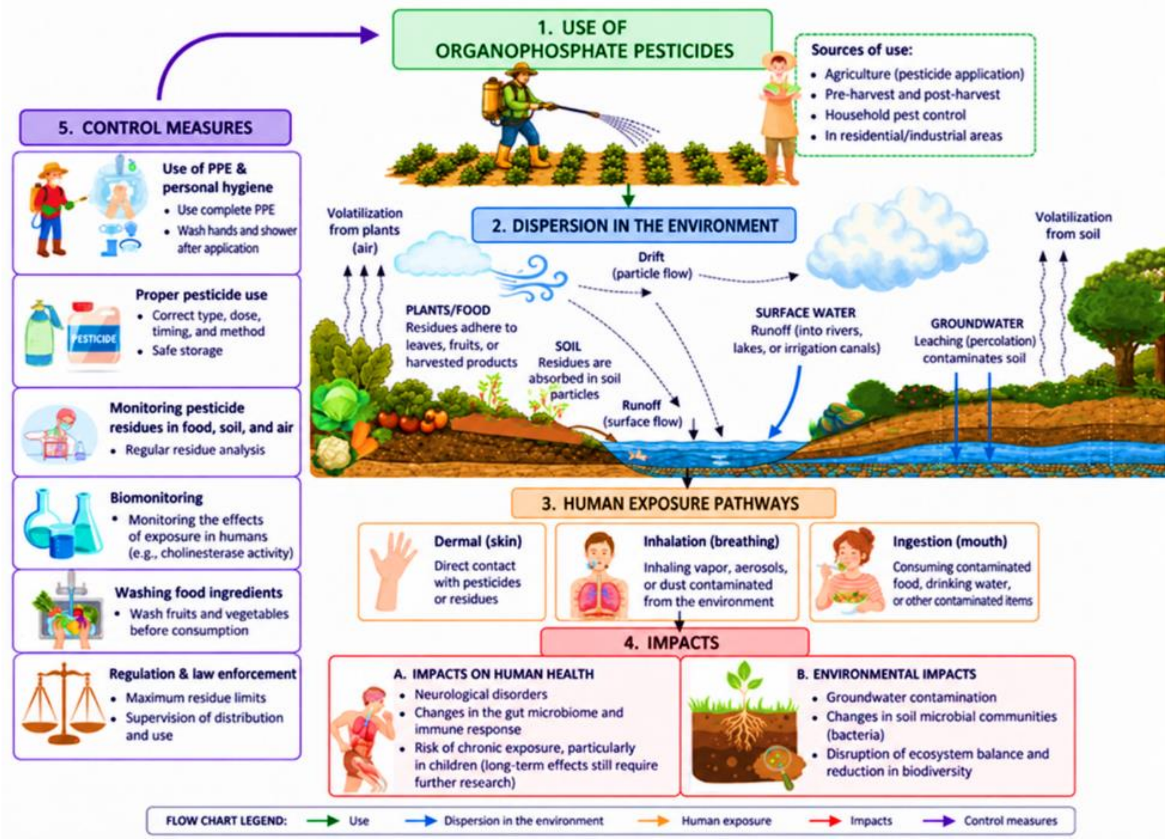

Figure 1. Flow of organophosphate pesticide usage, environmental dispersion, exposure pathways, impacts, and control measures.

Based on the sequence of organophosphate pesticide usage, dispersion, exposure pathways, and impacts shown in Figure 1, the toxicological risks and control strategies identified from the study results are summarized in Table 3.

Relevance of Pesticide Management in Lampung Province

These findings are relevant to the situation in Lampung Province, a region characterized by intensive agricultural activity. Local evidence indicates that pesticide exposure has been identified among horticultural farmers. A study involving 107 horticultural farmers in Gisting District, Tanggamus Regency, revealed that 32 farmers (29.9%) experienced a decline in cholinesterase levels. The study also demonstrated a link between topographical conditions and the reduction in cholinesterase levels (Saftarina et al., 2023).

Table 3. Toxicological Risks and Control Strategies for Organophosphate Pesticides

Toxicological Risk	Source/Route of Exposure	Reported Impacts	Control Strategies	Limitations
Decreased cholinesterase activity	Dermal, inhalation	Disruption of the cholinergic system	PPE use and cholinesterase biomonitoring	PPE compliance remains low
Food residues	Ingestion	Health risks to consumers	Washing and residue monitoring	Washing does not completely remove residues
Groundwater contamination	Leaching/ runoff	Health risks through water exposure	Residue monitoring and pesticide-use management	Residues/products may persist in the environment
Disruption of soil microbial communities	Soil contamination	Changes in bacterial community structure	Reduction of pesticide use and remediation	Long-term ecological impacts require further investigation
Chronic exposure	Inhalation, dermal, ingestion	Neurological effects and alterations in the microbiome	Biomonitoring and long-term monitoring	Longitudinal data remain limited
OP transformation products	Environmental/ food exposure	Potential toxicity equal to or greater than that of the parent compounds	Monitoring of transformation products and remediation approaches	Limited investigation at the local level
Risks associated with unsafe pesticide-use practices	Dermal/inhalation/ingestion	Increased occupational exposure	Education, hygiene, PPE, and regulation	Compliance and implementation remain suboptimal

In addition to exposure pathways affecting farmers, the presence of pesticide residues has also been reported in food products circulating in Bandar Lampung. Hartami et al. (2024) detected organophosphate pesticide residues—specifically dimethoate, diazinon, fenthion, chlorpyrifos, and profenofos—in cabbage sold in Bandar Lampung. Fenthion residues were the highest, recorded at 0.8607 mg/kg. These findings indicate that pesticide exposure in Lampung requires attention not only regarding agricultural workers but also concerning food-based exposure pathways.

These findings in Lampung align with research from other regions demonstrating that organophosphate pesticide exposure is a widespread health and environmental issue. Globally, organophosphate (OP) exposure has been linked to various toxicological effects on humans and the environment, including disruption of the cholinergic system and the presence of residues across various environmental compartments (Saad et al., 2025). Thus, the situation observed in Lampung reflects a pattern consistent with issues reported globally. However, specific evidence regarding pesticide exposure in Lampung remains limited to particular locations and populations. Therefore, enhanced monitoring of pesticide residues, biomonitoring of farmers, and multi-site research are needed to obtain a more representative picture of the risks in Lampung Province.

CONCLUSION

Organophosphate (OP) pesticides pose various toxicological risks to human health and the environment, including neurological disorders, alterations to the gut microbiome and immune responses, groundwater contamination, and disruption of ecosystem bacterial communities. However, existing control measures—such as the use of personal protective equipment (PPE) and pesticide-limiting regulations—remain suboptimal due to low compliance and a failure to account for the risks posed by pesticide transformation products in the environment. Furthermore, research gaps persist, particularly regarding the long-term monitoring of chronic exposure. Consequently, strategic measures are required in Lampung Province, including enhanced biomonitoring, education on pesticide poisoning management, and the development of more predictive and sustainable pesticide management policies.

This review has limitations, as research specifically addressing conditions in Lampung Province remains scarce, while the majority of the reviewed literature originates from regions outside Lampung. Therefore, the findings must be interpreted with caution when characterizing the overall situation in Lampung Province. Multi-site studies covering a broader geographical area are needed to obtain a more representative picture of organophosphate pesticide exposure and risks in Lampung Province.

ACKNOWLEDGMENT

The author expresses gratitude to the academic supervisor for providing guidance, support, and constructive suggestions during the preparation of this literature review. The author also extends thanks to the Master's Program in Biology, Faculty of Mathematics and Natural Sciences, University of Lampung, for the academic support that facilitated the completion of this article.

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