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Review

Operational Phase–Resolved HIRARC Framework for Occupational Pesticide Risk Characterization and Mitigation

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ABSTRACT

The use of pesticides in the agricultural sector plays a critical role in supporting food security; however, it simultaneously poses substantial risks to human health and the environment. This article aims to analyze occupational risks associated with pesticide use among farmers using the HIRARC (Hazard Identification, Risk Assessment, and Risk Control) framework. Through a structured literature review and synthesis of four case studies, the findings indicate that pesticide exposure generates physical, chemical, biological, and environmental hazards with risk levels ranging from moderate to very high. These risks are exacerbated by inadequate use of personal protective equipment (PPE), limited occupational safety training, and substandard working conditions. The reviewed evidence demonstrates chronic health impacts, including decreased cholinesterase enzyme activity, elevated heavy metal concentrations in farmers' biological samples, and high dermal exposure levels during pesticide mixing and loading activities. The analysis further identifies critical exposure nodes linked to specific work phases, underscoring the importance of activity-based risk characterization in informal agricultural settings. To address these challenges, this article proposes a field-activity-based HIRARC scenario as a practical analytical tool for systematic risk evaluation in small-scale and informal farming systems. Effective risk control requires a holistic intervention strategy encompassing safety education, improved access to certified PPE, regulatory reinforcement, and community-based as well as technology-supported approaches.

1. Introduction

The challenges arising from pesticide use cannot be overlooked (Hidayat et al., 2022; Sapta & Lestari, 2023). Inappropriate and excessive pesticide application contributes to environmental contamination, ecosystem degradation, and serious human health consequences (Komang

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Suparyana et al., 2019; Nurjannah et al., 2020; Singkoh & Katili, 2019; Theresia et al., 2023). A growing body of literature highlights the negative environmental impacts of pesticide use, particularly in developing countries where regulatory frameworks and enforcement mechanisms remain relatively weak. The socio-environmental consequences of pesticide application demonstrate that, although pesticides enhance crop productivity, they simultaneously contaminate soil and water bodies and affect non-target organisms, resulting in biodiversity loss and ecosystem disruption (de O. Gomes et al., 2020). Comparable findings have been reported in China, where ecological risk assessments in tea plantations identified moderate to high risk levels associated with heavy metals and pesticide residues in soil matrices (He et al., 2020). Similarly, evidence from Ghana indicates that current pesticide practices pose acute and chronic risks to both aquatic and terrestrial ecosystems, exacerbated by excessive and improper chemical usage (Onwona-Kwakye et al., 2020).

Health risks associated with pesticide exposure have also been extensively documented. Fucic et al. (2021) provided a comprehensive review of reproductive health risks linked to occupational and environmental pesticide exposure, emphasizing associations with infertility, abnormal sexual maturation, and adverse pregnancy outcomes. In Indonesia, pesticide poisoning among farmers has been significantly correlated with inadequate use of personal protective equipment (PPE), with reported symptoms including fatigue, dizziness, and blurred vision (Joko et al., 2020). In Kenya, Marete et al. (2021) reported that horticultural farmers frequently experienced adverse health effects due to occupational pesticide exposure, largely attributable to limited awareness and poor adherence to safety guidelines.

The agricultural sector in Indonesia plays a pivotal role in the national economy and food security (Gina et al., 2023; Setiartiti, 2021; Situmorang et al., 2020). Based on harvested area data, Indonesia's agricultural land covered 10,411,801.22 hectares in 2021, 10,452,672.00 hectares in 2022, and 10,213,705.17 hectares in 2023 (Badan Pusat Statistik & Badan Riset dan Inovasi Indonesia, 2024). Beyond its extensive land resources, food-related programs have become a central focus of Indonesia's national development agenda. Of the 77 National Strategic Projects (Proyek Strategis Nasional, PSN) planned for 2025–2029, at least five are directly related to food security: (1) the Free Nutritious Meals Program (Makan Bergizi Gratis/MBG), implemented nationally under the coordination of the National Nutrition Agency; (2) Food Estate Development in Central Kalimantan, South Sumatra, and South Papua, coordinated by the Ministry of Agriculture in collaboration with private entities; (3) Community-Based Forestry for Food Security, coordinated by the Ministry of Forestry; (4) Irrigation Services Supporting the National Food Estate, coordinated by the Ministry of Public Works; and (5) Increased Beef and Dairy Production, implemented nationally by the Ministry of Agriculture and private partners (Laksono, 2025). Farmers are central actors in achieving the success of these strategic initiatives.

Despite their crucial role in sustaining national food security, farmers face disproportionately high occupational health risks, a paradox that remains insufficiently addressed (Khan et al., 2008; Mungai et al., 2016; Q. Wang et al., 2015). Agricultural work environments are characterized by multiple hazards, including exposure to hazardous chemicals such as pesticides and fertilizers (Balkhair & Ashraf, 2016; Jiao et al., 2015; Xu et al., 2021), operation of heavy machinery without adequate training, and prolonged exposure to extreme weather conditions.

Unfortunately, many farmers—particularly in rural areas—have limited access to occupational safety information, formal safety training, and adequate healthcare services (Mohamed et al., 2023; Onyejekwe et al., 2019). This structural vulnerability increases their susceptibility to both acute and chronic health conditions, including respiratory disorders, neurological impairment, and long-term intergenerational effects (Briffa et al., 2020; Zaakour et al., 2023). Furthermore, the agricultural sector often operates outside formal employment systems that provide legal protection and social security coverage, thereby compounding occupational health inequities.

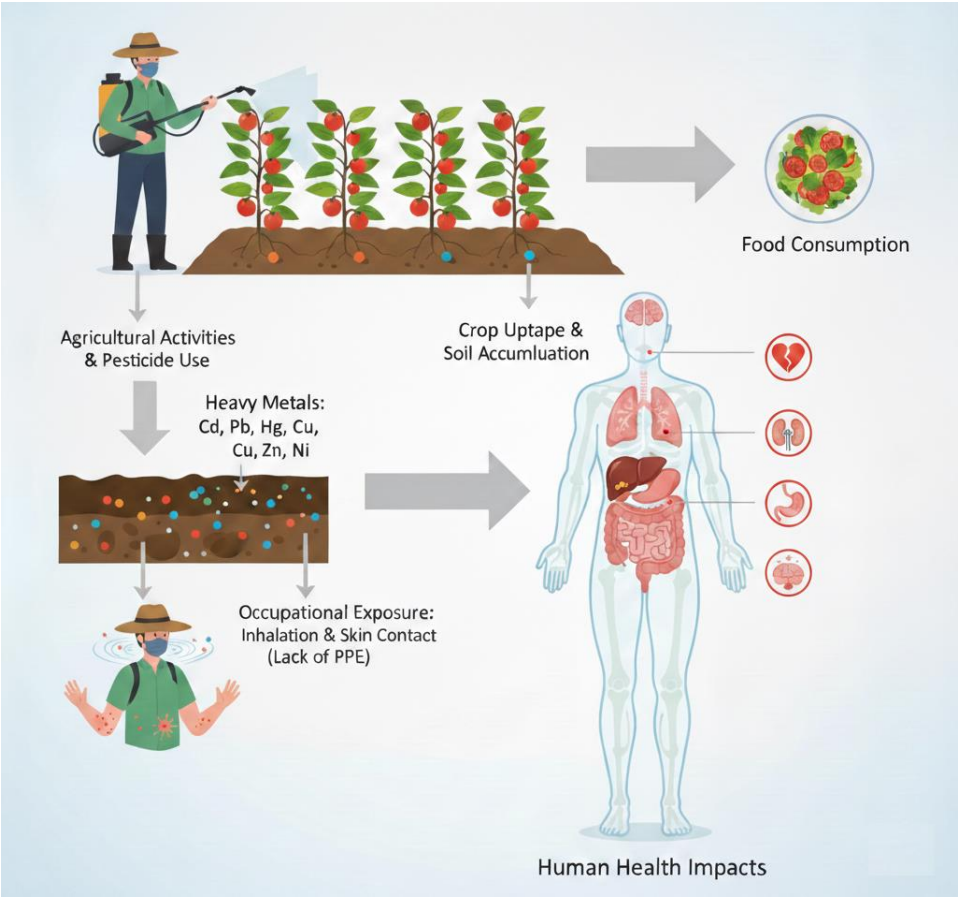


Figure 1. Illustration of the problems faced in pesticide use

Addressing farmers' health risks is essential not only within the framework of worker protection but also as part of broader efforts to promote social equity, safeguard public health, and ensure the sustainability of national food systems. A systematic approach such as HIRARC (Hazard Identification, Risk Assessment, and Risk Control) provides a structured mechanism to identify, evaluate, and control occupational risks more effectively.

2. Method

Study Design

This study adopted a literature-informed, semi-quantitative occupational risk modeling design to develop an activity-based pesticide risk framework using the HIRARC (Hazard Identification, Risk Assessment, and Risk Control) methodology. The study was not designed as a narrative review or systematic review; rather, it aimed to construct a structured occupational risk model grounded in secondary empirical evidence. The primary objective was to generate an operational HIRARC matrix representing the complete pesticide application lifecycle in agricultural settings.

Evidence Identification and Selection

Scientific evidence was identified through targeted searches of international databases, including Scopus, Web of Science, and PubMed. The search strategy combined keywords related to occupational pesticide exposure, dermal contamination, agricultural risk assessment, toxicological outcomes, exposure modeling, and pesticide risk control measures.

The selection process was purposive and concept-driven. Studies were included if they reported quantified exposure data, described task-specific exposure determinants, examined acute or chronic health outcomes, or evaluated the effectiveness of mitigation strategies such as personal protective equipment (PPE). Peer-reviewed empirical studies were prioritized, particularly those employing validated exposure assessment methods (e.g., whole-body dosimetry, biomonitoring, or structured exposure modeling). Opinion-based publications and non-scientific sources were excluded.

Activity-Based Operational Decomposition

To enable structured modeling, the pesticide handling process was analytically decomposed into sequential operational phases based on documented agricultural workflows. These phases included planning and pesticide selection, storage and warehousing, mixing and dilution of concentrated formulations, equipment filling, field spraying, post-application cleaning, waste disposal, transportation, and PPE maintenance.

Each operational phase was further disaggregated into task-level sub-activities to facilitate node-specific hazard identification. This activity-based decomposition allowed exposure characterization to be directly linked to operational determinants and behavioral practices rather than broad occupational categories.

Hazard Identification

Hazard identification was conducted through cross-disciplinary synthesis of toxicological, occupational health, and environmental research. Identified hazards were categorized into chemical, physical, environmental, and secondary contamination domains.

Chemical hazards included dermal absorption, inhalation exposure, accidental ingestion, and direct handling of concentrated pesticide formulations. Physical hazards encompassed mechanical injury risks and environmental stressors such as heat exposure and adverse weather conditions. Environmental hazards involved spray drift, runoff, and contamination of soil and water bodies.

Secondary contamination risks included pesticide residues on equipment, improper container handling, and contaminated PPE.

Particular emphasis was placed on dermal exposure during mixing and spraying phases, as empirical evidence consistently identifies dermal absorption as the dominant occupational exposure pathway in agricultural pesticide application.

Semi-Quantitative Risk Assessment

Risk characterization was performed using a semi-quantitative matrix integrating likelihood and severity parameters. Likelihood was assessed using an ordinal scale ranging from one to five, reflecting the probability of exposure occurrence based on frequency of task performance, intensity of chemical handling, formulation concentration, and environmental dispersion conditions.

Severity was assessed on a five-point ordinal scale reflecting the magnitude of potential health or ecological consequences. Severity considerations incorporated acute toxicity classification, documented chronic outcomes such as neurotoxicity or carcinogenic potential, and environmental persistence of active compounds.

The overall risk score was calculated as the product of likelihood and severity, generating a range from one to twenty-five. Risk levels were classified as low (1–5), moderate (6–10), high (11–15), and very high (16–25). Scoring decisions were evidence-informed and consistently applied across all operational phases to maintain internal coherence.

Risk Control Modeling

Risk control strategies were structured according to the hierarchy of controls, progressing from elimination and substitution to engineering controls, administrative measures, and personal protective equipment.

For activities classified as high or very high risk, layered control strategies were proposed. These included dedicated ventilated storage facilities, phase-specific standard operating procedures, meteorological monitoring prior to spraying, designated washing and waste containment infrastructure, and structured PPE inspection and replacement protocols.

Control recommendations were formulated with consideration of feasibility in small-scale and semi-formal agricultural systems, where infrastructure and regulatory oversight may be limited.

Methodological Rigor

Analytical rigor was enhanced through triangulation of exposure data across toxicological, epidemiological, and environmental studies. Preference was given to research employing validated exposure assessment techniques or quantitative modeling approaches. Risk scoring criteria were predefined and systematically applied to minimize subjectivity.

Although primary field data were not collected, internal validity was strengthened by grounding each modeled hazard and risk determinant in documented empirical findings rather than hypothetical assumptions.

Model Output

The methodological process produced a comprehensive activity-based HIRARC matrix covering the pesticide application lifecycle, identification of dominant exposure pathways and critical risk nodes, prioritization of occupational risk levels, and a structured control framework aligned with hierarchical risk management principles.

3. Results & Discussion

Hazard Identification in the Agricultural Sector

Table 1. Conceptual Framework for Hazard Identification in the Agricultural Sector

Hazard Domain	Specific Hazard Source	Exposure Determinant	Potential Health Impact	Environmental Impact	Critical Phase
Chemical	Concentrated pesticide formulation	Direct manual handling	Acute poisoning, neurotoxicity	Residual contamination	Mixing & dilution
Chemical	Spray droplets & drift	Wind speed, nozzle type	Respiratory irritation, systemic absorption	Off-target contamination	Field spraying
Chemical	Residue on equipment	Inadequate cleaning	Chronic dermal exposure	Secondary contamination	Post-application
Physical	Agricultural machinery	Lack of training	Injury, trauma	–	Field operation
Physical	Heat & UV exposure	Prolonged outdoor work	Heat stress, dehydration	–	Spraying phase
Environmental	Runoff	Rainfall & terrain slope	Indirect exposure	Soil & water pollution	Post-application
Environmental	Improper waste disposal	Lack of containment system	Community exposure	Long-term ecosystem damage	Waste handling
Secondary	Contaminated PPE	Improper maintenance	Repeated low-dose exposure	–	PPE management

Hazard identification in agriculture is a complex process involving the recognition of diverse occupational and environmental risks inherent to agricultural work. Extensive evidence indicates that agriculture is among the most hazardous industries due to the combined presence of physical, chemical, biological, and environmental risk factors, making systematic hazard identification and risk assessment indispensable (Jamshed et al., 2024; Lundqvist & Svennefelt, 2014).

Table 2. Comparative Matrix of Dermal Pesticide Exposure and PPE Effectiveness

Analytical Variable	Chlorothalonil – Mixing/Loading	Chlorothalonil – Application	Flubendiamide – Mixing/Loading	Flubendiamide – Application	Drone-Based Application (Mixer/Loader)
Active Agent	Chlorothalonil	Chlorothalonil	Flubendiamide	Flubendiamide	Multiple formulations
Measurement Method	Whole-Body Dosimetry (WBD)	WBD	WBD	WBD	Dermal exposure distribution modeling
Dominant Body Part	Hands (50%)	Pelvis (32%)	Hands (82%)	Thighs (40%)	Hands (52–94%)
Exposure Pattern	Upper extremities dominant	Shift to lower body	Highly concentrated on hands	Lower body dominant	Strongly concentrated on hands
Lower Body Exposure	Low–moderate	High	Low	High	Low baseline
Inhalation Contribution	0.002%	0.002%	~0.1%	~0.1%	Minimal
Primary Risk Determinant	Direct handling of concentrated formulation	Contact with treated vegetation and spray drift	Intensive manual contact	Vegetation contact	Direct formulation handling
PPE Effectiveness	Not specifically quantified	Not specifically quantified	Not specifically quantified	Not specifically quantified	83–98% reduction
Preventive Implication	Hand protection is priority	Lower body protection needed	Hand protection essential	Lower body + hand protection	Chemical-resistant gloves + C1 protective clothing mandatory

Main sources: Lee et al. 2024; Felkers et al. 2024

Physical hazards represent a major concern in this sector. Agricultural workers are routinely exposed to mechanical injuries associated with heavy equipment, including tractors and all-terrain vehicles, as well as trauma resulting from falls, cuts, and entanglement in machinery (Arana et al., 2010; Lagerstrom et al., 2015). Repetitive movements embedded in tasks such as lifting, bending, and manual harvesting further predispose workers to musculoskeletal disorders, a phenomenon intensified by the physically demanding nature of agricultural labor (Ramos et al., 2016). Moreover, age-related physiological changes among an aging agricultural workforce amplify injury risks, necessitating tailored hazard identification protocols for vulnerable subgroups (McLaughlin et al., 2009; McLaughlin & Sprufera, 2011).

Chemical hazards constitute another critical category. Farmworkers frequently handle pesticides, herbicides, fertilizers, and other agrochemicals that may cause acute and chronic health

effects, including respiratory disorders, dermatological cancers, and systemic diseases (L. Wang et al., 2022). Repeated low-dose and cumulative exposures further increase the likelihood of long-term health complications, underscoring the need for robust chemical hazard management strategies (Pilarczyk & Ulewicz, 2023). Biological hazards are closely intertwined with chemical risks, as agricultural environments often host toxic plants and zoonotic agents. This co-existence elevates exposure to allergens and pathogens, thereby complicating the overall risk landscape (Jamshed et al., 2024).

A comparative analysis of dermal pesticide exposure confirms that this route is the dominant pathway, far more significant than inhalation, which contributes less than 0.1% to total exposure. The exposure pattern is highly dependent on the specific work phase. During the mixing and loading phase, the highest concentration of exposure is concentrated on the hands. Data indicates that for the pesticide chlorothalonil, hand exposure accounts for 50% of total dermal contamination, while for flubendiamide, this figure is even higher at 82%. This confirms that the stage involving the handling of concentrated formulations is a critical exposure point, determined by the intensity of manual contact. Conversely, during the field application phase, the exposure pattern shifts to the lower body, including the pelvis, thighs, and shins. This shift is caused by a change in exposure determinants, moving from direct chemical handling to contact with treated vegetation and exposure from short-range spray drift. Interestingly, findings from drone-based spraying operations reinforce this conclusion. For drone operators involved in mixing and loading, hand exposure remains dominant, accounting for 52% to 94% of total dermal exposure in the absence of personal protective equipment (PPE). This proves that technological advancements in application methods do not inherently eliminate exposure risk at the formulation handling stage. From a risk management perspective, the use of PPE proves to be highly effective. Chemical-resistant gloves can reduce hand exposure by 97–98%, and certified protective clothing significantly reduces contamination on other parts of the body.

Environmental hazards in agriculture are multifactorial. Workers frequently perform tasks under extreme weather conditions, leading to heat stress, dehydration, and debilitating sunburn, particularly when prolonged outdoor exposure is involved (Jackson & Rosenberg, 2010). Empirical evidence demonstrates that agricultural workers commonly experience heat-related illnesses, and inadequate sun-protective practices further heighten the risk of severe dermatological damage (Backes et al., 2017).

Workforce diversity further diversifies the risk profile. Young and inexperienced workers—often family laborers or seasonal employees—are at elevated risk due to insufficient safety training and limited experience in hazard recognition (McCallum et al., 2013; Ramaswamy & Mosher, 2015). Additionally, evidence suggests that women in agriculture face distinct challenges, including gender-specific physical strain and a higher prevalence of musculoskeletal problems and fatigue (S & C, 2021). Child labor in certain agricultural subsectors introduces further risks, as children are particularly vulnerable to physical and chemical hazards due to lower body mass and developing immune systems (M. Kassab et al., 2024).

To address these hazards comprehensively, several methodological approaches for hazard identification have been developed and implemented within the sector. Risk assessment tools such

as Hazard Identification Risk Assessment (HIRA) and Failure Mode and Effects Analysis (FMEA) are widely recommended due to their replicability and systematic capacity to rapidly identify and mitigate risks associated with both conventional technologies and emerging innovations, including autonomous agricultural machinery (Aby et al., 2024). The implementation of comprehensive safety programs that integrate practical risk evaluation methods with safety education, technological improvements, and regulatory frameworks has been shown to reduce incident rates and enhance operational performance in agricultural organizations (Guthrie et al., 2009; Pilarczyk & Ulewicz, 2023). Hazard identification in agriculture must encompass a broad spectrum of risks, including physical, chemical, biological, and environmental hazards. Systematic identification through structured risk assessment tools, combined with targeted safety programs and regulatory interventions, represents the most effective strategy to mitigate these risks. Such an integrative approach is crucial to protecting a diverse workforce—from aging farmers to young and inexperienced laborers—while ensuring productivity and sustainable employment within the agricultural sector (Aby et al., 2024; Backes et al., 2017; Jamshed et al., 2024; Pilarczyk & Ulewicz, 2023; Ramos et al., 2016; Weyers, 2009).

Risk Assessment of Pesticide Use

Table 3. Analytical Framework for Risk Assessment of Pesticide Use

Component	Analytical Variable	Operational Definition	Measurement/Scoring Basis	Output
Likelihood (L)	Frequency of task	How often activity is performed	Ordinal scale (1–5)	Probability score
Likelihood (L)	Exposure intensity	Degree of chemical contact	Direct vs indirect handling	Adjusted likelihood
Severity (S)	Acute toxicity	Immediate adverse effect	Toxicity classification	Severity score
Severity (S)	Chronic impact	Long-term health outcome	Epidemiological evidence	Severity score
Severity (S)	Ecological persistence	Environmental half-life	Environmental risk literature	Severity score
Risk Score (R)	Risk magnitude	L × S	Semi-quantitative matrix	Risk category (Low–Very High)
Exposure Route Analysis	Dermal vs inhalation dominance	Primary pathway contribution	Empirical exposure distribution	Critical exposure node identification
Risk Ranking	Phase prioritization	Relative risk magnitude	Comparative scoring	Intervention priority level

Risk assessment related to pesticide exposure among farmers constitutes a critical component of agricultural safety and public health protection. The hazards posed by pesticides may result in both acute and chronic health effects, making it essential for farmers to understand not only the risks associated with handling these chemicals but also the broader environmental and social implications arising from their use. A growing body of literature underscores the complexity of these hazards and the necessity of comprehensive risk assessment approaches.

Pesticide exposure has been shown to increase vulnerability to a range of adverse health outcomes, particularly in relation to organophosphate pesticides. These compounds are widely used due to their effectiveness in pest control, yet they are well recognized for their toxicity. Farmers are commonly exposed through multiple routes, including dermal contact, inhalation, and accidental ingestion during handling and application. Such multi-route exposure significantly elevates the risk of acute poisoning incidents as well as long-term complications, including neurotoxicity and carcinogenic effects (Botinggo et al., 2021; C. A. Damalas & Eleftherohorinos, 2011). The absence of adequate training and safety protocols further exacerbates these risks, as many farmers may not fully comprehend the health implications of exposure or the appropriate preventive measures required (Haruna et al., 2024; Jallow et al., 2017).

Empirical evidence has also identified substantial gaps in knowledge and practice related to pesticide use. Many farmers rely heavily on informal information sources, which may lead to misinformation regarding safe handling and application practices. These knowledge deficits are particularly pronounced in rural communities, where educational resources and access to structured safety training are often limited (Budiyono et al., 2021; Jallow et al., 2017). For instance, documented cases reveal that some farmers reuse pesticide containers for food storage, inadvertently exposing themselves and their families to hazardous residues (Gesesew et al., 2016).

Demographic factors, including age and formal education level, significantly influence farmers' understanding of pesticide-related risks. Younger and less-educated farmers are more likely to engage in unsafe pesticide handling practices, thereby increasing the likelihood of adverse health outcomes (Li, 2017; Sulaiman et al., 2019). Furthermore, children residing in agricultural areas may be unintentionally exposed to pesticides, either through direct involvement in farming activities or via environmental contamination pathways (Ibrahim & Sillehu, 2023).

Quantifying health risks associated with pesticide exposure is fundamental for evidence-based policymaking and effective agricultural management. Risk assessment methodologies integrating hazard identification, exposure assessment, and dose–response evaluation have been developed to estimate potential health impacts among farmers. Metrics such as disability-adjusted life years (DALYs) are increasingly employed to measure the burden of morbidity and mortality attributable to pesticide exposure, thereby supporting more rational allocation of resources for agricultural health interventions (Atreya et al., 2012; Li, 2017).

Emerging research has also emphasized biomonitoring approaches and the development of reliable exposure assessment tools, including structured questionnaires and exposure matrices. These methodologies enhance understanding of how pesticide exposure influences both acute and chronic health outcomes among agricultural workers (Moreira et al., 2025; Okonya & Kroschel, 2015). Beyond facilitating direct risk estimation, such tools contribute to the development of targeted educational materials aimed at improving farmers' knowledge and promoting safer pesticide practices (C. Damalas & Koutroubas, 2016; Sulaiman et al., 2019).

Risk Control of Pesticide Use

Table 4. Hierarchical Framework for Risk Control of Pesticide Use

Control Level	Strategic Approach	Operational Application	Expected Risk Reduction Mechanism	Implementation Priority
Elimination	Avoid highly hazardous pesticide	Replace with non-chemical method	Remove hazard entirely	Highest
Substitution	Use lower-toxicity formulation	Biopesticide adoption	Reduce intrinsic hazard	High
Engineering Control	Closed mixing system	Ventilated storage, containment	Reduce exposure intensity	High
Engineering Control	Waste filtration	Liquid containment system	Prevent environmental dispersion	High
Administrative Control	Standard Operating Procedures	Phase-specific spraying SOP	Reduce behavioral risk	Moderate–High
Administrative Control	Training & certification	Label interpretation, dosage control	Increase safety compliance	Moderate–High
Environmental Monitoring	Meteorological threshold check	Wind-speed based spraying	Reduce spray drift	Moderate
PPE	Chemical-resistant gloves	Mixing phase protection	Reduce dermal exposure	Essential
PPE	Protective clothing & respirator	Spraying phase	Reduce systemic absorption	Essential
PPE Maintenance	Periodic inspection & replacement	PPE management system	Prevent protection failure	Essential

Effective risk control strategies for pesticide use must integrate educational, technical, regulatory, and socio-economic interventions to ensure sustainable reduction of occupational and environmental hazards. A primary strategy involves strengthening farmers' knowledge regarding pesticide safety and proper application practices. Training programs have been consistently shown to significantly improve farmers' understanding of safe handling procedures and compliance with safety measures. Empirical studies indicate that farmers who have participated in formal training demonstrate greater awareness of pesticide hazards and adopt safer practices, resulting in reduced exposure levels (Bandanaa et al., 2024; Mubushar et al., 2019). Importantly, access to training also increases the likelihood of adopting Integrated Pest Management (IPM) approaches, which emphasize biological control agents and non-chemical methods, thereby reducing reliance on synthetic pesticides (Lekei et al., 2014).

Provision and proper use of personal protective equipment (PPE) represent another critical component of risk control. Adequate access to and consistent use of protective gloves, masks, and protective clothing significantly decrease the probability of acute and chronic health effects associated with pesticide exposure (Gesesew et al., 2016). Nevertheless, existing evidence suggests

that many farmers remain insufficiently aware of the protective value of PPE, highlighting the need for comprehensive education on its essential role in minimizing occupational exposure during pesticide handling and application (Jallow et al., 2017; Rosanti et al., 2021).

Regulatory frameworks also play a central role in mitigating pesticide-related risks. Governments can implement and enforce stringent regulations that restrict the use of highly hazardous pesticides, establish monitoring systems for pesticide residues, and promote adherence to good agricultural practices (Gesesew et al., 2016). Effective monitoring mechanisms not only safeguard farmers and consumers but also encourage practices that minimize environmental contamination from pesticide runoff and drift (Rahaman et al., 2018). Furthermore, regulatory policies should actively support the development, commercialization, and adoption of biopesticides and other environmentally friendly alternatives to conventional chemical pesticides (Oshingbade et al., 2025).

Socio-economic factors significantly influence the effectiveness of pesticide risk control. Higher income levels enable farmers to invest in safer pest management technologies and improved safety practices, thereby enhancing compliance with occupational health standards. Economic empowerment facilitates the transition toward sustainable agricultural practices that reduce dependence on chemical pesticides (Hyde-Cooper et al., 2024). In this context, initiatives aimed at improving farmers' economic conditions—such as cooperative farming models or improved access to financial support—can incentivize safer pesticide use by shifting decision-making priorities from short-term economic gains toward long-term health and sustainability outcomes.

Table 5. HIRARC table for pesticide application scenarios

No	Activity	Sub-Activity	Potential Hazard	Risk	L	S	R	Existing Control	Recommended Control
1	Pesticide Application Planning	Pesticide Type Selection	Incorrect pesticide selection, inappropriate dosage	Pest resistance, ecological impact, poisoning	3	4	12 (High)	Reference from agricultural officers	Training on suitable pesticides, clear labeling and dosage guidelines
2	Pesticide Storage	Reading Labels and SDS	Misinterpretation of labels, failure to understand hazards	Unsafe usage, health risks	3	3	9 (Medium)	Labels available in local language	Training on reading labels and Safety Data Sheets (SDS)
3	Pesticide Preparation	Storage in Warehouse	Leakage, spills, poor ventilation	Worker poisoning, environmental pollution	3	4	12 (High)	Sealed containers, storage in warehouse	Dedicated storage room with adequate ventilation, use of PPE when handling
		Container Arrangement	Damaged or leaking containers	Accidental exposure to chemicals	3	3	9 (Medium)	Storage on shelves	SOP for checking container integrity before storage

No	Activity	Sub-Activity	Potential Hazard	Risk	L	S	R	Existing Control	Recommended Control
		Mixing and Dilution	Splashes to skin and eyes, inhalation of toxic fumes	Acute poisoning, allergic reactions	4	4	16 (High)	Use of gloves and masks	Full PPE (goggles, chemical-resistant apron), safe mixing SOP, adequate ventilation
		Filling Spraying Equipment	Spills, leakage	Direct exposure to workers	3	3	9 (Medium)	Measuring tools available	Safe filling SOP, worker training
4	Pesticide Application in Field	Spraying	Direct exposure through inhalation and skin contact, wind drift to residential areas	Respiratory issues, neurotoxic effects, environmental contamination	4	5	20 (Very High)	Use of masks and protective clothing	Full PPE, application during low wind conditions (morning/evening), warning signs
		Extreme Weather (Wind, Rain)	Uncontrolled dispersal of pesticides	Ineffective spraying, environmental pollution	4	4	16 (High)	Avoid spraying during high wind	Weather monitoring before spraying, SOP for optimal spraying times
5	Post-Application Handling	Cleaning Spraying Equipment	Pesticide residues on equipment	Skin exposure and inhalation	3	3	9 (Medium)	Cleaning conducted in open areas	Safe washing SOP, use of gloves and masks, designated washing area
		Storage of Spraying Equipment	Contamination of other tools and workers	Exposure to chemical residues	3	3	9 (Medium)	Stored in warehouse after washing	Dedicated storage room, regular equipment inspection
6	Pesticide Waste Disposal	Disposal of Empty Containers	Containers not cleaned, littered in the environment	Soil and water contamination	3	4	12 (High)	Disposed of in designated area	Waste disposal SOP aligned with regulations, secure waste storage area
		Liquid Waste from Equipment Washing	Contamination of soil and water	Long-term impact on ecosystems	3	4	12 (High)	Disposal in open land	Waste filtration system, appropriate disposal procedures
7	Pesticide Transportation	Transport to Spraying Location	Spills during transit, container leakage	Worker poisoning, environmental contamination	2	4	8 (Medium)	Use of sealed containers	Transport in enclosed vehicles, secure packaging, training on chemical transport

No	Activity	Sub-Activity	Potential Hazard	Risk	L	S	R	Existing Control	Recommended Control
8	PPE Storage and Maintenance	Storage of Gloves and Masks	Contamination from pesticide residues	Secondary exposure, skin irritation	3	3	9 (Medium)	PPE left as is after use	SOP for PPE cleaning after use, secure PPE storage area
		PPE Maintenance and Replacement	Damaged masks or gloves	Ineffective protection, direct exposure	3	4	12 (High)	Use of standard PPE	Periodic PPE replacement, pre-use inspection

This document presents a comprehensive Job Safety Analysis (JSA) for the entire process of pesticide application, from initial planning to final disposal. The analysis systematically breaks down the main activity into sub-activities, identifies potential hazards and their associated risks, evaluates the risk level, and proposes control measures. The primary goal is to protect worker health, prevent environmental contamination, and ensure the effectiveness of the pest control program.

The process begins with planning, where the incorrect selection of pesticide type or dosage is identified as a high-risk activity (Risk Score 12). This mistake can lead to pest resistance, ecological damage, and potential poisoning. While workers currently rely on references from agricultural officers, the analysis recommends formal training to ensure a deeper understanding of labels and dosage guidelines.

Following planning, the Storage of Pesticides presents significant dangers. Simply reading and interpreting labels and Safety Data Sheets (SDS) carries a medium risk (9) if misunderstood, leading to unsafe use. A more critical risk is improper storage within the warehouse itself. Potential leaks, spills, and poor ventilation pose a high risk (12) of worker poisoning and environmental pollution. Current controls like closed containers are a good start, but the recommendations call for dedicated storage with better ventilation and mandatory PPE. Even the seemingly simple task of arranging containers carries a medium risk (9) if containers are damaged, highlighting the need for a Standard Operating Procedure (SOP) for regular inspection.

The most hazardous phase is the Application of Pesticides in the Field. The sub-activity of mixing and diluting concentrated chemicals is rated as a high risk (16) due to the potential for splashes and inhalation of toxic vapors. While gloves and masks are currently used, the analysis recommends upgrading to full PPE, including goggles and chemical-resistant aprons, along with a safe mixing SOP. The act of spraying itself is identified as the single highest risk in the entire process, with a "Very High" score of 20. Workers face direct exposure through inhalation and skin contact, and drift can contaminate nearby settlements, causing respiratory issues and neurotoxic effects. Current PPE is deemed insufficient; the recommendations emphasize the use of complete PPE and strict adherence to spraying during optimal weather conditions (low wind, early morning/late afternoon) with clear warning signs. This is complemented by the need to monitor for extreme weather, as spraying in wind or rain leads to uncontrolled spread and ineffectiveness, a high risk (16) that requires pre-spray weather checks.

After application, the Post-Application Handling phase ensures that risks do not persist beyond the spraying itself. Cleaning equipment carries a medium risk (9) of exposure to residues, requiring a shift from open-air cleaning to a dedicated wash area with proper SOPs and PPE. Similarly, storing contaminated equipment poses a medium risk (9) of cross-contamination, which can be mitigated with a dedicated storage room and regular inspections.

The management of Pesticide Waste is another area of high concern. Improper disposal of empty containers (Risk 12) and liquid waste from equipment washing (Risk 12) can lead to significant soil and water contamination, with long-term ecological impacts. Current practices of disposing of waste in designated areas or open land are inadequate. The recommendations push for strict adherence to regulations, including safe waste storage and the implementation of filtration systems for liquid waste.

Supporting activities throughout the process also carry inherent risks. Transportation of pesticides to the site presents a medium risk (8) of spills and leaks, which can be controlled through the use of closed vehicles and secure packaging, coupled with specific training for handlers.

Finally, the Storage and Maintenance of Personal Protective Equipment (PPE) is critical for ensuring the long-term safety of workers. Storing contaminated PPE (Risk 9) can lead to secondary exposure, necessitating a clear SOP for cleaning after each use. Furthermore, the failure to maintain and replace damaged PPE, such as torn gloves or masks, renders the protection ineffective and poses a high risk (12) of direct exposure. Regular inspections and scheduled replacements are essential to mitigate this.

4. Conclusion

Pesticide use in the agricultural sector, while crucial for productivity and food security, has significant impacts on farmer health and the environment. Findings from various studies indicate that pesticide exposure—whether through skin, inhalation, or accidental exposure—is closely linked to acute and chronic health risks, such as poisoning, nervous system disorders, and heavy metal contamination. Through the HIRARC approach, these risks can be systematically identified, assessed, and controlled. This approach can be used to assess every stage of agricultural activity, from storage to application and disposal of pesticides.

However, implementing risk control remains challenging, particularly in the context of smallholder farmers and the informal sector, who lack access to training, information, and personal protective equipment. Therefore, control strategies must be holistic, encompassing farmer education, strict regulations, promotion of environmentally friendly pesticide alternatives, and socio-economic support that encourages safe and sustainable agricultural practices. Integrating the HIRARC approach into agricultural policies and field extension programs can be a strategic step in protecting farmer health and maintaining the sustainability of the national agricultural ecosystem.

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