



## EXPLANATORY MULTIVARIABLE MODEL FOR SPIROMETRIC ABNORMALITIES IN WETLAND FARMERS: CHRONIC ORGANOPHOSPHATE EXPOSURE AS A PRIMARY RISK FACTOR

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**Abstract:** This study aims to identify environmental factors within the wetland ecosystem in Pemulutan District, analyze organophosphate pesticide exposure among rice farmers, and evaluate the association between pesticide exposure and worker characteristics with pulmonary function abnormalities and respiratory symptoms. A case-control study was employed, involving 106 respondents—53 rice farmers with abnormal pulmonary function and 53 with normal pulmonary function. Data were collected using a standardized questionnaire and pulmonary function tests conducted with a digitally calibrated spirometer. The findings revealed that the average annual rainfall in the study area was 220.8 mm, with a mean air temperature of 26.5°C and an average relative humidity of 84.5% (2014–2024). Bivariate analysis indicated that several variables were significantly associated with pulmonary function abnormalities, including: exposure duration >4 hours/day ( $p=0.001$ ; Odds Ratio (OR)=6.272; 95% Confidence Interval (CI): 2.156–18.251), exposure frequency  $\geq 3$  times/week ( $p=0.004$ ; OR=4.882; 95% CI: 1.677–14.210), respiratory symptoms ( $p=0.032$ ; OR=2.946; 95% CI: 1.096–7.923), work duration  $\geq 5$  years ( $p=0.046$ ; OR=2.021; 95% CI: 1.025–15.764), and age  $\geq 35$  years ( $p=0.026$ ; OR=0.113; 95% CI: 0.017–0.773). The final logistic regression model identified exposure duration >4 hours/day as the primary predictor of pulmonary function abnormalities ( $p=0.001$ ; OR=6.272; 95% CI: 2.156–18.251), after adjusting for age, exposure frequency, respiratory symptoms, and work duration. These results underscore that cumulative high-level exposure to organophosphate pesticides significantly increases the risk of impaired pulmonary function among rice farmers in wetland areas. This study is expected to serve as a foundation for occupational health risk management strategies for rice farmers working in wetland ecosystems.

**Keywords:** Explanatory Model; Occupational Exposure; Organophosphate Pesticides; Spirometric Abnormalities; Wetland Rice Farmer.



## **INTRODUCTION:**

The escalation of agricultural productivity in developing countries, particularly Indonesia, has necessitated an intensive application of organophosphate pesticides [1], [2]. This intensification places rice farmers at the frontline of chronic occupational exposure, which is hypothesized to correlate with measurable clinical respiratory impairments, although large-scale objective data in specific ecosystems remain limited [3]. The toxicity of organophosphates stems from the irreversible inhibition of acetylcholinesterase (AChE), leading to an overaccumulation of acetylcholine at the muscarinic receptors of the bronchial smooth muscle [4]. Physiologically, this mechanism triggers persistent bronchoconstriction and excessive mucus secretion, which clinically manifests as restrictive or obstructive patterns in spirometric parameters, such as Forced Vital Capacity (FVC) and Forced Expiratory Volume in one second (FEV<sub>1</sub>) [5].

Farmers in Pemulutan District operate within a 'lebak' swamp (wetland) ecosystem, characterized by high average relative humidity (84.5%) and moderate temperatures (26.54°C). These microclimatic conditions are critical as high humidity may prolong the persistence of pesticide residues in the air and on crop surfaces, potentially enhancing inhalation exposure. However, while subjective respiratory complaints have been reported in this region [6], there is a lack of objective evidence regarding how these environmental factors interact with chronic exposure to affect pulmonary function. Several studies have indicated associations between pesticide exposure and respiratory symptoms or pulmonary disease diagnoses; however, the consistency of these findings, particularly among adult farmers in developing countries and in relation to specific occupational environments, remains debated [7], [8]. A study by Maksuk (2018) in the same region also reported predominant organophosphate use and subjective respiratory complaints, yet lacked objective functional assessment [6].

Spirometric abnormalities, as objective indicators of pulmonary function, can provide robust evidence of the respiratory health impacts of organophosphate pesticide exposure [9]. This study aims to evaluate the associations between chronic organophosphate exposure and spirometric abnormalities among wetland rice farmers and to construct an explanatory multivariable model to identify primary risk predictors. By integrating occupational practices and microclimatic context, this research fills the knowledge gap between subjective respiratory symptoms and objective lung function impairment in informal agricultural sectors.

## **Research Question**

The primary objective of this study is to construct a multivariable explanatory model to identify key occupational risk factors specifically duration and frequency of organophosphate exposure associated with spirometric abnormalities among wetland rice farmers. The research question asks: To what extent do cumulative exposure patterns predict impaired pulmonary function when adjusted for environmental and individual characteristics in a lebak swamp ecosystem?



## METHODOLOGY:

### Study Design

This study employed a case-control design to investigate the relationship between organophosphate pesticide exposure and pulmonary function among rice farmers in the wetland areas of Pemulutan District, South Sumatra. A total of 106 participants were selected using Lemeshow (1997) formula for hypothesis testing of two proportions, comprising 53 cases with abnormal pulmonary function and 53 controls with normal function.

$$n = \frac{[Z_1 - \alpha/2 \sqrt{2P(1-P)} + Z_1 - \beta \sqrt{P_1(1-P_1) + P_2(1-P_2)}]^2}{(P_1 - P_2)^2}$$

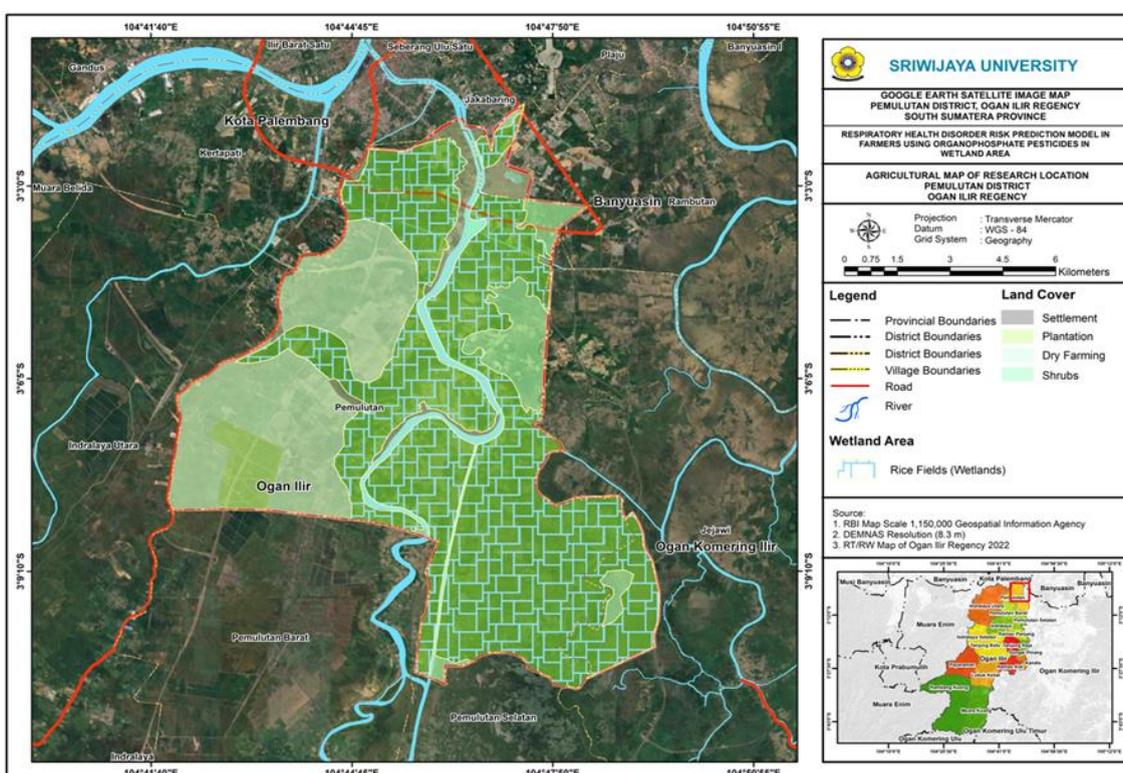
$$n = \frac{[1,96 \sqrt{2 \times 0,405(1 - 0,405)} + 0,84 \sqrt{0,538(1 - 0,538) + 0,272(1 - 0,272)}]^2}{(0,538 - 0,272)^2}$$

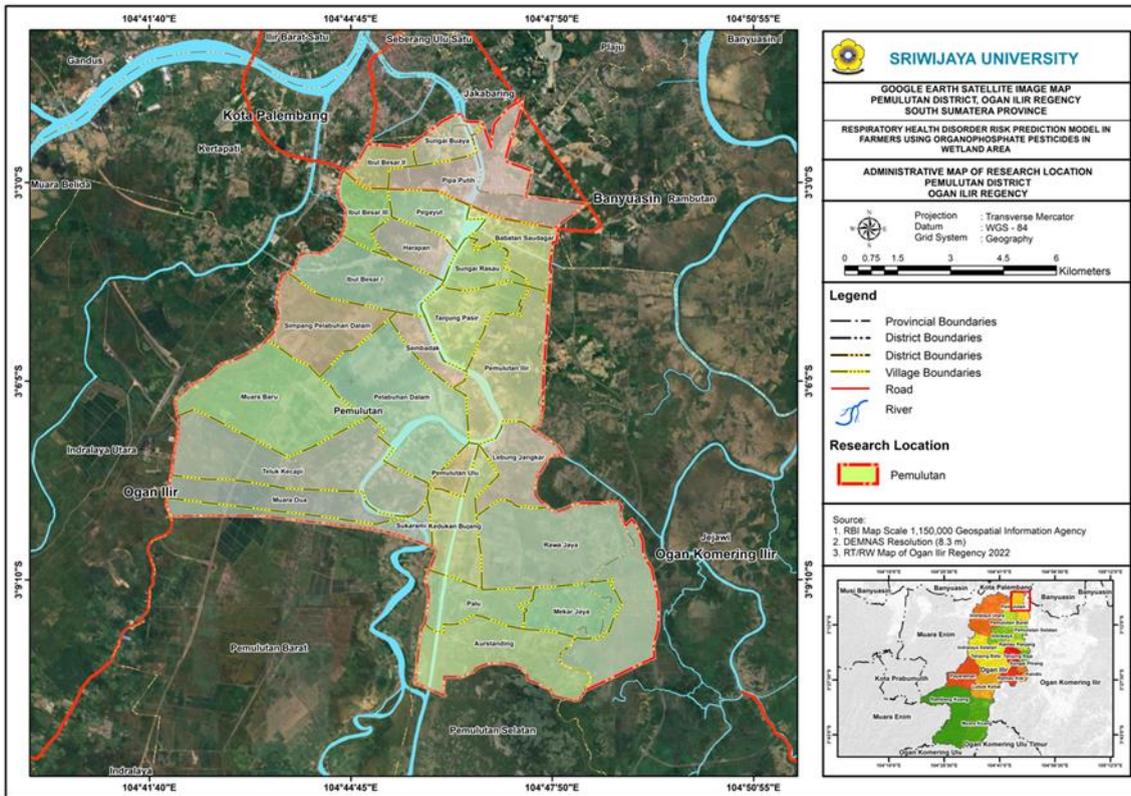
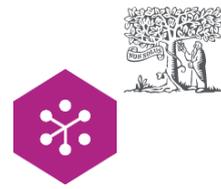
$$n = 53 \quad 2n = 106$$

The study site was chosen based on its hydrotopographic characteristics and intensive pesticide use in lebak swamp rice farming.

### Population and Sample

The study population included rice farmers involved in pesticide spraying in the lebak swamp fields of Pemulutan District. Cases were farmers with spirometric abnormalities, while controls were matched by age and sex but showed no respiratory symptoms. Participants with a history of non-occupational chronic respiratory diseases (e.g., asthma, tuberculosis), significant thoracic surgery, or a current smoking habit were excluded to minimize confounding effects on spirometric results.





**Figure 1.** Agricultural Map (a) and Administrative Map (b) of the Research Location in Pemulutan Subdistrict, ogan Ilir Regency

Preliminary data were collected from 10 villages in Pemulutan District. The geographic and administrative distribution of the research area in Pemulutan Subdistrict is illustrated in Figure 1. Minimum sample size for this case-control study was calculated using a two-proportion hypothesis test based on prior research, resulting in 106 participants (53 cases and 53 controls). Both groups were selected through purposive sampling. Data collection focused on environmental conditions, pesticide exposure, and respiratory health. All participants provided informed consent, and confidentiality was strictly upheld. The typical pesticide application practices by local farmers are documented in Figure 2.



**Figure 2.** Pesticide Spraying Practic by Farmers at Pemulutan District



Environmental data including average rainfall, temperature, and humidity from 2014 to 2024 were obtained from institutional records. Additional information on socio-demographics and work practices (e.g., spraying duration and frequency, Personal Protective Equipment (PPE) use, and pesticide handling) was gathered using a standardized questionnaire (Pulmonary ATS-DLD-78-A Form). PPE use was operationalized based on the completeness of protective gear during pesticide application. 'Completed PPE' was defined as the simultaneous use of five items: chemical-resistant mask, gloves, long-sleeved shirt, long pants, and boots. 'Incompleted PPE' was assigned if one or more of these items were absent. Respiratory symptoms were defined as the occurrence of chronic cough, nasal irritation, sore throat, or dyspnea within the last six months as reported by respondents.

Respiratory symptoms (e.g., cough, nasal irritation, sore throat, shortness of breath, chest pain) were assessed through structured interviews. Pulmonary function was measured using a digitally calibrated spirometer (BTPS-corrected) in accordance with ATS/ERS standards. Parameters included Forced Vital Capacity (FVC), Forced Expiratory Volume in one second (FEV<sub>1</sub>), FEV<sub>1</sub>/FVC ratio, and Peak Expiratory Flow (PEF), with abnormalities classified using predicted values or the Lower Limit of Normal (LLN).

#### **Data Processing and Analysis**

Data were meticulously reviewed for completeness and cleaned prior to statistical processing. Univariate analysis was initially performed to summarize demographic, behavioral, and occupational exposure variables using frequencies and percentages. Bivariate analysis employed Chi-square tests to evaluate the associations between independent variables and spirometric abnormalities, with a significance threshold set at  $\alpha = 0.05$ . Odds Ratios (OR) and 95% Confidence Intervals (CI) were calculated to determine the strength of these associations<sup>4</sup>. For the purpose of analysis, certain variables were categorized using specific thresholds:

- a. Age: A cut-off of 35 years was established based on the median age of the study population and physiological evidence suggesting a more rapid decline in pulmonary function and increased vulnerability to chemical stressors beyond this period.
- b. Work Duration: A threshold of  $\geq 5$  years was utilized to differentiate between short-term and chronic cumulative exposure, as the latency period for detectable chronic respiratory impairment from organophosphate inhalation typically spans several years of consistent application.

To identify independent predictors and construct a robust explanatory multivariable model, variables demonstrating a p-value  $\leq 0.25$  in the bivariate analysis, along with those of significant theoretical relevance, were entered into a multivariate logistic regression. The model was expressed using the following logit transformation:

$$\text{Logit}(P) = \ln \left( \frac{P}{1-P} \right) = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \dots + \beta_k X_k$$

Where P represents the probability of spirometric abnormality,  $\beta_0$  is the constant, and  $\beta_1 \dots \beta_k$  are the regression coefficients for the predictors such as exposure duration, frequency, and respiratory symptoms. A backward stepwise (likelihood ratio) selection method was applied to refine the model. The final model's goodness-of-fit was rigorously assessed using the Hosmer-Lemeshow test, while the explanatory power was determined through the Nagelkerke R<sup>2</sup>. All statistical procedures were executed using SPSS software.



**RESULTS AND DISCUSSION**

**Basic Characteristics of Respondent**

A total of 106 rice farmers involved in pesticide spraying activities participated in this study. The demographic and exposure-related characteristics of the participants are summarized in Table 1.

**Table 1.** Sociodemographic Characteristics

Variable	Category	Frequency	Percentage
<b>Age</b>	≥35 years	93	87,7
	<35 years	13	12,3
<b>Gender</b>	Male	93	87,7
	Female	13	12,3
<b>Use of PPE</b>	Incompleted	73	68,9
	Completed	33	31,1
<b>Exposure Duration</b>	>4 hours/day	57	53,8
	≤4 hours/day	49	46,2
<b>Work Duration</b>	≥5 years	74	69,8
	<5 years	32	30,2
<b>Exposure Frequency</b>	≥3 times/week	43	40,6
	<3 times/week	63	59,4
<b>Spirometric FVC</b>	Abnormal	53	50
	Normal	53	50
<b>Spirometric FEV<sub>1</sub></b>	Abnormal	47	44,3
	Normal	59	55,7
<b>Spirometric FEV<sub>1</sub>/FVC (%)</b>	Abnormal	52	49,1
	Normal	54	50,9
<b>Spirometric Abnormalities (FVC, FEV<sub>1</sub>, FEV<sub>1</sub>/FVC)</b>	Abnormal	53	50
	Normal	53	50
<b>Respiratory Symptoms</b>	Yes	45	42,5
	No	61	57,5

Notes: PPE: Personal Protective Equipment; FVC: Forced Vital Capacity; FEV<sub>1</sub>: Forced Expiratory Volume in one second.

The study reveals that the majority of respondents were male (87.7%) and aged 35 years or older (87.7%), indicating an older, predominantly male farming population. Most participants (69.8%) had been working as farmers for five years or more, suggesting long-term occupational exposure to pesticides. Over half (53.8%) reported daily exposure exceeding four hours, while 40.6% experienced exposure three times or more per week. Despite these high exposure levels, only 31.1% used complete personal protective equipment (PPE), with the majority (68.9%) reporting incomplete usage. Spirometric assessments showed that approximately half of the respondents had abnormal lung function: 50% had abnormal Forced Vital Capacity (FVC), 44.3% had abnormal Forced Expiratory Volume in one second (FEV<sub>1</sub>), and 49.1% had abnormal



FEV<sub>1</sub>/FVC ratios. Based on the criterion that two out of three abnormal spirometric results indicate impaired respiratory function, a substantial portion of the population can be classified as having abnormal lung function. Additionally, 42.5% of respondents reported experiencing respiratory symptoms, further supporting the presence of respiratory health concerns among this population. These findings suggest a significant risk of respiratory impairment among farmers, likely linked to prolonged and frequent pesticide exposure combined with inadequate protective measures.

To better understand the respiratory health risks faced by farmers, it is important to consider the environmental context of their work. The study area, located in wetland rice fields, is characterized by high humidity, fluctuating temperatures, and substantial rainfall—conditions that may prolong pesticide residue and enhance its dispersion. These microclimatic factors likely contribute to increased exposure and may intensify the respiratory effects observed. Thus, evaluating local environmental parameters such as rainfall, temperature, and humidity provides essential context for interpreting the health outcomes reported (see Table 2).

**Table 2.** Environmental Conditions of Wetland Areas (average from 2014-2024)

Variable	Average	Unit
Relative Humidity	±84,5	Percentage (%)
Air Temperature	±26,54	Degrees Celcius (°C)
Rainfall	±220,8	Milimeter (mm)

*Data Source: [https://developers.google.com/earth-engine/datasets/catalog/ECMWF\\_ERA5\\_LAND\\_HOURLY](https://developers.google.com/earth-engine/datasets/catalog/ECMWF_ERA5_LAND_HOURLY)*

Environmental monitoring in the wetland agricultural areas revealed consistently high levels of humidity, with an average relative humidity of 84.5%. Such conditions are typical of wetland ecosystems and may contribute to prolonged pesticide residue persistence in the air and on surfaces, potentially increasing exposure risks. The average air temperature was recorded at 26.54°C, which falls within the optimal range for many agricultural activities but may also facilitate volatilization of certain chemical agents, further influencing inhalation exposure. Additionally, the region experienced substantial rainfall, averaging 220.8 mm, which can affect pesticide runoff and redistribution, potentially impacting both environmental and occupational exposure pathways. These climatic factors, when considered alongside the respiratory health outcomes observed among the respondents, underscore the importance of integrating environmental context into occupational health risk assessments in wetland farming settings.

#### Bivariate Analysis of Risk Factors for Spirometric Abnormalities.

Bivariate analysis was conducted to identify associations between respondent characteristics and exposure-related factors with the occurrence of spirometric abnormalities. The complete results are presented in Table 3.



**Table 3.** Bivariate Analysis of Spirometry Risk Factor

Variable	Category	Spirometry Abnormality		Total	P-Value	OR (95%CI)
		Abnormal (%)	Normal (%)	n (%)		
Age	≥35 years	45 (84,9)	48 (90,6)	93 (87,7)	0,554	0,586 (0,178-1,924)
	<35 years	8 (15,1)	5 (9,4)	13 (12,3)		
Gender	Male	42 (79,2)	51 (96,2)	93 (87,7)	0.018	0,150 (0,031-0,713)
	Female	11 (20,8)	2 (3,8)	13 (12,3)		
Use of PPE	Incompleted	35 (66)	38 (71,7)	73 (68,9)	0.675	0,768 (0,336-1,751)
	Completed	18 (34)	15 (28,3)	33 (31,1)		
Work Duration	≥5 years	25 (47,2)	42 (79,2)	67 (63,2)	0,001	0,234 (0,099-0,550)
	<5 years	28 (52,8)	11 (20,8)	39 (36,8)		
Exposure Duration	>4 hours/day	38 (71,7)	19 (35,8)	57 (53,8)	0,000	4,533 (1,997-10,293)
	≤4 hours/day	15 (28,3)	34 (64,2)	49 (46,2)		
Exposure Frequency	≥3 times/week	31 (58,5)	12 (43)	43 (40,6)	0,000	4,814 (2,070-11,197)
	<3 times/week	22 (41,5)	41 (63)	63 (59,4)		
Respiratory Symptoms	Yes	33 (62,3)	12 (22,6)	45 (42,5)	0,000	5,638 (2,410-13,188)
	No	20 (37,7)	41 (77,4)	62 (57,5)		

Notes: OR: Odds Ratio; CI: Confidence Interval

Several factors demonstrated statistically significant associations ( $p < 0.05$ ) with spirometric abnormalities. Gender was significantly associated ( $p = 0.018$ ), with female respondents having lower odds of experiencing spirometric abnormalities compared to males (OR = 0.150; 95% CI: 0.031–0.713). Work duration also showed a significant association ( $p = 0.001$ ); farmers with less than five years of experience had lower odds of spirometric abnormalities compared to those with five years or more (OR = 0.234; 95% CI: 0.099–0.550), indicating longer work duration as a potential risk factor.

Exposure-related factors also showed strong associations with spirometric abnormalities. Exposure duration of more than 4 hours per day significantly increased the odds of spirometric abnormalities by 4.533 times (95% CI: 1.997–10.293;  $p = 0.000$ ) compared to those exposed for 4 hours or less per day. Similarly, pesticide exposure frequency of less than 3 times per week also pesticide exposure frequency of three times or more per week significantly increased the odds of spirometric abnormalities by 4.814 times (95% CI: 2.070–11.197;  $p = 0.000$ ) compared to those exposed less than three times per week. Meanwhile, age ( $p = 0.554$ ), completeness of PPE use ( $p = 0.675$ ), and wind direction during spraying ( $p = 0.816$ ) were not found to be significantly associated with spirometric abnormalities in this bivariate analysis (see Table 3).



**Explanatory Model for Spirometric Abnormalities Risk**

1. Initial Model

To identify independent predictors of spirometric abnormalities and to develop a risk prediction model, a multivariate logistic regression analysis was performed. In the initial modeling phase, all independent variables that showed potential associations with spirometric abnormalities in the bivariate analysis were included in the full model. These variables included: age, gender, PPE use, work duration, exposure duration, and exposure frequency. The results of this initial model are presented in Table 3.

Following the initial modeling, a confounding assessment was conducted by sequentially removing variables with p-values greater than 0.05. The first variable excluded was PPE use, which had a p-value of 0.695, indicating no significant contribution to the model. This was followed by the removal of gender (p = 0.286), which also did not meet the significance threshold.

Following the initial modelling, a confounding assessment was conducted by sequentially removing variables with p-values greater than > 0.05. The first variable excluded was PPE use, which had a p-value of 0.695, indicating no significant contribution to the model. This was followed by the removal of gender (p=0.286), which also did not meet the significance threshold.

**Tabel 5.** Initial Multivariate Logistic Regression Model

Variable	P-Value	Remarks
Use of PPE	0,697	Excluded (not a confounder)
Gender	0,290	Excluded (not a confounder)

2. Final Model

Based on Table 6, the multivariate analysis identified the final model comprising the variables: age, length of employment, exposure duration, exposure frequency and respiratory symptoms. Among these, the most influential factor associated with spirometric abnormalities was exposure duration, with an odds ratio (OR) of 6.272. This indicates that respondents exposed for more than 4 hours per day were over six times more likely to experience spirometric abnormalities compared to those exposed for 4 hours or less per day, after adjusting for age, respiratory complaints, length of employment, and exposure frequency. Furthermore, the researchers are 95% confident that in the general population, exposure duration exceeding 4 hours per day is a risk factor for spirometric abnormalities, with a confidence interval (CI) ranging from 2.156 to 18.251.

Exposure frequency was also found to increase the likelihood of spirometric abnormalities by approximately five times, after controlling for age, respiratory complaints, length of employment, and exposure duration. The 95% confidence interval for this association ranged from 1.677 to 14.210.



**Table 6.** Table Final Model (Full Model)

Variable	B	EXP(B)	P-Value	95% CI	R <sup>2</sup>
Age	-2,179	0,113	0,026	0,017-0,773	0,451
Respiratory Symptoms	1,081	2,946	0,032	1,096-7,923	
Work Duration	1,391	2,021	0,046	1,025-15,764	
Exposure Duration	1,836	<b>6,272</b>	0,001	2,156-18,251	
Exposure Frequency	1,585	4,882	0,004	1,677-14,210	

Respiratory symptoms were found to be three times more likely to exhibit spirometric abnormalities, even after adjusting for age, work duration, exposure duration, and exposure frequency. Furthermore, the researchers are 95% confident that, in the general population, respiratory symptoms act as a risk factor for spirometric abnormalities, with a confidence interval ranging from 1.096 to 7.923.

Length of employment was associated with a twofold increase in the risk of spirometric abnormalities, after adjusting for age, respiratory complaints, exposure duration, and exposure frequency. The 95% confidence interval for this variable ranged from 1.025 to 15.764.

Age was found to have a protective effect against spirometric abnormalities, after controlling for respiratory complaints, length of employment, exposure duration, and exposure frequency. The researchers are 95% confident that in the general population, age serves as a protective factor, with a confidence interval ranging from 0.017 to 0.773.

Additionally, the analysis yielded an R-squared value of 0.451, indicating that the five independent variables collectively explained 45.1% of the variance in spirometric abnormalities, while the remaining 54.9% was attributed to other unmeasured factors.

**Probability of Individual Experiencing Spirometric Abnormalities**

Based on the results of the logistic regression analysis, a statistical model was developed to estimate the probability of an individual experiencing spirometric abnormalities, as follows:

*Logit (spirometric abnormality)*

$$= -6,282 + (-2,179 (Age)) + 1,081 (Respiratory Symptoms) + 1,391 (Work Duration) + 1,836 (Exposure Duration) + 1,585 (Exposure Frequency)$$

$$P(X) = f(Z) = \frac{1}{1 + e^{-(\alpha + \beta_1 X_1 + \beta_2 X_2 + \dots + \beta_i X_i)}}$$

*Probability of Spirometric Abnormality*

$$= \frac{1}{1 + e^{-(-6,282 + (-2,179 (Age)) + 1,081 (Respiratory Symptoms) + 1,391 (Work Duration) + 1,836 (Exposure Duration) + 1,585 (Exposure Frequency))}}$$

In the logistic regression model, spirometric abnormality is coded as 1 for "Yes" and 0 for "No". The independent variables are defined as follows:

1. Age is coded as 1 if the individual is aged  $\geq 35$  years, and 0 if  $< 35$  years.
2. Respiratory Symptoms is coded as 1 if yes and 0 if no.
3. Work Duration is coded as 1 if the individual has worked for  $\geq 5$  years, and 0 if  $< 5$  years.



4. Exposure Duration is coded as 1 if the individual is exposed for >4 hours/day, and 0 if ≤4 hours/day.
5. Exposure Frequency is coded as 1 if the individual is exposed ≥3 times/week, and 0 if <3 times/week.

### Probability Calculation of Spirometric Abnormalities

If a respondent is aged ≥35 years, has ≥5 years of work experience, with an exposure duration of more than 4 hours per day, and an exposure frequency of ≥3 times per week, the probability of experiencing spirometric abnormality can be estimated using the following logistic regression model:

$$\text{Probability of Spirometric Abnormality} = \frac{1}{1 + e^{-(-6,282 + (-2,179 (1)) + 1,081 (1) + 1,391 (1) + 1,836 (1) + 1,585 (1))}}$$
$$\text{Probability of Spirometric Abnormality} = \frac{1}{1 + e^{(5,462)}} = 0.0712$$

This means that, based on the fitted model, the respondent has an estimated 7,12% risk of developing spirometric abnormalities during the follow up period.

### Discussion

This study provides empirical evidence of heightened respiratory risks among wetland rice farmers resulting from chronic organophosphate exposure. Our findings demonstrate a significant prevalence of spirometric abnormalities (50% in FVC), which is clinically associated with the mechanism of acetylcholinesterase (AChE) inhibition. The accumulation of acetylcholine at the muscarinic receptors of the bronchial smooth muscle triggers persistent bronchoconstriction and mucus hypersecretion, manifesting as reduced FVC, FEV<sub>1</sub>, and PEF<sub>R</sub> values as reported by Chakraborty et al, Peirish John et al and Joshi et al. (2019) [10], [11], [12].

These findings are consistent with international evidence indicating that chronic pesticide exposure (particularly to organophosphates and carbamates) contributes to impaired respiratory function, often presenting with restrictive or mixed patterns [13], [14]. These results are further supported by a prospective cohort study in Uganda by Hansen et al. (2021), which demonstrated a dose–response relationship between pesticide exposure (AChE/Hb ratio) and FEV<sub>1</sub> decline [15].

Prolonged daily exposure to pesticides exceeding four hours was the strongest predictor of spirometric abnormalities (OR = 6.272), emphasizing the cumulative respiratory risks of chronic contact. This finding aligns with prior studies, including Peiris-John et al. (2005) and Thetkathuek et al. (2020), which reported reduced pulmonary function and increased respiratory symptoms among long-term pesticide-exposed workers [10], [16]. In this study, 42.5% of farmers reported respiratory symptoms, which were significantly associated with abnormal spirometry (OR = 5.638; 95% CI: 2.410–13.188), supporting the value of symptom-based screening. Frequent pesticide application (≥3 times/week) also correlated with impaired lung function, consistent with Dhansola et al. (2022), who observed reduced FEV<sub>1</sub>/FVC ratios among chronically exposed farmers [17].



The study also demonstrated that longer work duration ( $\geq 5$  years) significantly contributed to spirometric abnormalities, suggesting a cumulative effect over time. Similar conclusions have been drawn in studies by Kumar et al. (2024), who noted declining cholinesterase activity with increasing exposure duration [18]. This highlights the need for longitudinal monitoring and early intervention strategies for workers engaged in pesticide spraying for extended periods.

Work duration of  $\geq 5$  years was also a strong predictor of respiratory impairment, suggesting a cumulative effect of long-term exposure. Kumar et al. (2024) demonstrated that AChE activity declines with increasing work duration, reinforcing the link between cumulative pesticide exposure and both neurological and respiratory dysfunction [19]. Additionally, Sutoluk et al. (2011) found that direct pesticide exposure resulted in more pronounced pulmonary impairment compared to environmental or indirect exposure [20].

Notably, age  $\geq 35$  years showed a protective effect against spirometric abnormalities (OR = 0.113). This phenomenon is likely a manifestation of the 'Healthy Worker Effect', where individuals with higher respiratory resilience tend to remain in the demanding task of pesticide spraying, while those who experience early health issues are more likely to leave the sector [21], [22]. This interpretation is supported by Hu et al. (2023), who found that FEV<sub>1</sub> decline due to organophosphate ester exposure was only significant among non-smoking individuals over 35 years of age [23].

The use of Personal Protective Equipment (PPE) did not show a significant protective association ( $p = 0.675$ ), which is likely due to inconsistent or incomplete PPE use. In this study, complete PPE was defined as the simultaneous use of chemical masks, gloves, long-sleeved shirts, long pants, and boots. The lack of field effectiveness for PPE is often attributed to discomfort from heat stress in humid environments, aligning with the meta-analysis by Tudi et al. (2023) regarding the limitations of PPE protection in real-world work practices.[24]. Furthermore, El Afandi et al. (2024) noted that pesticide drift is more influenced by application methods, topography, and microclimatic conditions than by wind direction alone [25].

The specific microclimatic conditions in the Pemulutan wetlands—characterized by high relative humidity (84.5%), moderate temperature (26.54°C), and substantial rainfall (220.8 mm)—contribute to a hazardous work environment. High humidity theoretically slows the evaporation of pesticide droplets and prolongs residue persistence in the air, significantly increasing inhalation exposure risks. This underscores the argument that topographical and microclimatic factors play a crucial role in the distribution of pesticide residues in agricultural areas. The explanatory model developed in this study demonstrated moderate accuracy ( $R^2 = 0.451$ ) in explaining the occurrence of spirometric abnormalities. Similar models have been developed by Hu et al. (2023) and Mendy et al. (2023), incorporating demographic variables and biomarkers to predict FEV<sub>1</sub> and PEF decline due to pesticide and flame retardant exposure [23], [26].



The study's explanatory model can serve as a valuable tool for early identification of at-risk workers, enabling targeted interventions such as enhanced training on pesticide handling and PPE usage. However, findings also highlight that PPE alone may be insufficient in mitigating exposure risks [27], [28]. This underscores the need for regulatory measures to limit daily exposure duration and spraying frequency in agricultural settings.

This study underscores the urgency of implementing periodic lung function screening among pesticide-spraying farmers, enhancing training on proper PPE use, regulating work duration and frequency, and institutionalizing biomarker-based exposure monitoring systems. These findings are particularly relevant for the informal agricultural sector in low- and middle-income countries like Indonesia, where occupational health infrastructure remains limited. The consistency of these findings with studies from India, Egypt, Thailand, Sri Lanka, Uganda, and Latin America highlights the global respiratory risks associated with pesticide exposure and the need for integrated preventive policies [11], [13], [29], [30].

## CONCLUSIONS

This study confirmed that spirometric abnormalities among pesticide-spraying farmers were significantly associated with prolonged daily exposure (>4 hours), frequent spraying ( $\geq 3$  times/week), and long-term work duration ( $\geq 5$  years). Among these, daily exposure duration was the strongest predictor of impaired lung function. Interestingly, age  $\geq 35$  years appeared to have a protective effect, possibly due to the "healthy worker effect." Respiratory symptoms were also strongly linked to abnormal spirometry, highlighting the importance of symptom-based screening.

The explanatory model developed in this study offers a practical tool for identifying high-risk individuals. To reduce respiratory risks, it is recommended to implement routine spirometry screening, enhance training on proper PPE use, and establish regulations limiting daily and weekly pesticide exposure. These findings are particularly relevant for informal agricultural sectors in low- and middle-income countries.

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## Conflict of Interest Statement

The authors affirm that there are no conflicts of interest associated with the execution, interpretation, or publication of this study. The research process and the presentation of its findings were conducted independently, without any institutional pressure or external influence that could compromise objectivity.



### Declaration of Funding

The authors declare that no funding or sponsorship was received for this research project.

### Ethical Consideration

This study was conducted in accordance with the ethical principles outlined in the Declaration of Helsinki. Ethical approval was obtained from the Faculty of Public Health, Universitas Sriwijaya, under the institutional review process. All procedures involving human participants complied with institutional and national research committee standards.

### References:

- [1] S. Sarkar, J. D. B. Gil, J. Keeley, and K. Jansen, *The use of pesticides in developing countries and their impact on health and the right to food*. European Union, 2021.
- [2] Y. A. Dewi *et al.*, "Farmers' knowledge and practice regarding good agricultural practices (GAP) on safe pesticide usage in Indonesia," *Heliyon*, vol. 8, no. 1, 2022.
- [3] E. Safety, "Health at Work in a Changing Climate," *Int. Labour Off. Geneva, Switz.*, 2024.
- [4] V. Aroniadou-Anderjaska, T. H. Figueiredo, M. de Araujo Furtado, V. I. Pidoplichko, and M. F. M. Braga, "Mechanisms of organophosphate toxicity and the role of acetylcholinesterase inhibition," *Toxics*, vol. 11, no. 10, p. 866, 2023.
- [5] Kementerian Pertanian Republik Indonesia, "Penggunaan Pestisida Dalam Perspektif Produksi Dan Keamanan Pangan."
- [6] M. Maksuk, T. Malaka, S. Suheryanto, and A. Umayah, "Risk quotient of airborne paraquat exposure among workers in palm oil plantation," *Int. J. Public Heal. Sci*, vol. 7, p. 97, 2018.
- [7] A. Mamane, C. Raheison, J.-F. Tessier, I. Baldi, and G. Bouvier, "Environmental exposure to pesticides and respiratory health," *Eur. Respir. Rev.*, vol. 24, no. 137, pp. 462–473, 2015.
- [8] D. Fishwick, A.-H. Harding, D. Fox, C. Yiqun, N. Pearce, and G. Frost, "O2A. 2 Pesticides and respiratory health; the GB based pipah study," 2019, *BMJ Publishing Group Ltd*.
- [9] J. N. D. Koussé *et al.*, "Pulmonary function assessment among conventional and organic cotton farmers exposed to pesticides in the Central-West region of Burkina Faso," *Int. Arch. Occup. Environ. Health*, vol. 97, no. 6, pp. 681–693, 2024.
- [10] R. J. Peiris-John, D. K. Ruberu, A. R. Wickremasinghe, and W. van-der-Hoek, "Low-level exposure to organophosphate pesticides leads to restrictive lung dysfunction," *Respir. Med.*, vol. 99, no. 10, pp. 1319–1324, 2005.
- [11] S. Salehipour *et al.*, "The Impact of Pesticides Exposure on Thyroid Function in Rafsanjan Farmers in 2023-2024: A Case-Control Study," *J. Environ. Heal. Sustain. Dev.*, 2024.
- [12] I. Setyopranoto *et al.*, "Brief Report Associations between pesticide exposure with biomarkers of stroke risk factors in farmers.," *J. Neurosci. Rural Pract.*, no. 1, 2024.
- [13] S. Chakraborty, S. Mukherjee, S. Roychoudhury, S. Siddique, T. Lahiri, and M. R. Ray, "Chronic exposures to cholinesterase-inhibiting pesticides adversely affect respiratory health of agricultural workers in India," *J. Occup. Health*, vol. 51, no. 6, pp. 488–497, 2009.
- [14] G. Joshi, A. G. Joshi, S. N. Patil, and A. Sontakke, "Effects of Pesticides on Lung Function Test in Farmers of Satara District, Maharashtra, India," *Scopus IJPHRD Cit. Score*, vol. 10, no. 7, p. 186, 2019.
- [15] M. R. H. Hansen *et al.*, "Organophosphate and carbamate insecticide exposure is related to lung function change among smallholder farmers: a prospective study," *Thorax*, vol. 76, no. 8, pp. 780–789, 2021.



- [16] A. Thetkathuek, T. Sa-Ngiamsak, and P. Choedkiattikool, "Association of respiratory impairment with use of anti-cholinesterase pesticides in migrant fruit farm workers in eastern Thailand," *Int. J. Environ. Sci. Dev.*, vol. 11, no. 5, 2020.
- [17] V. Dhansoia, V. Majumdar, N. K. Manjunath, U. Singh Gaharwar, and D. Singh, "Breathing-focused yoga intervention on respiratory decline in chronically pesticide-exposed farmers: A randomized controlled trial," *Front. Med.*, vol. 9, p. 807612, 2022.
- [18] D. Kumar *et al.*, "Biomonitoring of pesticide exposure and its health implications in agricultural areas of Telangana, India: A brief data report," *Data Br.*, vol. 55, p. 110632, 2024.
- [19] D. Kumar and S. N. Sinha, "Chronic exposures to cholinesterase-inhibiting pesticides adversely affects the health of agricultural workers in India," *Environ. Res.*, vol. 252, p. 118961, 2024.
- [20] Z. Sutoluk, Z. Kekec, N. Daglioglu, and I. Hant, "Association of chronic pesticide exposure with serum cholinesterase levels and pulmonary functions," *Arch. Environ. Occup. Health*, vol. 66, no. 2, pp. 95–99, 2011.
- [21] M. A. Rashidi, H. A. Mahabadi, A. Khavanin, and L. Tajik, "The association between blood, urine, respiratory, neurobehavioral parameters and occupational exposure to organophosphorus pesticides: a cross-sectional study among formulators," *Afr. Health Sci.*, vol. 22, no. 3, pp. 681–696, 2022.
- [22] C. L. Callahan *et al.*, "Chlorpyrifos exposure and respiratory health among adolescent agricultural workers," *Int. J. Environ. Res. Public Health*, vol. 11, no. 12, pp. 13117–13129, 2014.
- [23] P. Hu, S. Ke, A. Vinturache, Y. Chen, G. Ding, and Y. Zhang, "Organophosphate esters, airway inflammation, and lung function among US Participants: A nationally representative cross-sectional study from NHANES, 2011–2012," *Sci. Total Environ.*, vol. 892, p. 164755, 2023.
- [24] M. Tudi *et al.*, "Environmental and human health hazards from chlorpyrifos, pymetrozine and avermectin application in China under a climate change scenario: a comprehensive review," *Agriculture*, vol. 13, no. 9, p. 1683, 2023.
- [25] G. El Afandi, H. Ismael, and S. Fall, "A Hybrid Modeling Approach for Estimating the Exposure to Organophosphate Pesticide Drift in Sangamon County, Illinois," *Sustainability*, vol. 16, no. 7, p. 2908, 2024.
- [26] A. Mendy *et al.*, "Exposure to dust organophosphate and replacement brominated flame retardants during infancy and risk of subsequent adverse respiratory outcomes," *Environ. Res.*, vol. 235, p. 116560, 2023.
- [27] X. Song *et al.*, "Association of organophosphorus pesticides and glyphosate exposure with nasal flora and total IgE in solar greenhouse workers: A unique farmer group," *Environ. Pollut.*, vol. 368, p. 125698, 2025.
- [28] D. Nguyen and C. S. J. Tsai, "Inadequate personal protective equipment factors and odds related to acute pesticide poisoning: a meta-analysis report," *Int. J. Environ. Res. Public Health*, vol. 21, no. 3, p. 257, 2024.
- [29] E. E. Mendez *et al.*, "Impact of chlorpyrifos exposure on lung function in Egyptian adolescent agriculture workers," *Arch. Environ. Occup. Health*, vol. 79, no. 3–4, pp. 121–129, 2024.
- [30] K. B. Fieten, H. Kromhout, D. Heederik, and B. Van Wendel de Joode, "Pesticide exposure and respiratory health of indigenous women in Costa Rica," *Am. J. Epidemiol.*, vol. 169, no. 12, pp. 1500–1506, 2009.