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EFFECTS OF WIND SPEED AND CONIDIAL DENSITY ON EDAMAME LEAF RUST (*Phakopsora pachyrhizi*) IN IMMATURE OIL PALM PLANTATIONS

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Abstract
This study analyzed the effects of wind speed and conidial density on edamame leaf rust caused by *Phakopsora pachyrhizi* in an immature oil palm plantation. The research was conducted at the Oil Palm Teaching and Research Farm of Institut Teknologi Sawit Indonesia, Deli Serdang, North Sumatra. Wind speed was measured, airborne conidia were collected using spore traps, and disease intensity was assessed. Data were analyzed using multiple linear regression in SPSS, including classical assumption tests, an F-test, and the coefficient of determination. The regression model satisfied the normality assumption, showed no multicollinearity, and exhibited no evidence of heteroscedasticity. Partially, wind speed had no significant effect on disease intensity ($p = 0.437$), whereas conidial count had a significant effect ($p < 0.001$). Simultaneously, both variables significantly affected disease intensity ($F = 442.472$; $p < 0.001$), with an R Square value of 0.955. These findings indicate that conidial density is an important indicator of edamame leaf rust development.

Keywords: Conidia; Edamame; Leaf rust; *Phakopsora pachyrhizi*; Wind speed

INTRODUCTION

Oil palm is a strategic commodity that plays an important role in the national economy (Rahmawati, 2023). During the immature phase, the spaces between oil palm rows can still be utilized for intercrops, including edamame. Intercropping can improve land-use efficiency, diversify income sources, and support food diversification through economically valuable commodities (Judijanto, 2024). Edamame (*Glycine max (L.) Merr.*) is a soybean harvested while the seeds are still immature. It has high nutritional and economic value; however, its productivity may be constrained by disease. One of the most important diseases affecting edamame and soybean is leaf rust caused by the fungus *Phakopsora pachyrhizi*. The disease can develop rapidly because the pathogen produces large numbers of urediniospores that are readily dispersed by wind (Hossain et al., 2024).

The development of leaf rust is determined not only by the presence of the pathogen but also by environmental conditions that favor infection. Wind speed is associated with the movement of spores from inoculum sources to healthy plants (Santiago-Pérez et al., 2022), whereas conidial density reflects the amount of airborne inoculum. When dispersed spores encounter moist leaf surfaces and susceptible hosts, the likelihood of infection increases (Longo Sartor Zagui et al., 2024).

Investigating the effects of wind speed and conidial density is important because these variables can provide a basis for disease-risk monitoring (Santiago-Pérez et al., 2022). Such information is needed to determine more appropriate disease-control timing, particularly in edamame intercropping systems within young oil palm plantations, which have distinctive microclimatic conditions such as high humidity, relatively dense canopies, and air circulation that changes as the palms mature (Belinelli et al., 2022). This study aimed to analyze the effects of wind speed and conidial density on the intensity of edamame leaf rust in an immature oil palm plantation. The findings are expected to support the development of disease-management strategies based on environmental monitoring and inoculum density.

LITERATURE REVIEW

Edamame Intercropping in Immature Oil Palm Plantations

Edamame is a leguminous crop that can adapt to a wide range of land conditions provided that its requirements for light, water, and nutrients are met (Fitri et al., 2025). In immature oil palm plantations, edamame can be cultivated as

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an intercrop because light intensity between the palm rows remains relatively adequate. This system has the potential to increase land productivity before the oil palm canopy closes completely (Judijanto, 2024). Intercropping can also alter microclimatic conditions. The oil palm canopy, surrounding weeds, and soil-surface cover provided by mulch may affect humidity, temperature, and airflow (Belinelli et al., 2022). These factors require attention because foliar pathogens generally develop more rapidly under humid conditions with limited air circulation (Uge et al., 2023).

Leaf Rust Disease and Inoculum Sources

Soybean leaf rust is caused by *Phakopsora pachyrhizi*, which is recognized as an aggressive pathogen (Hossain et al., 2024). Initial symptoms appear as small leaf spots that subsequently develop into brown-to-orange pustules. Under severe infection, leaves turn yellow, dry out, and fall, thereby reducing the photosynthetically active leaf area (Uge et al., 2023).

The primary inoculum sources of this disease are urediniospores or conidia produced on infected leaf tissue. Mature spores can be released into the air and transported to other plants (Santiago-Pérez et al., 2022). As the number of conidia increases, the probability of spores being deposited on leaf surfaces also rises. Therefore, monitoring conidia using spore traps can be an important approach for predicting disease risk (Hossain et al., 2024).

Wind Speed and Infection Dynamics

Wind transports spores from one location to another. However, successful infection is not necessarily directly proportional to wind speed alone because spores require moist leaf conditions to germinate. In highly humid environments, spores deposited on leaf surfaces can germinate more readily and form infection structures (Hossain et al., 2024).

Inoculum density, humidity, and leaf-surface conditions interact with one another. Wind can broaden spore dispersal, whereas conidial density determines inoculum pressure (Santiago-Pérez et al., 2022). The combination of these factors may explain why leaf rust epidemics intensify during certain periods, particularly when crops are in the vegetative to early reproductive stages and provide abundant young leaves as host tissue (Longo Sartor Zagui et al., 2024).

MATERIALS AND METHODS

The study was conducted at the Oil Palm Teaching and Research Farm of Institut Teknologi Sawit Indonesia, Jalan Williem Iskandar, Kenangan Baru, Percut Sei Tuan District, Deli Serdang Regency, North Sumatra. The research site is located at 3.616702° N and 98.709846° E, at an elevation of 27 m above sea level. The study was carried out for three months, from March to May 2026.

The materials used included Ryoko edamame seeds, growing media, basal fertilizer (rock phosphate), water, petroleum jelly, lactophenol cotton blue, fungicide, and insecticide. The equipment included an anemometer, spore traps, microscope slides, coverslips, a microscope, a camera, stationery, and SPSS software for data analysis.

Figure 1. Spore trap

Spore traps were placed within the crop area to capture airborne conidia. Microscope slides coated with petroleum jelly were attached to the traps so that conidia would adhere to the glass surfaces. The samples were then examined under a microscope to count the conidia captured during each observation period. Wind speed was measured using an anemometer in the morning, at midday, and in the afternoon. Measurements were taken near the crop area so that the data represented the field microclimate. Disease intensity was assessed using a 0-4 scale based on the proportion of leaf area showing disease symptoms.

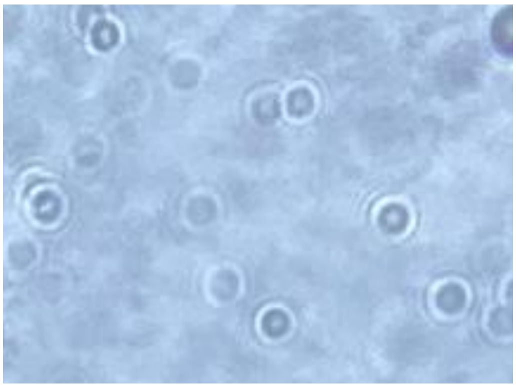

Figure 2. Microscopic observation of conidia

Microscopic observation was used to confirm the presence of spore particles captured by the traps. The micrographs showed round-to-elliptical particles distributed across the field of view. Counts were performed consistently so that conidial abundance could be compared with disease intensity in the plants. Data were analyzed using multiple linear regression based on the model $Y = a + b1X1 + b2X2$, where Y represented transformed disease intensity, X1 represented wind speed, and X2 represented conidial count. The classical assumption tests included normality, multicollinearity, and heteroscedasticity. Hypotheses were tested using the F-test and the coefficient of determination at a 5% significance level (Ali et al., 2022).

RESULTS AND DISCUSSION

Field conditions showed that edamame plants grew in open spaces between rows of young oil palms. This cropping arrangement allowed air movement among the plants; however, the surrounding environment remained relatively humid because of nearby vegetation and the oil palm canopy. These conditions may support spore deposition on leaf surfaces (Belinelli et al., 2022).

Figure 3. Edamame plants showing leaf spot symptoms at the research site

Field symptoms ranged from small spots to widely distributed lesions on the leaves. Some leaves became yellowish and showed tissue damage along their margins. These symptoms indicated disruption of photosynthetic tissue. As disease intensity increases, damaged leaves may dry and fall prematurely, potentially reducing the plant's ability to form pods (Hossain et al., 2024).

Figure 4. Variation in edamame leaf spot symptoms from mild to severe

Figure 4 presents variations in symptom severity across several leaves. Relatively healthy leaves were dark green with only a few spots, whereas more severely affected leaves displayed numerous lesions, discoloration, and holes caused by tissue damage. This variation provided an important basis for disease-intensity assessment because the observations considered not only the presence or absence of symptoms but also the severity of each leaf category (Uge et al., 2023).

Figure 5. Edamame plants at the pod-formation stage as a reference for growth condition

Plants at the pod-formation stage still require healthy leaves to support photosynthesis and seed filling. Consequently, leaf rust infection at this stage requires particular attention because leaf loss can reduce yield. Relatively healthy plants were used as references to assess visual differences between plants with mild symptoms and those showing more pronounced leaf damage (Fitri et al., 2025).

Classical Assumption Tests

Classical assumption tests were performed before interpreting the multiple linear regression model to ensure that the data met the normality requirement, did not exhibit multicollinearity, and showed no evidence of heteroscedasticity. Based on the SPSS output, the Kolmogorov-Smirnov Asymp. Sig. values were 0.067 for wind speed, 0.200 for conidial count, and 0.200 for disease intensity. Because all significance values exceeded 0.05, the data satisfied the normality assumption. The residual histogram and normal P-P plot also showed a residual pattern that approximated a normal distribution (Ali et al., 2022).

Table 1. Summary of Classical Assumption Test Results Based on SPSS Output

Classical assumption test	Variable/indicator	SPSS output value	Criterion	Interpretation
Normality	Wind speed; conidial count; disease intensity	K-S/Sig.: 0.1267/0.067; 0.1109/0.200; 0.0627/0.200	Sig. > 0.05	Normal
Multicollinearity	Wind speed and conidial count	Tolerance = 0.878; VIF = 1.139	Tolerance > 0.10; VIF < 10	No multicollinearity
Heteroscedasticity	SRESID-ZPRED scatterplot	Residual points are randomly dispersed around the zero line	No distinct pattern	No heteroscedasticity

As shown in Table 1, all data met the classical assumptions. The tolerance values for both wind speed and conidial count were 0.878, while the VIF values were 1.139. These values indicated that multicollinearity was not present. In the heteroscedasticity test, the scatterplot of the regression standardized predicted values against the regression standardized residuals showed residual points randomly dispersed around the zero line without forming a distinct pattern. Therefore, the regression model was suitable for further analysis (Ali et al., 2022).

Multiple Linear Regression Results

The multiple linear regression results produced an R value of 0.977, an R Square value of 0.955, and an Adjusted R Square value of 0.953. These values indicated that the model had a very strong ability to explain variation in leaf rust disease intensity. A summary of the regression model is presented in Table 2 (Ali et al., 2022).

Table 2. Summary of the Regression Model

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	0.977	0.955	0.953	0.07380

As shown in Table 2, the R Square value of 0.955 indicates that 95.5% of the variation in disease intensity was explained by wind speed and conidial count, whereas the remaining 4.5% was explained by factors outside the model, such as humidity, temperature, rainfall, canopy condition, and plant resistance (Belinelli et al., 2022; Uge et al., 2023).

The F-test was used to determine the simultaneous effects of wind speed and conidial count on disease intensity. The F-test results are presented in Table 3.

Table 3. F-Test Results for the Multiple Linear Regression

Source of variation	Sum of Squares	df	Mean Square	F	Sig.
Regression	4.820	2	2.410	442.472	0.000
Residual	0.229	42	0.005	-	-
Total	5.048	44	-	-	-

The calculated F value of 442.472 with a significance value of 0.000 indicates that wind speed and conidial count simultaneously had a significant effect on edamame leaf rust intensity. Therefore, the regression model was suitable for explaining the relationship between the two independent variables and the dependent variable.

The t-test was used to determine the partial effect of each independent variable. The regression coefficients, t-test results, and multicollinearity statistics are presented in Table 4.

Table 4. Regression Coefficients, t-Test Results, and Multicollinearity Statistics

Variable	B	Std. Error	Beta	t	Sig.	Tolerance	VIF
Constant	-1.194	0.044	-	-27.114	0.000	-	-
Wind speed	0.028	0.036	0.027	0.784	0.437	0.878	1.139
Conidial count	0.033	0.001	0.967	27.588	0.000	0.878	1.139

Based on these results, the following regression equation was obtained:

$$Y = -1.194 + 0.028X1 + 0.033X2 \quad (1)$$

Note: Y = disease intensity, X1 = wind speed, and X2 = conidial count.

The wind-speed coefficient was positive at 0.028; however, its significance value was 0.437, which exceeded 0.05. This result indicates that wind speed did not have a statistically significant partial effect on disease intensity in this study. Biologically, wind still serves as a medium for spore transport, but symptom development after spores land on leaves is also influenced by humidity, the duration of leaf wetness, and the susceptibility of plant tissues (Hossain et al., 2024).

Conidial count had a positive coefficient of 0.033 with a significance value of 0.000. This finding means that a higher number of conidia in the crop environment was associated with greater edamame leaf rust intensity. The beta value of 0.967 indicates that conidial count was the most dominant variable in the regression model (Santiago-Pérez et al., 2022; Pakpahan, 2026).

This result is consistent with the principles of plant-disease epidemiology, in which inoculum density is an important factor determining the probability of infection. The greater the number of airborne spores, the greater the likelihood that they will be deposited on leaves and initiate new infections. In edamame intercropping systems within immature oil palm plantations, information on conidial abundance may serve as an early indicator for estimating disease risk and determining more appropriate control timing (Hossain et al., 2024; Longo Sartor Zagui et al., 2024).

Table 5. Pod Weight

Treatment	Mean Pod Weight (g)	Decrease (%)
Control plot	4.798	-
Experimental plot	2.615	45.50

As shown in Table 5, the mean edamame pod weight in the control plot was 4.798 g, whereas that in the experimental plot was 2.615 g, representing a decrease of 45.50%. This reduction indicates that *Phakopsora pachyrhizi* infection adversely affected pod formation and filling by disrupting photosynthesis, thereby reducing edamame productivity.

CONCLUSION

The multiple linear regression model used in this study satisfied the classical assumptions: the data were normally distributed, multicollinearity was absent, and no visual evidence of heteroscedasticity was observed. Partially, wind speed did not have a significant effect on edamame leaf rust intensity, whereas conidial count had a significant effect and was the most dominant factor in the model. Simultaneously, wind speed and conidial count significantly affected disease intensity, with an R Square value of 0.955. Monitoring conidial abundance should therefore be incorporated into an early-warning strategy for edamame leaf rust, particularly in immature oil palm plantations that use intercropping systems. Further studies should include humidity, temperature, rainfall, and leaf-wetness duration to develop a more comprehensive disease-prediction model.

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