International Journal of Agriculture and Biosciences 2025 14(6): 1098-1108.
https://doi.org/10.47278/journal.ijab/2025.115
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RESEARCH ARTICLE
eISSN: 2306-3599; pISSN: 2305-6622

Sustainability Analysis of Wetland Rice Farming System Based on Integrated Pest Management

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ABSTRACT

Integrated pest management in wetland rice is a crucial strategy for enhancing the sustainability of this agricultural system. The study aims to examine sustainability and the factors that influence it. Respondents were 187 people from the total population of farmer households in Siak Regency, Riau Province. Data analysis using Rapid Appraisal with multidimensional scaling. The results of the study showed that four dimensions were included in the "quite sustainable" category, namely ecology (52.46), economy (65.53), social (69.12), and institutions (68.80), and "less sustainable" for technology (48.01), sustainability status was included in the "sustainable" category, with an average value of 60.78 percent. Soil pH is the most critical attribute for the sustainability of the ecological dimension. The economic dimension, with factors such as availability of capital, the dependence of household income sources on agriculture, availability of pest control facilities, and the price of dry-harvested grain, has a significant weight in agricultural decisions. The social dimension includes various factors, including participation in training, local knowledge of pest and disease control, farmer motivation to implement integrated pest management, farming experience, and periodic observations. The technological dimension refers to the physical, biological, and mechanical methods used for control. Finally, the institutional dimension is shaped by the availability of integrated pest management resources, access to information, and the presence of agricultural extension officers, pest control officers, and pest control teams.

Keywords: Integrated pest management (IPM); Multidimensional; Sustainability; Wetland rice.

Article History
Article # 25-246
Received: 05-May-25
Revised: 03-Jun-25
Accepted: 09-Jul-25
Online First: 28-Jul-25

INTRODUCTION

The right to food is a fundamental human right, explicitly enshrined in the 1945 Constitution of the Republic of Indonesia. This constitutional mandate compels the government to ensure national food security, with rice being the cornerstone of the nation's food system. Per capita rice consumption in Indonesia remains among the highest in Asia, reaching 79.68 kg/year, compared to the regional average of 77.2 kg/year (Statistics Indonesia, 2024). Amid ongoing trends of population growth, economic development, and increasing food demand, Indonesia faces a critical challenge in sustaining adequate rice production. According to the 2023 Mid-Year Population Census, Indonesia's population has reached 278 million-an increase of nearly 30 million from the 248.8 million recorded in 2013. This rapid demographic expansion underscores the urgency of enhancing rice production capacity to meet rising domestic needs.

To address these challenges, strategic priorities include not only increasing rice yields but also ensuring food safety, improving quality standards, and promoting environmental sustainability. National efforts to boost rice production have relied on both extensification (expansion of arable land) and intensification (increased yield per unit area). Key initiatives include the “Special Efforts for Rice Production” (UPSUS), integrated pest management (IPM) field schools, and the development of new rice fields. Despite these efforts, several constraints continue to impede progress, most notably the persistent threat of pests and diseases, compounded by the effects of climate change. These biotic stressors significantly contribute to yield losses and quality

Cite this Article as: Fuadi I, Pato U, Thamrin, Putra RM and Yusuf R, 2025. Sustainability analysis of wetland rice farming system based on integrated pest management. International Journal of Agriculture and Biosciences 14(6): 1098-1108. https://doi.org/10.47278/journal.ijab/2025.115

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degradation, ultimately undermining farmers' confidence in agricultural advancement programs. Although pest and disease management strategies have been widely implemented, farmers frequently rely on synthetic chemical pesticides. This overreliance has led to numerous adverse consequences, including the destruction of non-target organisms, development of pesticide resistance, pest resurgence, emergence of secondary pests, and residual contamination of crops and the environment (Netra et al., 2024; Benzing et al., 2025; Hasan et al., 2025).

Plant pests and diseases are inherently dynamic, influenced by a range of biotic and abiotic factors. Biotic influences include the growth stage of the host plant, physiological stress and interactions with other organisms. Abiotic factors encompass temperature fluctuations, humidity, rainfall variability, seasonal patterns, and broader agroecosystem characteristics (Finch et al., 2021; Mutz et al., 2021). Furthermore, climate change, cultivation practices, cropping patterns, the presence of natural enemies, and the chosen control methods also modulate the dynamics of pest and disease development (Maniçoba et al., 2023; Gass et al., 2024; Paterson, 2025). The challenge of implementing environmentally sustainable pest and disease control remains a major constraint to improving rice productivity. To address this issue, the Indonesian government has adopted a community-based empowerment approach through the Integrated Pest Management (IPM) program. This program incorporates multiple components, including cultural, mechanical, physical, biological and chemical control strategies. IPM was conceptualized as a corrective alternative to conventional pest management practices that rely heavily on chemical pesticides. Conventional pesticide-based approaches have been associated with significant negative impacts on human health, environmental integrity, and economic sustainability, particularly when pesticides are applied excessively or inappropriately (Fahad et al., 2021).

IPM educates farmers on cultivating robust crops and implementing judicious control measures, considering ecological, economic and technological aspects. The integrated pest management is a comprehensive approach that emphasizes the existing ecosystem in a given environment, seeks the integration of various compatible control techniques so that plant pest and disease populations can be maintained below economically harmless thresholds, as well as conserving the environment and benefiting farmers (Deguine et al., 2021). This approach aims to ensure agricultural products are sustainable and safe for consumption. Adopting sustainable agriculture is not merely an option but necessary to maintain food security, environmental preservation, and social well-being. Sustainable agriculture is emerging as an alternative approach to conventional agriculture, which includes the use of on-farm resources or local resources, the use of synthetic fertilizers and pesticides, the increased use of crop rotation and organic matter as soil improvement, diversification of plant and animal species (Ceballos et al., 2020). The sustainability of agriculture needs to consider the economic, social, and environmental issues associated with agriculture. Economic sustainability is related to the ability of farmers to produce sufficient amounts of food to maintain economic sustainability (Valizadeh & Hayati, 2021). Social sustainability refers to the equality of lives and quality of farmers, consumers, and agricultural community members (Giller et al., 2021). Environmental sustainability includes improving the quality of the environment and natural resources (Erdoğan et al., 2021).

On the other hand, the players in the processing industry, suppliers of agricultural products, and market players define sustainable agriculture as a farming business that can supply high-quality products that are safe for consumption, stable, and continuous throughout the period. Farmers, as the leading actors in agricultural cultivation, define sustainable agriculture as a production business that can produce agrarian products optimally, with relatively low input of production facilities, and the sale of products provides decent economic benefits for family life. These stakeholders have different interpretations of the substance of the definition. Still, a common thread unites these definitions, emphasizing the guarantee of the sustainability of natural resources and the environment (Rao et al., 2023).

Sustainable agriculture relies on the interactions and resilience of agricultural systems to be adaptive, continue to evolve, remain functional, withstand stress, be productive, use resources efficiently and balance sustainability objectives at all scales. Sustainability in agricultural systems combines the concepts of resilience (the capacity of a system to withstand shocks and stresses) and persistence (the capacity of a system to continue over time) and addresses broader economic, social and environmental outcomes (Bennett et al., 2021; Mucharam et al., 2020). Implementing the sustainability concept in rice IPM necessitates the application of sustainability attributes across five dimensions: ecology, economic, technology, social, and institution (Purvis et al., 2019; Shi et al., 2019). Sustainable agriculture aims to maintain high crop yields and profitability without causing environmental harm (Ceballos et al., 2020). Each dimension's sustainability index and status were evaluated using the multidimensional scaling (MDS) method, employing rapid appraisal for fisheries software modified into the rapid appraisal for integrated pest management (Rap-IPM) method efficiently and accurately depicts resource utilization and management in a given area, indicating sustainable development performance. This method is expected to illustrate the sustainability of IPM in wetland rice cultivation. From an ecological standpoint, IPM sustainability should avoid environmental pollution; economically, it should benefit and improve farmers' livelihoods; technologically, it should enhance productivity; socially, it should gain community acceptance and increase employment opportunities; and institutionally, it should prevent conflicts of interest among stakeholders (Yusuf et al., 2020; Valizadeh & Hayati, 2021). The study aimed to identify the index, status, and key attributes influencing rice farming sustainability based on IPM. This study was conducted in the District of Siak, Province of Riau, Indonesia, in 2024. This site was deliberately selected because of the rice production center, high productivity, and location, which is the location of implementing the national Integrated Pest Management program for Wetland rice.

MATERIALS & METHODS

Data Type and Source

This study categorizes data into two main types: primary and secondary. Primary data was gathered through meticulous field observations and comprehensive, in-depth interviews with respondents, utilizing a structured interview guide. Secondary data was collected from various sources, including publications from the Siak District Agriculture Office and Riau Province Agriculture Office, statistical information from district and provincial agencies, and research reports in scientific journals, proceedings, and studies conducted by research institutions and universities.

Determination of Respondents

The selection of participants utilized purposive sampling, focusing on wetland rice farmers who had completed IPM training. The sample size was determined with a 7% error margin from the total wet-rice farming households' population. According to the Siak Regency Agriculture Service (2023), 2,268 farmer households in the Siak district have undergone IPM training. The Slovin equation, as presented by Yusuf et al. (2020), was utilized to determine the quantity of research samples. This calculation was performed using Eq. 1 (Yusuf et al., 2020):

$$n = \frac{N}{1+N*a^2} \quad (1)$$

where;

n= number of samples

N= total population

a= percentage error

Using the Slovin equation, a sample size of 187 respondents was determined from 2,268 farmer households that had undergone IPM training.

The process entails constructing an X (n x p) matrix based on attribute scores, where n indicates the number of regions and benchmarks. In contrast, p signifies the number of attributes utilized.

Analysis Method

The Rap-IPM approach, utilizing MDS techniques, is employed to evaluate the sustainability of IPM-based wetland rice farming systems. As described by Kavanagh & Pitcher (2004), this method generates an index of sustainability that evaluates ecological practices and resource management. The Rap-IPM approach adapts the Rapfish program created by the Fisheries Center of the University of British Columbia. Yusuf et al. (2021) explain that MDS techniques map similar points or objects close together while dissimilar ones are positioned farther apart. The process involves creating an X (n x p) matrix from attribute scores, where *n* represents the number of regions and benchmarks and *p* denotes the number of attributes used. Each attribute score is standardized to ensure uniform weighting and eliminate differences in measurement scales. The standardization process follows a specific method, using Eq. 2 (Dzikrillah et al., 2017):

$$X_{ik}sd = \frac{X_{ik} - X_k}{S_k} \quad (2)$$

where;

Xik sd= Normalized score values of the region (encompassing its benchmark points) to i = 1,2 n, for each attribute to k = 1,2 p;

Xik= The starting score value for the area (encompassing its benchmark i = 1,2 n, for each attribute k = 1,2 p);

Xk= The median score for each characteristic = 1,2 p;

Sk Standard deviation of the score at each attribute k = 1,2 p.

(Kavanagh & Pitcher, 2004) state that the MDS method in Rapfish calculates the nearest Euclidean distance using Eq. 3 (Dzikrillah et al., 2017):

$$d_{12} = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2 + \cdots} \quad (3)$$

The Euclidean distance between the two points, denoted as d_12, is effectively represented with a two-dimensional space, emphasizing the clarity and precision of this geometric relationship based on Eq. 4 (Dzikrillah et al., 2017):

$$d_{12} = a + bD_{12} + e \text{ ; } e \text{ is error} \quad (4)$$

The Rapfish method employs the ALSCAL algorithm in its regression process, which involves repeated iterations to minimize the error value. Kavanagh & Pitcher (2004) note that within Rapfish, the ALSCAL algorithm sets the intercept value in the equation to zero (a = 0), transforming Eqs. 4 into Eq. 5, as shown in Eq. 5 (Dzikrillah et al., 2017):

$$d_{12} = bD_{12} + e \quad (5)$$

The iteration process concludes when the stress value falls below 0.25. This stress value is calculated by Kruskal's Stress using Eq. 6 (Rabbani, 2020):

$$Strees = \sqrt{\frac{\sum_{i,j}^{n}(d_{ij} - \hat{d'}_{ij})^2}{\sum_{ij}^{n}(d_{ij} - d)^2}} \quad (6)$$

The threshold for acceptable stress is < 25%. Montecarlo method was employed to investigate the effect of errors on determining the sustainability ordination value. Following a predefined systematic approach, the Rapfish technique establishes the sustainability index of IPM-based wetland rice farming systems. As stated by Yusuf et al. (2020), the sustainability index and status are determined through a three-step process: 1) evaluating attributes for each dimension; 2) scoring each feature on an ordinal scale (bad to good) depending on criteria of sustainability; and 3) categorize the index value of sustainability using sustainability intervals to ascertain the status. The score of sustainability score ranges for every dimension are classified as "poor" (0.00-25.00%), "lacking" (25.01-50.00%), "fair" (50.01-75.00%), and "good" (75.01-100.00%). Besides generating an index of sustainability, the Rap-PHT investigation also assembles a result known as the leverage of attributes. This leverage examination aims to identify attributes that significantly influence the index values of sustainability across all dimensions. According to Kavanagh & Pitcher (2004), the RMS value indicates the level of every attribute's role in affecting the sensitivity of the sustainability status, with the leverage properties providing the highest percentage value to a dimension's sustainability.

RESULTS

Multidimensional Sustainability Index and Status

The Rap-IPM analysis findings (Fig. 1) indicate that wetland rice cultivation in the District of Siak has an index of sustainability of 60.78%, categorizing it as moderately sustainable (exceeding 50%). This sustainability index is derived from evaluating attributes across five sustainability dimensions: eight characteristics in the ecology, seven in economic, seven in social, eight in technology, and nine in the institutional dimensions.

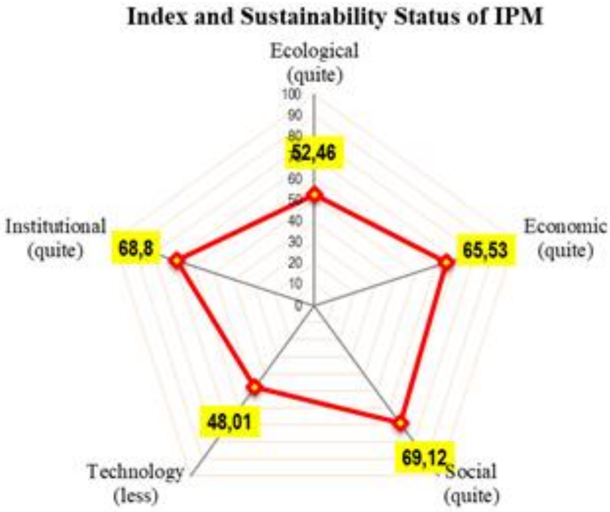

Fig. 1: Evaluation of IPM-based wetland rice farming system's index and sustainability in Siak District, Riau Province.

The MDS analysis results depicted in Fig. 1 reveal that four dimensions fall within the moderately sustainable range (>50%): ecological (52.46%), economic (65.53%), social (69.12%), and institutional (68.80%). However, the technological dimension is classified as "less sustainable" (<50%) with a value of 48.01%.

This data indicates that the technological aspect has not adequately supported the IPM sustainability for wetland rice in the District of Siak. The findings suggest that IPM-based wetland rice farming primarily focuses on ecology, economic, social, and institutional aspects while neglecting the technological dimension. To increase the sustainability of wetland rice farming, it is essential to improve the technology dimension, as technological advancements are now considered crucial for increasing production. The study findings indicated that farmers readily adopt new technologies when they offer economic advantages, align with local social norms, suit the physical environment, are cost-effective and straightforward to implement and reduce labor and time requirements. This observation aligns with Haryanto et al. (2015) and Northrup et al. (2021), who noted that novel rice farming techniques complement or replace existing methods rather than completely replace them. As a result, new technologies must be compatible with current practices that have adapted to specific agroecological conditions, as it is rare for innovative approaches to supplant established, locally adapted techniques entirely.

Stress Value and Multidimensional Coefficient of Determination

The Stress value from the Rap-IPM ordination analysis results can be used to evaluate how accurately a point configuration represents the original data for each analyzed dimension. One can examine the coefficient value (R^2) for each analyzed dimension to assess how well each attribute explains and contributes to system sustainability. Table 1 displays the Stress values and determination coefficients for the ecology, economic, social, technological, and institutional dimensions.

Table 1: Stress values and multidimensional coefficient of determination

Value	Dimensions					Multidimensional
	Ecology	Economy	Social	Technology	Institutional	
Stress	0.15	0.14	0.14	0.15	0.14	0.14
R^2	0.93	0.94	0.94	0.94	0.95	0.95

As indicated in Table 1, the multidimensional Stress value is 0.14, while R^2 is 0.94. According to Pitcher et al. (2013), a Stress value below 0.25 is considered favorable. This finding implies that the output resembles the actual situation more closely as the Stress value approaches zero. In other words, a lower Stress value indicates a better or more fitting model. Consequently, the model can be deemed acceptable since the obtained stress value does not exceed 0.15. The goodness-of-fit test results indicate that the estimation model of sustainability is viable, with a multidimensional R^2 value of 0.94, which is close to 1. A higher R^2 value, closer to 1, suggests a more accurate data mapping. Table 1 demonstrates that 94% of the model can be effectively explained, while the remaining 6% is attributed to other factors. According to Pitcher et al. (2013), an R^2 value exceeding 80% is considered satisfactory.

The Effect of Error

The Monte Carlo method is employed to assess the impact of errors by examining (a) mistakes in attribute scoring, (b) variations in scoring, (c) the robustness of the iterative MDS examination procedure, and (d) data input errors or incomplete information. Table 2 presents the outcomes of the Monte Carlo analysis across all dimensions.

As depicted in Table 2, the Monte Carlo analysis results reveal a minimal discrepancy between the MDS and Monte Carlo index values of sustainability within a confidence interval of 95%. This slight variation in values indicates that a) individual attribute scoring has a minimal error, b) scoring variability due to differing opinions is limited, c) the iterative MDS analysis process demonstrates stability, and d) data entry mistakes and omissions can be circumvented. The slight difference also suggests a high confidence level in the analysis. The statistical test parameters indicate that the Rap-IPM method is sufficiently reliable for sustainability assessment. The Rap-IPM analysis findings are deemed

Table 2: Findings from the Monte Carlo simulation of the Rap-PHT sustainability index (MDS), including the variance at the 95% confidence level

Value	Dimensions (%)					Multidimensional
	Ecology	Economy	Social	Technology	Institutional	
MDS	52.46	65.53	69.12	48.01	68.80	60.78
Monte Carlo	52.14	63.78	67.66	47.82	66.66	59.61
difference	0.32	1.75	1.46	0.19	2.14	1.17

acceptable due to the minimal difference between the MDS index value of sustainability and the Monte Carlo value at the 95% confidence level, ranging from 0.19 to 2.14% (less than 5%). This data indicates that the Rap-IPM model for assessing the sustainability of IPM-based wetland rice farming is considered an appropriate predictor of the sustainability index value. Suppose the discrepancy between the Rap-IPM (MDS) analysis and the Monte Carlo analysis exceeds 5% (Pitcher et al., 2013). In that case, the results are insufficient for the estimation of the index value of sustainability. Conversely, if the difference is less than 5%, the analysis is considered suitable for estimating the index value of sustainability.

Leverage Analysis of Ecological

Leverage attributes are examined by sorting out attributes with a root mean square (RMS) change value of more than half the value scale on the X-axis. The analysis of the leverage ecological dimension (Fig. 2) shows that of the eight attributes analyzed, there is 1 Leverage attribute that is very influential on IPM-based rice farming, namely the soil potential of hydrogen (pH). The results of the soil pH test at the research site averaged between 4.8-5.5, meaning that it was included in the acidic category.

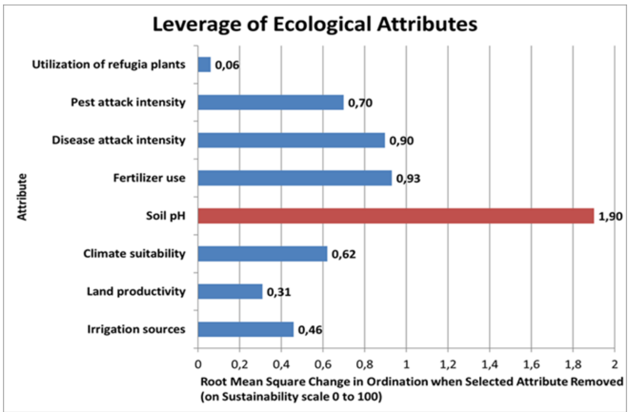

Fig. 2: Leverage attributes that affect the sustainability of ecological dimensions of IPM-based wetland rice farming.

From the results of the study, it can be seen that pH is a factor that significantly affects the ecological sustainability of pest management in rice fields. Acidic soil conditions have a higher toxic effect on microorganisms that live in the soil, resulting in plants not being able to absorb nutrients properly; while to grow and develop as well as defend against disease, plants require nutrients such as nitrogen (N), potassium (K) and phosphorus (P) in specific amounts. Qian et al. (2021) state that if the soil pH is above 5.5, then nitrogen (in the form of nitrate) becomes available to plants; on the other hand, microorganisms as organic matter decomposers will work well, and phosphorus and potassium will be available to plants at pH (6.0-7.0). Plants generally grow well in the neutral pH range (6.0-7.0); at neutral pH, almost all nutrients are available in sufficient quantities for plant needs. While the number of micronutrients available at neutral pH tends to be smaller than at low or high pH, the amount is adequate for plant needs (Rodríguez-Vila et al., 2022). Therefore, pH becomes one of the limiting factors in plants' absorption of nutrients. Generally, the pH value is still within the range rice plants require. This statement is supported by research results by Chen et al. (2022) and Lu et al. (2022), which state that rice plants will grow well in soil acidity between 4.0 and 7.0. Improvement of soil pH at the research site can be made by applying amelioration technology, namely by adding ameliorant materials in organic, inorganic, or a combination of both organic and inorganic compounds. Inorganic ameliorants are lime or dolomite, zeolite, and volcanic ash. This finding follows the findings stated by Shen et al. (2020) and Maydayana et al. (2023) which explains that the application of calcium, silicon, magnesium, and potassium fertilizers can significantly increase soil pH, and the long-term use of crop residues or organic fertilizers can increase soil base ions and reduce soil acidity in wetland rice.

Leverage Analysis of Economic

The economic dimension leverage analysis (Fig. 3) indicated that of the seven attributes analyzed, there are 4 Leverage attributes affecting IPM-based rice farming. The four attributes are the availability of capital, source of income dependence on agriculture, availability of pest control facilities, and the price of harvested dry grain.

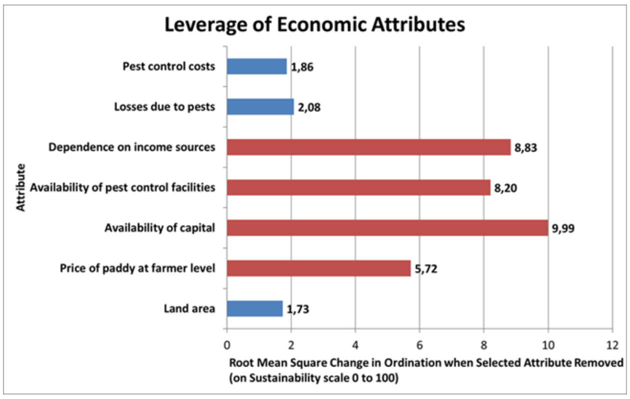

Fig. 3: Leverage attributes affecting the sustainability of the economic dimension of IPM-based wetland rice farming.

Capital is the most crucial factor in Integrated Pest Management for wetland rice. This statement aligns with Kehinde et al. (2021) and Villano et al. (2019), asserting that farmers' primary challenge is insufficient capital. The lack of financial resources often hinders farmers from fully implementing new technologies in their agricultural endeavors, as there is a direct correlation between capital and increased productivity. At the farm level, productivity enhancement is frequently impeded by farmers' inability to self-finance their operations or access government-provided capital assistance. This difficulty stems from various lending constraints, such as unfamiliar credit procedures and the absence of collateral, which discourage farmers from seeking external funding sources. These obstacles result in limited farmer access to formal financing and credit programs (Pratiwi et al., 2019; Ullah et al., 2020). In Siak District, wetland rice farming is the primary income source for respondent farmer households. As the main livelihood, wetland rice farming receives more serious attention and effort from farmers. This dedication is evident in their participation in training and counseling sessions, with farmers showing enthusiasm to attend even when activities are held outside the district, given their reliance on rice farming for all their needs. Field schools, meetings, and technical guidance programs to enhance farmers' knowledge and skills in wet-rice cultivation are expected to promote the adoption of recommended technologies. This approach is consistent with the findings of Antwi-Agyei & Stringer (2021), who stated that extension support is a key determinant in the successful implementation of innovation adoption. The presence of control infrastructure serves as a crucial factor in sustaining IPM in Siak District. The accessibility of adequate equipment such as hand sprayers, electric knapsack sprayers, mist blowers, power sprayers, pest control teams, and IPM clinics is essential for effectively implementing IPM in the field. This finding aligns with the findings of Ergashev & Ravshanov (2021) and Jayne et al. (2019), which indicated that access to capital, technology, strong farmer cooperation, and suitable infrastructure contributes to a robust local food system and determines the longevity of agricultural enterprises.

The price of rice is a key attribute influencing the sustainability of wetland rice farming. The lack of guaranteed prices for rice resulting from IPM practices affects the viability of IPM-based rice farming at the farm level. Farmers anticipate higher prices for their produce when applying IPM principles than when cultivating conventional rice. Interviews revealed that current rice prices in the field exceed government-set prices. However, these prices still fall short of farmer expectations, as IPM-based rice farming demands meticulous care and increased labor for maintenance, resulting in higher labor costs. To enhance economic sustainability, the Department of Agriculture, farmer groups, and cooperatives are expected to play a role in providing improved price guarantees. Price assurance is a significant factor influencing farmers' adoption of IPM. This finding is consistent with research by Lipatova et al. (2021) and Velten et al. (2021) emphasizing that cooperation within farmer groups, supported by favorable market access and farmer-friendly price policies, are key success factors in agricultural business development. Therefore, to maintain and improve economic sustainability, it is crucial to focus on managing and handling Leverage attributes in a comprehensive and integrated manner to achieve optimal effects.

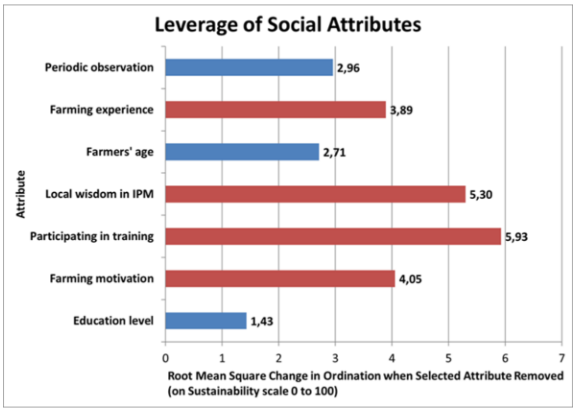

Fig. 4: Leverage attributes affecting the sustainability of the social dimension of IPM-based wetland rice farming.

Leverage Analysis of Social

An examination of the social aspect's leverage analysis (Fig. 4) reveals that five of the seven attributes studied are crucial in influencing IPM-based wetland rice farming. These key attributes include participation in training, adherence to local wisdom, farmers' drive to implement IPM technology, wetland rice farming experience, and regular field observations. The study indicates that training positively impacts long-term agricultural practices by enhancing expertise, developing skills, and providing solutions to challenges in IPM for wetland rice cultivation. Training is a valuable investment for farmers, improving human capital and boosting their enthusiasm for agricultural pursuits.

The results of the analysis of the social dimension show that the most influential factor on social sustainability is participating in training, such as nonformal education and pest control training, which enhances farmers' rice cultivation skills. Farmers who frequently participate in training sessions develop a more adaptable mindset, enabling them to address better challenges associated with IPM in their rice fields. Zhang et al. (2021) and Prajapati et al. (2025) emphasized the importance of training in expanding farmers' knowledge base, reducing production expenses, and significantly boosting productivity and income by as much as 40%. These findings align with Listiana et al. (2020) and Mgendi et al. (2022), who assert that training is beneficial for acquiring and refining skills and fostering more productive behavioral changes in individuals. Instruction in IPM offers several advantages, including exposure to cutting-edge techniques for cultivating healthy plants, learning about the deployment and use of natural predators, understanding the creation and application of plant-based pesticides, and exploring eco-friendly pest control methods using biological agents. To enhance farmers' comprehension of IPM for rice crops, it is beneficial to increase the number of training sessions through various approaches (such as on-site gatherings, agricultural education programs, and expert guidance) and utilize diverse educational resources (including brochures, visual aids, periodicals, and publications). Local wisdom is a key factor in sustaining the social dimension. It is commonly described as Indigenous knowledge encompassing various strategies and insights for addressing environmental challenges, ensuring food security, and adapting to changes in both natural and social environments. The available natural resources and environmental conditions heavily influence the development of local wisdom (Afriawan et al., 2024; Norhadi et al., 2024). This form of knowledge plays a crucial role in community resilience and problem-solving (Nurzakiyah et al., 2024). Traditional practices incorporate rituals, including field-based prayers seeking divine blessings for improved yields, protection from obstacles and pests, and increased productivity. In rice cultivation, a common practice involves placing scarecrows around rice plants during the grain-filling stage to deter avian pests. Nurzakiyah et al. (2024) note that scarecrows are cost-effective and environmentally friendly. Additional customs include group prayers before the initial harvest, refraining from harvesting on Fridays (considered a sacred day), abstaining from harvest during a neighbor's funeral, avoiding conflicts, refraining from using profanity, and performing earth offerings as a gesture of gratitude to the divine. These practices reflect the community's deeply rooted beliefs and values in agricultural activities. The attribute of farmer motivation in implementing IPM is one of the driving factors for social sustainability. The attribute of farmer motivation in the implementation of IPM of wetland rice is inseparable from the support of local governments that assist farmers in providing supporting facilities and infrastructure including the construction and repair of irrigation channels, repair of farm roads, and procurement of water pumps and provision of training. Listiana et al. (2020) explain that training will affect a person's motivation to work and try more seriously, both in terms of creativity and productivity towards oneself or the environment. Farmers' accumulated knowledge significantly influences the growth in agricultural output and efficiency. This knowledge, called farmer experience, is acquired through day-to-day farming practices and encountered situations. Their agricultural background shapes an individual's capability and proficiency in farm management. As farmers spend more time in their profession, they develop a deeper understanding of effective farming techniques. According to Listiana et al. (2020), the duration of farming experience can enhance a farmer's receptiveness to new technologies. Those with extensive farming backgrounds are typically more adept at evaluating and selecting appropriate methods for their agricultural practices. The study's respondents had an average of over 20 years of experience in rice cultivation, indicating a substantial level of expertise in this field. This wealth of experience is a valuable resource for knowledge and lessons in managing pests and plant disturbances. Consequently, it can be utilized as a guide to mitigate the risk of crop failure due to plant diseases in future farming endeavors. Regular monitoring offers significant insight into the sustainability of social aspects. This monitoring involves weekly assessments of farm crop and land conditions as part of plant protection strategies. These assessments include gathering data on pest populations, infestation levels, soil conditions, and factors influencing pest development. Farmers conduct these observations under the guidance of plant pest specialists. In this study, the periodic monitoring observed involves respondents consistently examining their fields, assessing soil quality, rice plants, beneficial organisms, and pests. They then discuss their findings and determine appropriate actions. The IPM concept requires respondents to observe plant pest organisms, including the types of pests and diseases affecting rice crops, the status of natural predators, and overall plant growth. Regular monitoring is crucial for farmers as it impacts rice crop yields. Farmers can assess the rice field agroecosystem through consistent checks, particularly regarding pest infestations and natural predators. This effort enables farmers to take immediate preventive measures if analysis indicates the need for action. To ensure the effective implementation of IPM, support from various stakeholders is essential, especially regarding local government policies and the involvement of agricultural extension workers and field pest observers. This action aligns with findings from Syahza et al. (2023), which emphasize that business sustainability is not solely the responsibility of farmers but is significantly influenced by government policies.

Leverage Analysis of Technology

The technology dimension leverage analysis findings (Fig. 5) indicate that three of the eight evaluated attributes are crucial for IPM-based rice cultivation: physical, biological, and mechanical control. Physical control involves the application of heat and air circulation. The study revealed that none of the surveyed farmers implemented physical control methods. This approach is typically employed in small-scale farming operations or controlled environments like warehouses or greenhouses.

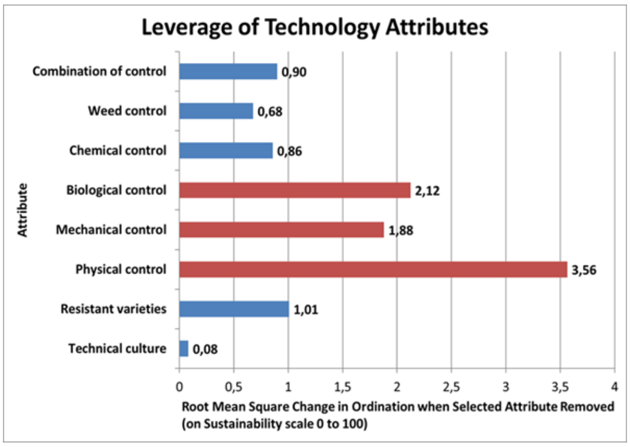

Fig. 5: Leverage attributes affecting the sustainability of IPM-based wetland rice farming technology dimensions.

IPM in rice cultivation relies heavily on biological control as a key component. Bande et al. (2020) and Wisdawati et al. (2022) suggested that employing biological agents and natural substances such as vegetable pesticides offers an eco-friendly approach to managing plant diseases and pests without compromising environmental health or human well-being. However, the farmers surveyed express hesitation in adopting these methods, as they do not guarantee complete pest eradication. The uncertainty associated with IPM techniques, perceived as more complex, deters farmers from embracing this approach. Respondents note that utilizing vegetable pesticides and biological agent's demands patience and persistence in their preparation, contrasting with the immediate results of conventional pest control methods to which farmers have grown accustomed. There is a need to enhance the development of plant-based pesticides due to their numerous benefits, including readily available materials and non-toxic effects on plants during application. Sattler et al. (2021) highlight several advantages of plant-based pesticide development, such as eco-friendliness, affordability, ease of acquisition, plant safety, compatibility with other control methods and producing pesticide residue-free agricultural goods. Despite these benefits, farmers tend to prefer chemical pesticides because they are ready for immediate use, more convenient, and produce quicker results compared to biological or mechanical control methods. IPM-based rice farming benefits greatly from the high sensitivity provided by mechanical control methods. These techniques involve direct intervention, such as manually removing insect pests, hunting, fumigation, and using traps. Repelling strategies can also be employed to deter or approach pests already present in the crop or approach it. Farmers who participated in the study implemented this approach by placing scarecrows in the center of their rice fields or installing brightly colored or reflective ropes. These measures are designed to frighten and drive away birds that attack rice grains as they mature.

Leverage Analysis of Institutional

The institutional dimension leverage analysis (Fig. 6) findings revealed that four of the nine evaluated attributes significantly influenced the sustainability of IPM-based rice cultivation. These crucial attributes include access to IPM information, the availability of extension agents, Pest control officers, and pest management teams.

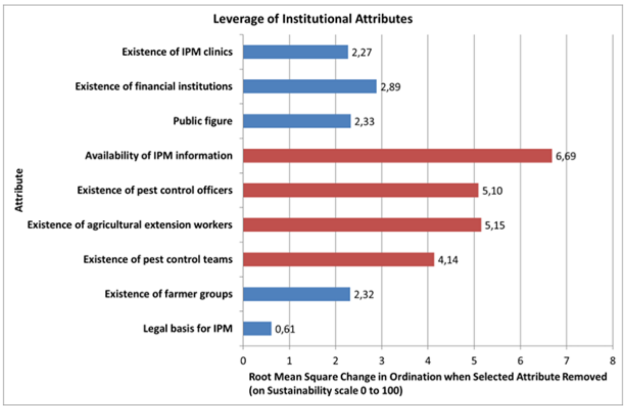

Fig. 6: Leverage attributes affecting the institutional dimension sustainability of IPM-based wetland rice farming.

The accessibility of IPM information dramatically enhances IPM-based rice farming sustainability. This information is disseminated through various channels, including discussions, educational sessions (such as field schools, field meetings, monthly gatherings, and technical guidance), implementation of demonstration plots in experimental gardens or on farmers' land, and through diverse extension media like leaflets, posters, magazines, and books. This information distribution focuses on eco-friendly farming techniques, encompassing the utilization of natural predators, the creation of plant-derived pesticides, the application of biological agents, and consistent monitoring. According to Bello-Bravo et al. (2022), (Lane et al. (2023), and Umehai et al. (2024), IPM content must be innovative and effectively communicated by the provider to ensure farmers' comprehension of the conveyed message. Information can be available from officers and from the experiences of other farmers who have successfully implemented IPM. This information is so important that farmers can learn from other farmers by sharing experiences. Some of the information that is often conveyed in meetings is the introduction of plant pests and diseases, including the characteristics of plants that are attacked and the types of pests and diseases, how to cultivate healthy plants (rice cultivation techniques), fertilization (type, dose, method and time of fertilization). The interview findings revealed that the provided crop cultivation information aligned with the respondents' existing farming practices, making it comprehensible for them. Respondents indicated regular field inspections were common during their farm visits. However, farmers did not adhere strictly to the observation guidelines they received, perceiving them as complex, time-consuming, unfamiliar, and burdensome. Instead, they opted for a more straightforward approach, visually scanning rice plants from the field's edge to detect signs of pest infestations. Survey participants found the information on natural enemy utilization highly informative, providing valuable insights into their role as biological control agents. However, they noted that implementing natural enemies for pest management in the field is challenging due to the extended time required for these organisms to establish and adapt to local environmental and plant conditions. Consequently, respondents have not effectively incorporated this IPM component in their fields. This reluctance stems from a lack of confidence in the ability of biological agents to control pest populations on their farms swiftly. Agricultural extension officers are crucial in sustaining IPM. These professionals are responsible for facilitating meetings with farmer groups, disseminating information, and enhancing farmers' managerial and entrepreneurial capabilities. In today's context, extension workers are expected to go beyond merely providing information; they must act as motivators, communicators, and facilitators (Bakari et al., 2021; Silvert et al., 2022). Gurning et al. (2023) also emphasized that practical communication skills are essential for extension workers to socialize, enhance farmers' knowledge, foster positive attitudes, and encourage farmers to adopt innovations. Plant pest observers are instrumental in maintaining the sustainability of IPM for wetland rice from an institutional perspective. Their responsibilities include monitoring plant pests and diseases, offering technical guidance and control recommendations, promoting integrated pest control methods, encouraging healthy plant cultivation practices, serving as resource persons and discussion partners, and distributing plant protection information. The implementation of IPM is closely linked to the role of pest control officers. Consequently, the farming communities' development can be achieved through more intensive guidance and training conducted by these officers, enabling them to fulfill their duties and function more effectively to farmers' needs and challenges. A pest control team is an organizational resource for farmers or joint farmer groups equipped with the necessary expertise and responsibilities to manage pest issues. In Siak District, these teams demonstrate significant involvement, evidenced by their frequent and ongoing mass pest control initiatives. Through their observational efforts, pest control teams identify various pest and disease types, monitor pest and natural enemy population dynamics, and assess the severity of pest and disease infestations. When field observations reveal pest attack intensity below the control threshold, the teams employ biological control agents or plant-based pesticides. Conversely, if pest attack intensity surpasses the control threshold and shows an upward trend, chemical pesticides are applied according to established guidelines. In Siak District, the pest control team is crucial in assisting farmers to anticipate and combat pest infestations on their agricultural lands. The combined efforts of farmer group members, pest control teams, extension workers, and pest observers are essential in effectively reducing pest attacks on farmland, thereby mitigating crop losses. These findings align with (Al-Emran & Griffy-Brown, (2023) who emphasize that group involvement significantly impacts technology adoption. Furthermore, effective collaboration among farmers, supported by sufficient resources, contributes to developing a robust local food system.

Conclusion

In Siak District, the index and condition of multidimensional sustainability for IPM-based wetland rice is classified as moderately sustainable at 60.78%. MDS analysis reveals that four dimensions are moderately sustainable (>50%): ecological (52.46%), economic (65.53%), social (69.12%), and institutional (68.80%). The technological dimension, however, is less sustainable (<50%), with a value of 48.01%. The most crucial attribute for ecological sustainability is soil, which is an important factor. Soil pH greatly affects the availability of nutrients, the activity of microorganisms, and soil fertility. In the availability of nutrients, soil pH influences the absorption of macro elements N, P, and K, and microelements such as Iron, Zinc, and copper. Normal pH will increase the availability of nutrients that plants can absorb so that plant growth will be better. Then, soil pH also affects the activity of soil microorganisms, which ultimately increases soil fertility. So, soil pH becomes an important ecological factor in IPM. For the economic dimension, critical factors include capital availability, which is essential for farmers in managing their agricultural land because capital is used to buy equipment, seeds, fertilizers, pest control materials, and technology that can increase agricultural yields. Without sufficient capital, farmers will have difficulty developing their agricultural businesses. Reliance on farming for family income, whereas for the people in Siak in general, agricultural businesses are the main source of family income. High dependence on agricultural products makes families very vulnerable to changes in crop yields, such as those affected by pest and plant disease attacks, so the comprehensive implementation of IPM will greatly affect farmers' income. Accessibility of pest control resources, where the availability of pest control materials plays an important role in the sustainability of IPM because these materials are one of the main components in efforts to control pests effectively and environmentally friendly. IPM is an approach that combines various methods to control pests in a way that minimizes risks to human health, the environment, and biodiversity. The availability of various control materials also supports integrated pest control, which combines various control techniques and materials (biological, physical, chemical, and cultivation) to reduce losses due to pests without damaging the balance of the ecosystem. Harvested dry grain prices: Although the price is not directly related to the pest control technique, paddy can influence farmers' decisions in choosing and implementing their farming efforts, such as applying IPM. High paddy prices can increase farmers' motivation to manage their farms more efficiently and sustainably. With higher incomes, farmers are more likely to invest part of their harvest in environmentally friendly agricultural practices, namely with quality pest control materials, such as environmentally friendly pesticides, biological agents, or agricultural technologies that can increase the efficiency of pest control. Key social dimension attributes include participation in training, which is crucial in equipping farmers with the knowledge and skills needed to implement IPM effectively, such as the latest pest control methods, environmentally friendly control, and suppressing pest populations. The more farmers who receive training, the greater the likelihood that they will succeed in integrating IPM into their farming systems. Local wisdom in IPM is pest control methods that do not damage the environment, such as using repellent plants, using natural enemies (predators or parasitoids), and physical pest control techniques (such as traps or barriers). Local wisdom focuses on the balance of the ecosystem so that it is more sustainable in the long term, maintains soil health and biodiversity, and reduces dependence on hazardous chemicals. Farmer motivation in carrying out their farming business is to meet their families' needs, where agriculture is the main source of income. Farming experience greatly influences farmers' understanding of land conditions and pest behavior. Farmers with long farming experience tend to have good intuition in recognizing signs of pest or disease attacks and can anticipate problems in the field. Biological, mechanical, and physical control are crucial in IPM sustainability in rice farming. These three methods support the principles of IPM, namely controlling pests in an environmentally friendly way, reducing dependence on chemical pesticides, and maintaining the balance of the agricultural ecosystem. Institutional sustainability is influenced by IPM information availability, the presence of agricultural extension workers, pest observation personnel, and pest control teams. Agricultural institutions play an important role in the sustainability of IPM because farmers still need assistance in their farming efforts, especially in implementing IPM. The high motivation of farmers to apply the principles of IPM causes this IPM-based rice farming to be quite sustainable. However, improving the quality of human resources, namely awareness of the importance of applying IPM in their farms, still needs to be done, both for government agencies, especially the Department of Agriculture, farmers, and the community to improve the sustainability of wetland rice farming in Siak District, Riau Province.

DECLARATIONS

Funding: This study did not get any financial support from any organization/agency.

Acknowledgement: This study was conducted in Siak Regency, Riau Province, involving Government Agencies, Agricultural Field Officers, Farmers, as well as stakeholders related to wetland rice farming.

Conflict of Interest: None.

Data Availability: All the data is available in the article.

Ethics Statement: This study did not require ethical review, as it did not involve sensitive human data or animal subjects. All participants were informed about the purpose of the test and voluntarily agreed to participate. No personal identifying information was collected.

Author's Contribution: Indra Fuadi, the first author, has conducted research, data analysis, and processing, writing descriptions, and preparing the manuscript; Usman Pato has contributed to guiding the first author in research and data analysis of the rapid appraisal program with multidimensional scaling and interpreting the results, Thamrin guided the first author in preparing the manuscript and analyzing the results, Ridwan Manda Putra guided the first author in data analysis and processing of the rapid appraisal program with multidimensional scaling and interpreting the results, Rachmiwati Yusuf, the corresponding author, participated in data processing and analysis, preparing graphs and images and analyzing the results.

Generative AI Statement: The authors declare that no Gen AI/DeepSeek was used in the writing/creation of this manuscript.

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