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The sustainability index on rainfed paddy cultivation in Bengkulu, Indonesia

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Abstract Sustainability status on agricultural paddy cultivation determines food security and important to social equity and prosperity, economic development, and environmental services however land use changes accelerated by socio-economical perceptions and ecological constraints put the paddy agricultural activities and sustainability under threaten. Agricultural rice cultivation on rainfed paddy fields in Bengkulu less sustain with index of 40.38. Farmers age getting older with the range of 40- 60 years old as the poorest attribute with root mean square (RMS) 6.77 determined socio-cultural dimension with sustainability index of 35.01. As a consequence of that, the older farmers were difficult to adapt new technologies such as implementation of certified seeds, fertilizers applied in efficient, and agricultural mechanization systems however they cultivate their land with the motivation and knowledge passed down from previous generations (RMS = 4.13). Also, with the knowledge their hold from the previous generation, implementation recommended planting pattern and period was difficult to adapt by the local farmers (RMS= 3.12) therefore this attribute suppressed the institution and policies dimension on less sustainable (33.01). Low policies supported on the agricultural product prices especially on the harvest period could cause the farmers sold their production in low prices (RMS= 3.58) put the economic dimension on less sustainable status with value of 41.46. Rice cultivation is usually faced with the pests and diseases attacks causing harvested failure therefore the older farmers controlled their crops with effective pesticides without concerning the pesticides polluted their lands and environment or not. They were no consider whatever synthetic pesticides or bio-pesticides (RMS=3.64) applied however the important ones the crop could be protected from the pest and disease attacks. Last, soil fertility (RMS= 2.06) and soil acidity (RMS= 2.27) put the ecological dimension on less sustainability in rainfed paddy cultivation in Bengkulu.

Keywords: Agricultural input-product price, Farmers getting older, Rainfed paddy cultivation, Sustainability index

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Introduction

Lays on the monsoon climate region which is available water in high amount through the year therefore so many traditional farmers cultivate their potential lands with paddy and other agricultural food crops to support the economy and household welfare. At the same time Indonesian government seriously considers how to achieve self-sufficient and food security by building irrigation networks and facilities to support the farmers activities with those irrigation systems for providing water flowing through the year (Apriyana *et al*., 2017). However, some productive areas could not be facilitated with irrigation networks because of no water supply sources such as spring, lake, far from river, the water requirements for the agricultural food crops cultivation depend on rainfall (Istiqomah *et al*., 2023). The rainfed agricultural areas have a great potential to be developed as paddy fields for efforts in reaching the self-sufficient and staple food security in Indonesia in the future. However, unpredictable climatic patterns such as rainfall seasonal change even extreme climate occurrence carry out traditional irrigation in some constraints for paddy cultivation activities because of lack of water available in a certain period giving a significant impact on seasonal crops, especially food crops. When the food crops cultivation especially paddy run into drought stress, and pest and disease infestation stimulated by the unpredictable seasonal climatic changes, the traditional paddy farmers could face with harvest failures (Al Viandari *et al*., 2022).

Escaping crop growth failure due to lack of water available at a certain period of plant growth on rain-fed rice cultivation, the traditional farmers should set an appropriate planting calendar (Hasnuri *et al*., 2019). Unfortunately, most customary farmers could have enough knowledge and not fully understood how to use as a reference in determining the planting season. In fact, the simple solution used by the farmers could consider a diminution in cultivation area and re-scheduling water supplies from the irrigation facilities to avoid plants encounter stress during sensitive growth periods. The traditional farmers in Indonesia have long recognized the traditional rice and food annual crops-planting calendar using different terms in each region. The time is used as a starting point for indigenous awareness of agriculture planning. Nevertheless, additional local wisdom cannot be fully referenced early in the season due to climate change and difficulty finding an indicator of a seasonal marker (Apriyana *et al*., 2021). In order to avoid harvest failure and to improve agricultural land productivities, to day many farmers rehabilitated their rainfed agricultural food crops to perennial-industrial agricultural commodities like oil palm and rubber plantation.

Land Use and Land Cover Change (LUCC) represents a primary concern in global change research, particularly in relation to environmental issues and the sustainability of food production. Moreover, the issue of land conversion from annual food crop areas to oil palm plantations in Indonesia has consistently increased over the past two decades (Sudrajat *et al*., 2021). Land use changes from annual food crop areas to alternative functions are influenced by various factors, including soil fertility degradation, limited water supply, pest and disease infestations, the appeal of non-rice agricultural options, and the profitability of non-agricultural land uses (Barchia *et al*., 2023). From a macro perspective, changes in agricultural land use were expedited by structural and economic transformations (Setiawan *et al*., 2024). Land-use and land-cover change is affected by numerous biophysical and societal factors that operate across various spatial and temporal scales, interacting within complex, context-specific relationships. In other words, land use change was influenced by the interplay of endogenous factors (bio-geophysical, sociocultural, and socio-economic conditions) and exogenous factors (normative values and societal land use demands). Economic factors significantly influenced changes in agricultural land use, with social, management and policy-related, personal, and technical factors following in impact (Allahyari *et al*., 2013).

The declining capacities of ecosystems to deliver essential products and services are already impacting the productivity of rain-fed paddy fields, which are critical food-producing areas. If they persist, the effects on rice productivity would be most detrimental for rain-fed rice in Indonesia, where both water and soil nutrients are least available. Sustainable rice production, as a component of sustainable agricultural development, must consider present social behaviours and economic requirements while preserving the ability of natural resources for future generations to meet their own needs (Yusuf *et al*., 2019). Moreover, sustainable agricultural development encompasses activities that are commercially, environmentally, and socially viable. Achieving a balance among economic, environmental, and social advantages was nearly unattainable without institutional mechanisms to attain sustainable development (Cottrell *et al*., 2011). The institutional functions provide a crucial perspective to guarantee appropriate and valuable development with the other three aspects (Shen *et al*., 2009). Robust environmental and immediate economic forecasts have motivated civilisations to pursue greater ecological balance in resource consumption; thus, technological innovation and knowledge management present an extraordinary perspective on sustainable development. The application of technology has been crucial in enhancing rice production within agricultural practices (Faisal *et al*., 2019). Consequently, to achieve sustainable development metrics (Pitcher *et al*., 2013), it is essential to incorporate a conceptual analysis that encompasses ecological, technological, economic, social, ethical, and institutional dimensions.

Numerous studies have been conducted focussing on specific aspects of rice cultivation in the marginal rainfed paddy fields of Indonesia. However, a broader understanding of the various determinants and the sustainability index related to rainfed rice cultivation remains insufficient. The objectives of this study were to identify various factors that influenced the sustainability of rice cultivation in the Ipuh rainfed rice fields of Bengkulu.

Materials and methods

This study was carried out from August to November 2024 in the Ipuh Sub-district, Mukomuko District, Bengkulu Province. The geographical coordinates are 02°16'06"–03°07'08" latitude and 101°01'36"–101°51'08" longitude, with a mean annual precipitation of 3,495 mm, maximum temperatures of 31.38°C, lowest temperatures of 24.71°C, and a relative humidity of around 68.5% (Hardiansyah *et al*., 2023).

A combination of purposive and snowball sampling techniques was applied to select 60 rice farmers cultivating paddy fields, along with five experts representing each relevant dimension of analysis. The data collected encompassed a broad spectrum of ecological, economic, socio-cultural, technological, and institutional aspects, reflecting the perspectives of the farmers regarding sustainable rice cultivation on marginal peatlands. Additionally, secondary data were obtained from various sources, including government action plans, policies and regulations, infrastructure development (such as road networks), and market access, among others.

To evaluate the sustainability of rainfed rice farming in the Ipuh Sub-district, Bengkulu Province, a rapid appraisal method using Multidimensional Scaling (MDS) was employed. This analytical approach was a tailored version of the Rapid Appraisal for Fisheries (Rapfish) methodology, originally developed by the Fisheries Centre at the University of British Columbia (Pitcher and Preikshot, 2001), and later adapted for both unidimensional and multidimensional assessments in rice farming systems (Rao and Rogers, 2006). To account for potential errors in the analysis, Monte Carlo simulations were conducted. Furthermore, leverage analysis was used to determine which factors had the most significant influence on the sustainability of rainfed rice systems.

The Rapfish-based ordination process included several stages: (1) identifying attributes for each sustainability dimension; (2) scoring each attribute on an ordinal scale ranging from 0 to 3; and (3) conducting ordination analysis to determine stress values and ordination patterns. The MDS ordination procedure utilized a Euclidean distance matrix, calculated using the following formula:

$$sd_{i,j} = \sqrt{(Xi - Xj)^2 + (Yi - Yj)^2 + (Zi - Zj)^2 + ...)}$$

Which $d_{i,j}$ = Euclidian distance; X, Y, Z = Attributes; i, j = observation.
Euclidian distance between two points ($d_{i,j}$) in calculated with regression formula in the following equation

$$d_{i,j} = \alpha + \beta_{i,j} + \sigma$$

Note: di,j = Euclidean distance; α = intercept; βi,j = regression coefficient; σ = standard error.

Regression analysis was conducted using the ASCAL algorithm available in the SPSS software. This algorithm optimizes the square Euclidean distance d_{ijk} for three-dimensional ordinal data, originating from the initial point 0_{ijk} through a process that minimizes S-stress. The S-stress value, which represents the goodness-of-fit in multidimensional scaling (MDS), is calculated using the following formula:

$$\text{S-stress} = \sqrt{\frac{1}{m}\sum_{k-1}^{m}\left(\frac{\sum_i \sum_j \left(d_{ijk}^2 - O^2\right)_{ijk}^2)}{\sum_i \sum_j O_{ijk}^2}\right)}$$

Which m = number of attributes, d_{ijk} = Euclidian distance within *i, j, k* dimensions, O_{ijk} = initial point within *i, j, k* dimensions. S-stress value S <0.25) and and determinant coefficient R^2 > 80% expressed the accuracy of statistical analysis (Kavanagh and Pitcher, 2004). Furthermore, the evaluation of the index value and sustainability status across each dimension and multidimensional aspect of rice cultivation is represented on a scale from 0% (poor) to 100% (excellent) across four categories (Table 1). Generally, a sustainability index value exceeding 50 indicates that the system is sustainable, whereas a value below 50 signifies that the system is not yet sustainable.

Additionally, the assessment of sustainability index values and the overall sustainability status—both at the dimensional and multidimensional levels of rice farming—are illustrated on a scale ranging from 0% (very poor) to 100% (excellent), categorized into four levels (refer to Table 1). In general, an index score above 50 reflects a sustainable system, while a score below 50 indicates that the system has not yet achieved sustainability.

Tabel 1. Index value and sustainability status

No	Index value	Category
1	00.00 – 25.00	Bad (not sustainable)
2	25.01 – 50.00	Poor (less sustainable)
3	50.01 – 75.00	Fair (fairly sustainable)
4	75.01 – 100.00	Good (highly sustainable)

Fifth, a sensitivity analysis was performed to identify variables with the greatest influence, as indicated by their percentage contribution to the Root Mean Square (RMS); higher RMS values reflect greater sensitivity. Sixth, a Monte Carlo simulation was conducted to evaluate the effect of random errors on the Multidimensional Scaling (MDS) results, using a 95% confidence level. When the difference between the MDS outcomes and the Monte Carlo simulation results was less than one, the model was considered valid and reflective of actual field conditions.

Results

The sustainability index for paddy agriculture in the Ipuh rainfed rice field area of Mukomuko District, Bengkulu Province, is deemed less sustainable, with an average value of 40.38. The sustainability value for rice farming in this location is low, as all tested dimensions provide sustainability indices below 50.00 (Figure 1 and Table 2). The accuracy and validity of the determinant factors was examined, as well as the external variables influencing the sustainability of paddy cultivation in rainfed rice fields, indicated by the stress value, determination coefficient (R^2), and Monte Carlo indices obtained from the MDS analysis utilising Rap-Fish software (Table 2).

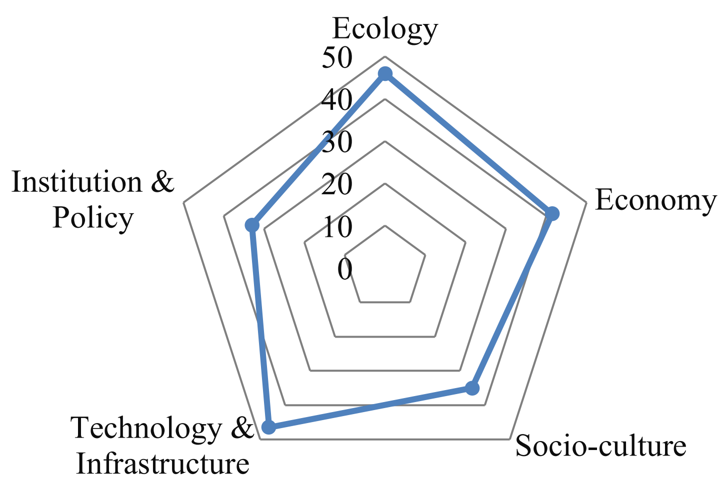

Figure 1. Sustainability indices of the rainfed rice fields in Ipuh Sub-district

Table 2. Sustainability indices, Monte Carlo, stress and determination coefficient

Dimensions	Indices		Differences	Stress (%)	R^2 (%)
	MDS	Monte Carlo			
Ecology	45.92	45.79	0.13	24.89	90.48
Socio-culture	35.01	35.54	0.53	24.07	92.40
Economy	41.46	41.43	0.03	24.56	91.56
Technology and infrastructure	46.50	46.60	0.10	24.27	91.47
Institution and policies	33.01	33.27	0.26	19.03	95.03
Multidimension	40.38	40.53	0.21	23.36	92.19

The disparity between MDS and Monte Carlo analysis, as demonstrated by a 95% confidence test, revealed no significant differences, with scores ranging from 0.03 to 0.53 and a mean value of 0.21 (less than 1). Furthermore, the MDS values validated by S-stress (%) ranged from 19.03 to 24.89, with an average of 23.36, while the MDS values validated by R2 ranged from 90.48% to 95.03%, with an average of 92.19%.

The ecological sustainability of rice cultivation in the rainfed paddy fields of the Ipuh Sub-district is potentially compromised due to three predominant factors: 1) marginal soil fertility (RMS=2.06), 2) elevated soil acidity (RMS=2.27), and 3) the expansion of oil palm plantations (RMS=1.46). The ecological attributes threatening sustainability are illustrated in Figure 2.

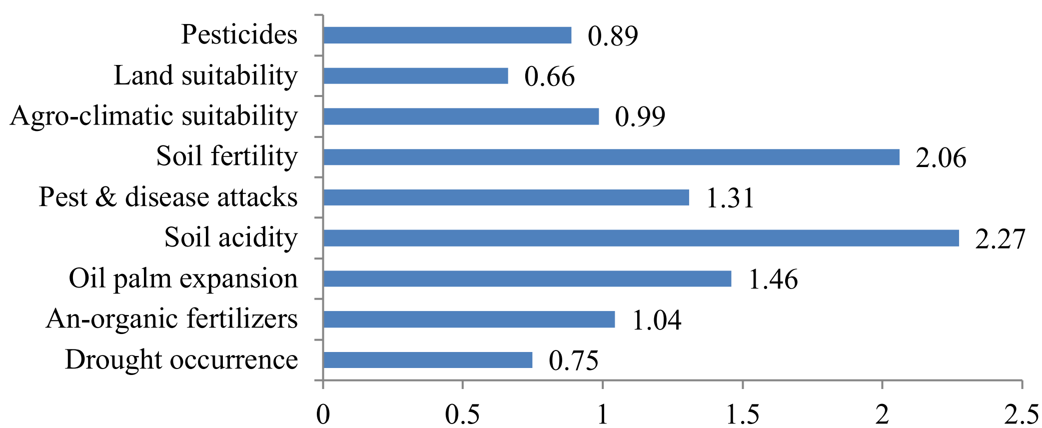

Figure 2. RMS values of leverage analysis of ecological attributes

The rice cultivation sustainability on the rainfed paddy fields in Ipuh was pressured by economical viewpoints due to rice prices (RMS = 3.58) of dry harvested grain under uncertainty follows the price determined by middleman buyers and the farmers facing with long market chain therefore the farmers having low rice cultivation revenue (Figure 3).

Serious problems faced with the rice cultivation seen from socio-cultural perspectives in these areas was the paddy farmers getting older (RMS=6.77) while the millennial farmers were less interested in rice cultivation activities because of not just a lack experience but also a low motivation (RMS=4.14) to 3 daily mud-covered work (RMS=3.50).

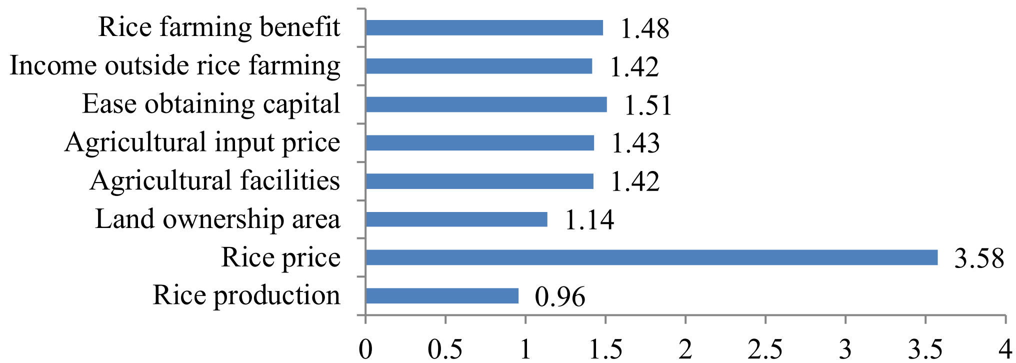

Figure 3. RMS values of leverage analysis of economical attributes

This perception is not only appeared in the minds of the younger generation but also among four housewives in this region (RMS=3.75). The significant values of RMS tested for the leverage analysis of the socio-cultural attributes is revealed in Figure 4.

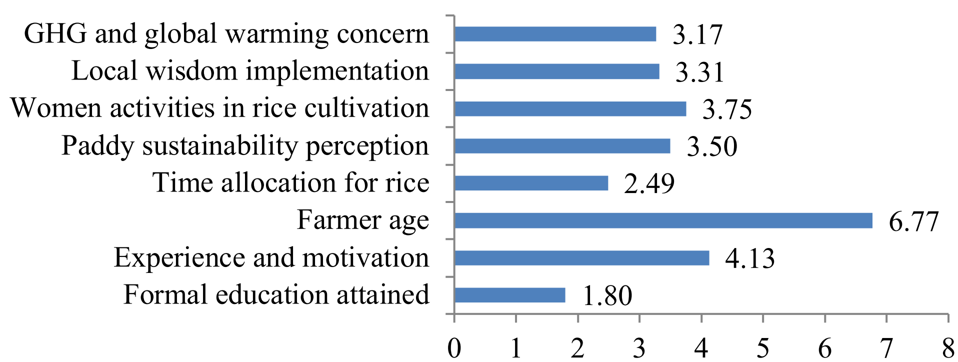

Figure 4. RMS values of leverage analysis of socio-cultural attributes

The primary technological and infrastructural constraints hindering the sustainability of rainfed paddy cultivation included the limited use of biopesticides for pest and disease control (RMS = 3.64) and the inadequate application of organic fertilizers to enhance soil fertility (RMS = 2.41). Another significant challenge is the low level of agricultural mechanization, particularly the scarcity of soil tillage machinery (RMS = 2.17), which is critical given the shortage of family labor and the high cost of hiring external labor. Many smallholder farmers lack the financial resources to purchase or rent such machinery for land preparation. Furthermore, poor infrastructure—especially inadequate farm road access (RMS = 2.96)—adds substantial transportation costs, as muddy and poorly maintained roads make it difficult to move agricultural products from farms to markets. Accessibility to farmland was also found to significantly influence farmers' motivation to work intensively on their land (Figure 5).

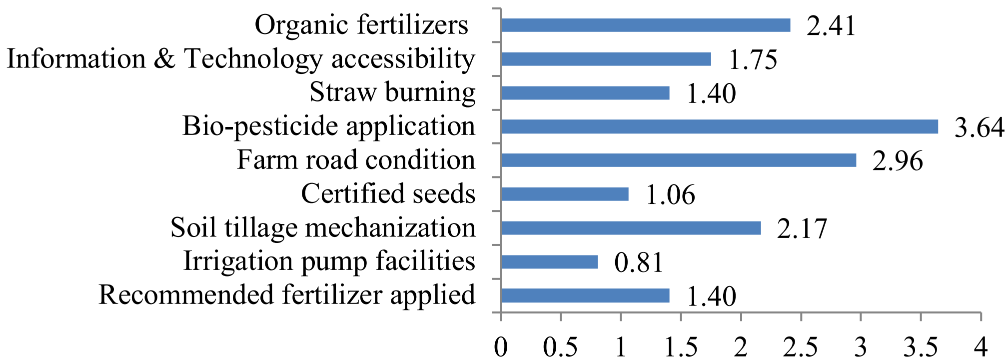

Figure 5. RMS values of leverage analysis of technological and infrastructure attributes

The limited hold in formal education, lack of opportunities to take part in training to improve knowledge, and difficult accessing information technologies, on the contrary, the traditional farmers which is inherited through hereditary customs sometime they were difficult to adapt government recommendation about planting schedule program (RMS=3.12) and they disobey about legal regulation (RMS=2.93) on sustainable agricultural land. The weak capacities from the local farmers accompanied by lack of strengthening of farmer institutions, the local farmer groups lost their existence and activity (RMS=2.87). The above conditions are exacerbated by rarely the coordination among stakeholders (RMS=2.17) involves farmer groups causing the farmers still lagging behind. The small hold land farmers for their agricultural activities have financial weakness at the same time financial supports and facilities limited (RMS=1.82), for example, they face with harvested failure because of pest and diseases attacks, the government provided lack of pest control facilities (RMS=2.38) and agricultural insurance (RMS=2.10) (Figure 6).

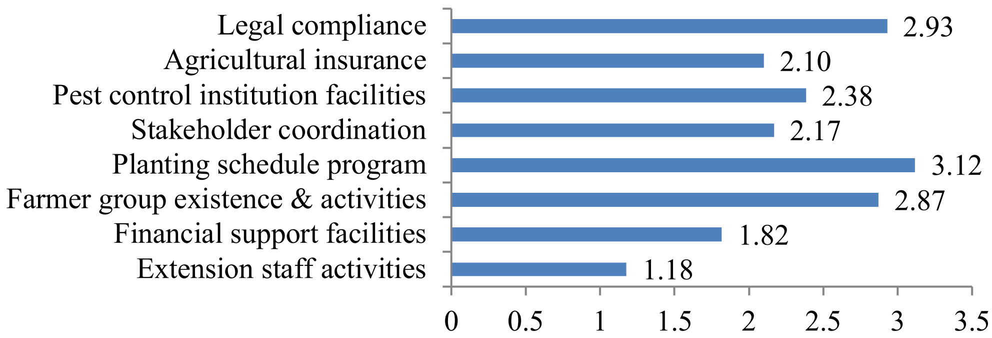

Figure 6. RMS values of leverage analysis of institution and policies

Discussion

The sustainability cultivation practices of the rainfed paddy fields in the Ipuh Sub-district are under strain, resulting in a less sustainable condition with an average score of 40.38. All evaluated dimensions could enhance sustainable rice agriculture and food security in this region, providing paddy farmers the opportunity to utilise their land for alternative purposes, particularly oil palm plantations. Compared to findings from previous research conducted in Kubu Raya Regency, West Kalimantan Province, rice cultivation on peat soils exhibited a relatively lower sustainability index, recorded at 47.05, indicating that most dimensions fell below sustainable thresholds. The dimension-specific index values were 48.77 for ecological, 50.02 for socio-cultural, 49.33 for economic, 46.70 for technological, and 43.24 for institutional aspects.

The primary ecological variables influencing sustainable rice agriculture in rainfed paddy soils in the Ipuh Sub-district were inherent soil fertility and soil acidity, with an overall ecological sustainability index of 45.92. The chemical characteristics of soil fertility and acidity greatly influenced sustainable rice growing in marginal tropical soil in Bengkulu. Agricultural activities on tropical soils are primarily constrained by several limiting factors, including low soil pH, reduced base saturation, and limited availability of essential nutrients (Hadi *et al*., 2019). These limitations are further compounded by decreased levels of exchangeable bases, along with low concentrations of total phosphorus and potassium (Hikmatullah and Sukarman, 2015). Additionally, deficiencies in key micronutrients such as iron (Fe), copper (Cu), zinc (Zn), manganese (Mn), and molybdenum (Mo) have been identified as critical challenges (Nelvia, 2014). To enhance soil acidity and nutrient levels in cultivated tropical soils, the application of lime, such as calcite or dolomite, together with fertilisers, is recommended. The amendments of limes and fertilisers may enhance soil pH, elevate nutrient availability, and augment soil adsorption for nutrient exchanges. In tropical soils with acidity levels between pH 5.0 and pH 5.6, the application of lime for soil amendment in rice cultivation necessitated dolomite quantities ranging from 2,600 kg ha-1 to 5,490 kg ha-1(Gultom and Mardaleni, 2017). Conversely, another study indicated that the application of dolomite up to 2,000 kg ha-1 positively influenced rice growth and yield in a linear trend. The fertility of tropical soils may be improved through optimal fertilisation (Allamah *et al*., 2018). A deficiency of nitrogen, phosphorus, and potassium minerals can hinder optimal plant growth, but an excess of these nutrients can impede growth and lead to environmental contamination (Duan *et al*., 2007). Rice yields were enhanced with the application of adequate levels of fertiliser N, P, and K (90 kg N, 90 kg P2O5, and 90 kg K2O per hectare) to rectify deficiencies and sustain soil fertility. The recommended nitrogen fertiliser application rates for rice are as follows: low productivity (5 tonnes ha−1) requires 200 kg urea ha−1, medium productivity (5-6 tonnes ha−1) necessitates 250-300 kg urea ha−1, and high productivity (>6 tonnes ha−1) demands 300-400 kg urea ha−1 (Buresh, 2010).

The third detrimental factor potentially undermining the viability of the Ipuh rainfed paddy field is the increase of oil palm cultivation. Proximate to rice fields, oil palm plantations expanded rapidly and extensively, with farmers' inclination to transform their rainfed rice fields into oil palm plantations influenced by numerous advantageous aspects. The rental cost of paddy fields, in comparison to oil palm, may significantly influence the transition to oil palm plantations, hence affecting rice farming under uncertain conditions. The land rent value from oil palm plantations exceeded that of paddy production, resulting in higher revenue. This, combined with many challenges encountered by small-scale rice farmers, rendered the sustainability of the land use system difficult to uphold (Daulay *et al*., 2016). Farmers were drawn to the transition from rice cultivation to oil palm plantations due to the desire to enhance their living standards, anticipating increased income, reduced labour requirements, and mitigated risks of harvest failure (Zahri *et al*., 2019).

The sustainability index of 41.46 for rice farming in the rainfed areas of Ipuh Sub-district signifies vulnerability in sustainability from an economic standpoint for smallholder paddy farmers. The economic factor that largely contributes to future uncertainty regarding the sustainability of rice production is that farmers harvested products, typically in the form of dried grain, are acquired by middlemen at low and unpredictable prices. The losses incurred by farmers selling grain in wet weather to middlemen are substantial. In other words, the substantial profit margin will be realised not by the farmers, but by the intermediaries and wholesalers. The diminished price of the dry grain harvest obtained by smallholder farmers resulted in reduced exchange revenue, an unfavourable benefit-cost ratio, diminished farmer income relative to the regional minimum wage, and inefficient agricultural food production. Rice farmers encountered numerous challenges in the agricultural practices, as all components of production remain non-technical, economically inefficient, and price-ineffective, although farming efficiency significantly contributes to enhancing farmers' income.

Paddy production demands significantly more labour than other agricultural tasks. Previous studies combined shown a favourable and statistically significant correlation between labour input and rice production. Diverse factors among farmers, including variations in educational attainment, age, and agricultural experience, affect rice cultivation productivity. A significant problem for future farming sustainability and food security is the ageing demographic of farmers (Marbun, 2024). Moreover, agricultural production depends on an ageing farmer demographic. This syndrome adversely affects both agricultural output and the sustainability of family farming, posing challenges to future food security. Older farmers exhibit diminished physical strength, mobility, and motivation, leading to a decline in agricultural productivity. Senior farmers generally exhibit diminished independence. They also receive diminished income. Unless they modify their agricultural practices (Jansuwan and Zander, 2021). The management of agriculture by ageing farmers leads to suboptimal production outcomes. Suboptimal agricultural outputs can lead to regional food insecurity, perhaps escalating to a broader scale (Ruiz Salvago *et al*., 2019). The absence of young farmers as a productives workforce results in agricultural production relying solely on ageing farmers.

The declining number of young professionals in agriculture indicates a diminished enthusiasm among the younger generation in pursuing careers in this field. These phenomena may affect the food crisis owing to the lack of individuals wanting to engage in agricultural cultivation. The dilemma of an elderly farming population and inadequate farmer replacement is becoming a significant issue in countries with population expansion, particularly in Indonesia. The youth in rural regions often lack the confidence required to pursue employment in agriculture, presenting a significant challenge. Sustainable agriculture faces threats from an ageing demographic and diminishing interest among the youth (Mercado and Osbahr, 2023). Farmer regeneration is crucial for the sustained viability and resilience of agricultural communities and food systems.

A significant issue observed in rice farming from socio-cultural perspectives in Ipuh Sub-district was the diminishing engagement of women in rice cultivation activities. The participation of women in the Malaysian agriculture sector continues to dwindle (Amran and Abdul Fatah, 2020).

Furthermore, the absence of involvement in the planning process and community groups constituted substantial barriers to the advancement of women's empowerment among rice farmers. In several developing nations, women persistently encounter obstacles in accessing agricultural knowledge and research for development projects, stemming from the belief that women are not engaged in farming (Mishra *et al*., 2017). Women constitute the foundation of the home economy and significantly contribute to agricultural operations in rural regions (Arumugam and Manida, 2023). Consequently, enhancing rural women's agricultural activities is a very successful method for increasing family income, as empowering women by providing access to resources will stimulate rural economic activity.

The use of pesticides is an effective method for reducing the risk of crop failure, provided that the pest population reaches its economic threshold (Yusuf and Syamsuddin, 2021). The utilisation of pesticides has a statistically significant and favourable effect on rice crop yields. Cultural, mechanical, and physical pest control measures with minimal chemical input constitute one of the most successful strategies for mitigating insect pests in rice within a contemporary integrated pest management framework. If misused, they can present significant health risks to humans, domestic animals, natural predators of agricultural pests, and other living forms due to unintended contamination of food, feed, water sources, and the environment (Rahaman *et al*., 2018). Consequently, via the deployment of integrated pest management, environmentally conscious individuals endeavoured to substitute pesticides with eco-friendly alternatives. Paddy farmers in this region continue to utilise chemical pesticides to manage pest and disease infestations. A comparable situation transpired in Indramayu Regency, where farmers utilised chemical pesticides at a rate of 75.6%, while biopesticide usage constituted only 24.4% (Ichdayati, 2022).

The excessive application of inorganic fertilizers has been linked to adverse environmental consequences, including greenhouse gas emissions and water contamination. Such negative impacts arise from nutrient leaching, the degradation of soil properties, and the buildup of toxic substances in water bodies (Tawakal *et al*., 2025). Therefore, minimizing the overuse of inorganic fertilizers is essential for maintaining agricultural sustainability and safeguarding environmental health. In contrast, the use of organic fertilizers offers a more sustainable alternative, as they contribute to improved soil structure and fertility by enhancing its physical, chemical, and biological characteristics. Organic amendments, such as manure, are rich in beneficial components including humic and fulvic acids, plant hormones, and enzymes, all of which are vital for soil vitality and plant development.

Furthermore, agricultural mechanization plays a vital role in enhancing productivity and improving the livelihoods of farmers in Indonesia, particularly in response to the increasing demand for food driven by population growth. Empirical studies across various Indonesian provinces have shown that rice farmers who adopted mechanized farming practices reported significantly higher productivity and income levels, alongside reduced labor expenditures, compared to those relying on manual labor (Chairunnisya *et al*., 2025). However, in the Ipuh Sub-district, the adoption of agricultural machinery remains limited due to a shortage of equipment and inadequate technical skills among farmers. Financial constraints pose a major barrier, especially for smallholder farmers, who lack the capital required to purchase or rent such costly machinery. Although mechanization could address the shortage of family labor, its implementation remains hindered by the unaffordability of the equipment. To support these small-scale farmers, access to microfinance and institutional credit facilities is essential. Additionally, government subsidies and policy interventions are crucial to facilitate the adoption of agricultural technologies and ensure the sustainability of food production systems (Wildayana, 2015).

Poor condition of the transportation infrastructure also could be a limiting factor for sustainability rice cultivation in Ipuh Sub-district paddy cultivation areas. This condition caused the transportation to bring the bulk grain harvest to market costly. The presence of muddy soils along farm roads significantly reduces their load-bearing capacity, compromising the stability and reliability of transportation infrastructure across rice cultivation areas. These roads often remain in poor condition and require frequent maintenance unless reinforced with durable materials such as concrete. Inadequate and inefficient rural transportation is widely recognized as a major constraint on agricultural productivity, as it not only limits market access for harvested crops but also escalates production costs (Aboyeji and Aguda, 2024). Improving the condition of rural transport infrastructure and services is essential for enhancing food security, promoting agricultural development, and supporting rural livelihoods. This is particularly critical for the timely and cost-effective movement of agricultural commodities, which are typically bulky, perishable, and of relatively low economic value.

Climate change is projected to significantly impact various regions of Indonesia throughout the 21st century, with an anticipated rise in the frequency and severity of agricultural droughts and irregular rainfall patterns. These climatic shifts are likely to increase the risk of rice crop failures. One notable consequence of climate change is the alteration of traditional crop sowing calendars across many paddy-growing areas in Indonesia. Accordingly, accurately determining optimal sowing periods has become essential to mitigate the negative effects of climate variability and enhance rice production outcomes. Traditional farmers which are inherited through hereditary customs sometime they were difficult to adapt government recommendation about planting schedule program. With limited knowledge and lack of opportunities to take part in training, their planting calendar always followed the prediction of dry season and wet season based on their previous knowledge. Currently, the integration of planting calendars with information technology—particularly in relation to recommended planting schedules and fertilizer dosages—offers numerous advantages for farmers by providing essential guidance on seed and fertilizer requirements. However, in practice, the use of this integrated system among farmers remains limited. It is predominantly utilized as a reference for determining fertilizer demand in relation to government subsidy programs, rather than being fully adopted as a decision-support tool for crop management (Setiapermas and Nurlaily, 2021).

The unpredictability of rice cultivation in Indonesia, largely driven by land-use changes, poses a significant challenge to agricultural production and national food security (Barchia *et al*., 2022). In response, both the central and local governments have recognized the urgency of preserving agricultural land to ensure food availability for present and future generations (Raharja *et al*., 2021). However, in practice, many local rice farmers in the Ipuh Sub-district continue to disregard the legal provisions outlined in the Law on the Protection of Sustainable Food Agricultural Land. Similar implementation challenges have also been observed more broadly, where the policy enforcement and administrative processes remain suboptimal (Anggalini *et al*., 2020).

Another significant issue causing the rainfed paddy cultivation sustainability in doubt was lack of training for capacity building to farmers and farmers group institution. To enhance the ongoing efforts toward agricultural sustainability, it is essential to strengthen community empowerment at both individual and institutional levels. This approach aims to foster awareness and build the capacity of local actors to manage rice production in a sustainable manner. Community empowerment serves as a critical driver in promoting efficient and effective rice cultivation practices that align with long-term sustainability goals. An actual participation and empowerment of local communities are practical indicators of the sustainable cultivation effectiveness. Therefore, facilitation from various stakeholders is needed to improve the institutional capacity of the community in managing the rice production activities. The extension of social innovation for the capacity building and network development could become an engine of the paddy cultivation sustainability.

Smallholder rice farmers often face financial limitations that prevent them from purchasing essential agricultural inputs and equipment in adequate quantities. As such, they require access to capital support to secure necessary resources for production. Additionally, during peak harvest periods when large volumes of rice are harvested simultaneously across extensive areas, farmers frequently encounter price suppression by intermediaries. This underscores the need for government intervention in the form of price protection and guaranteed procurement policies to stabilize farmers' incomes.

In the current context of increasing climate variability—marked by irregular rainfall, droughts, floods, and heightened vulnerability to pests and diseases—rice farmers are at heightened risk of crop failure. Consequently, many have advocated for agricultural insurance as a necessary form of government support. To foster sustainable agricultural practices, the government is encouraged to implement both fiscal and non-fiscal incentives. Fiscal incentives may include financial assistance programs, while non-fiscal measures should encompass legal clarity regarding agricultural insurance schemes and improved access to credit for local farmers. These initiatives must be accompanied by effective monitoring and evaluation frameworks involving relevant stakeholders to ensure accountability and effectiveness (Budiman *et al*., 2020).

Conflicts of interest

The authors declare no conflict of interest.

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