International Journal of Agriculture and Biosciences 2026 15(6): 3273-3289.
https://doi.org/10.47278/journal.ijab/2026.187
This is an open-access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).
RESEARCH ARTICLE
eISSN: 2306-3599; pISSN: 2305-6622

Multidimensional Sustainability Assessment of Rice Farming Systems Using the RAPFISH–MDS Approach: Evidence from Pangandaran Regency, West Java, Indonesia

Reny Sukmawani [1]*, Mai Fernando Nainggolan [2], Sri Ayu Andayani [3], Wa Ode Al Zarliani [4] and Muhamad Nurdin Yusuf [5]

[1]Faculty of Agriculture, Universitas Muhammadiyah Sukabumi, Indonesia
[2]Faculty of Agriculture, Universitas Santo Thomas Medan, Indonesia
[3]Faculty of Agriculture, Universitas Majalengka, Indonesia
[4]Faculty of Agriculture, Universitas Muhammadiyah Buton, Indonesia
[5]Faculty of Agriculture, Universitas Galuh, Ciamis, Indonesia
*Corresponding author: renysukmawani@ummi.ac.id

ABSTRACT

Rice is a strategic food commodity that underpins Indonesia national food security; therefore, ensuring the sustainability of rice farming systems remains a key priority in agricultural development. This study evaluates the sustainability status of rice farming in Pangandaran Regency using a multidimensional framework covering economic, social, ecological, institutional, and technological dimensions. The analysis employed the Rapid Appraisal for Rice Farming (RAPRF), adapted from the RAPFISH method and operationalized using Multidimensional Scaling (MDS). Data were collected from 258 rice farmers (n = 258), and a total of 39 sustainability attributes were assessed based on established sustainable rice farming criteria. Model reliability was evaluated using S-Stress values, coefficient of determination (R^2), leverage analysis, and Monte Carlo simulation at a 95% confidence level. The results show that the overall sustainability index reached 52.13, indicating a moderately sustainable rice farming system. The S-Stress value (<0.25) and R^2 (>0.90) confirm a strong model fit. Among the evaluated dimensions, the social dimension recorded the highest score (75.86), followed by the institutional (58.15) and technological (55.65) dimensions, while the economic (44.93) and ecological (47.18) dimensions were categorized as less sustainable and identified as the main limiting factors. Leverage analysis further revealed that paddy price stability and local labour absorption were key drivers within the economic dimension, while environmental legality and pesticide-related pollution were critical ecological determinants. Farmers' formal education, the role of cooperatives, and the use of certified superior seeds were also identified as strategic attributes influencing sustainability performance. The findings highlight structural imbalances across sustainability dimensions and emphasize the need for integrated improvement strategies. These results provide evidence-based guidance for policymakers to prioritize economic strengthening programs for farmers, enhance environmental governance, and promote sustainable agricultural technologies to improve long-term rice farming sustainability and regional food security resilience.

Keywords: Rice farming sustainability, Multidimensional scaling, RAPFISH adaptation, Sustainability assessment, Agricultural institutions, Indonesia.

Article History
Article # 26-141
Received: 23-Feb-26
Revised: 23-May-26
Accepted: 03-Jun-26
Online First: 02-Aug-26

INTRODUCTION

Rice plays a fundamental role in ensuring global food security and sustaining livelihoods across many regions worldwide (Ashfaq et al., 2023; Rupasinghe, 2024). As one of the most widely consumed staple foods, rice provides daily caloric intake for more than half of the global population, particularly in Asia, where rice-based diets dominate household consumption patterns (Abeysekara & Rathnayake, 2024; Hibatullah et al., 2024).

Cite this Article as: Sukmawani R, Nainggolan MF, Andayani SA, Zarliani WOA and Yusuf MN, 2026. Multidimensional sustainability assessment of rice farming systems using the RAPFISH–MDS approach: evidence from Pangandaran Regency, West Java, Indonesia. International Journal of Agriculture and Biosciences 15(6): 3273-3289. https://doi.org/10.47278/journal.ijab/2026.187

A Publication of Unique Scientific Publishers

According to recent global agricultural statistics published by the FAO (2023), global rice production reached approximately 787–800 million tons in 2023, with Asian countries contributing nearly 90% of total production. This concentration of production highlights the strategic importance of sustainable rice-based agroecosystems in maintaining global food supply stability, reducing hunger risks, and supporting rural economic resilience (Islam et al., 2025). Despite stable global production levels, the sustainability of rice farming systems continues to face increasing pressure due to population growth, environmental degradation, and climate variability, which collectively threaten long-term food security sustainability (Khatri et al., 2024; Naqvi et al., 2025; Aljaafreh, 2026).

In the Indonesian context, rice plays an even more critical role as the primary staple food consumed by the majority of the population. National rice production trends indicate both significant achievements and emerging sustainability challenges. Data from BPS - Statistics Indonesia (2023) indicate that the national harvested area of paddy reached approximately 10.20 million hectares, producing about 53.63 million tons of dry unhusked paddy (GKG), equivalent to approximately 30.90 million tons of rice for consumption. However, recent statistics reveal a gradual decline in production indicators. BPS - Statistics Indonesia (2025) reported that in 2024, the harvested area for rice production decreased to approximately 10.05 million hectares, with total production reaching 53.14 million tons of dry unhusked paddy, indicating a downward trend compared to previous years. Such declining trends highlight increasing pressure on agricultural land resources and demonstrate the vulnerability of rice production systems to environmental, climatic, and structural challenges.

One of the most significant sustainability challenges affecting rice farming systems is the rapid conversion of agricultural land into non-agricultural uses, including residential expansion, tourism infrastructure development, and industrial activities. Land conversion reduces the availability of productive farmland and increases production pressure on remaining agricultural areas, often resulting in intensified input use and environmental degradation (Prabhakar, 2021). Excessive use of chemical fertilizers and pesticides has contributed to declining soil fertility, water pollution, and biodiversity loss, which ultimately reduce long-term agricultural productivity (Imbiri & Wambrauw, 2025). Climate change introduces further uncertainties through irregular rainfall patterns, prolonged drought periods, and extreme weather events that disrupt cropping cycles and reduce yield stability (Nguyen-Thi-Kim et al., 2024). These interconnected environmental pressures demonstrate the urgent need for sustainable agricultural management strategies capable of balancing productivity with long-term ecological stability.

Beyond environmental challenges, socio-economic and institutional constraints also significantly influence the sustainability of rice farming systems. Many smallholder farmers face limited access to financial resources, fluctuating market prices, restricted access to modern technology, and insufficient institutional support. Such constraints reduce farmers' capacity to adopt sustainable agricultural practices and respond effectively to changing environmental conditions (Chang, 2024; Naik et al., 2025). Demographic challenges such as aging farmer populations and limited youth participation in agriculture threaten the continuity of farming systems in many rural areas (Shah et al., 2021). These conditions highlight the importance of adopting a multidimensional perspective in evaluating agricultural sustainability, as sustainability outcomes are shaped by complex interactions among ecological, economic, social, institutional, and technological factors (Nguyen et al., 2024; Fitriani et al., 2025).

The concept of agricultural sustainability has therefore evolved from productivity-oriented approaches toward multidimensional evaluation frameworks capable of capturing system-wide interactions. Contemporary sustainability research emphasizes that agricultural sustainability cannot be adequately assessed using single indicators such as yield or income alone. Instead, integrated frameworks that incorporate multiple sustainability dimensions are required to provide comprehensive insights into system performance and resilience. Multidimensional sustainability assessments enable researchers to identify critical constraints, evaluate system vulnerabilities, and support strategic decision-making for long-term agricultural development (Anam et al., 2025).

Among the various anal'ytical tools available for multidimensional sustainability assessment, the Rapid Appraisal for Fisheries (RAPFISH) framework has gained considerable attention due to its analytical flexibility and efficiency. Although initially developed for fisheries sustainability evaluation, RAPFISH has been widely adapted to agricultural sustainability assessment due to its ability to integrate multiple sustainability dimensions into a unified analytical model (Santoso et al., 2023). The method utilizes Multidimensional Scaling (MDS) to transform complex attribute data into sustainability index values that represent system performance across multiple dimensions. One of the key advantages of RAPFISH lies in its ability to identify leverage attributes that significantly influence sustainability outcomes, enabling policymakers to prioritize targeted intervention strategies. Such capabilities make RAPFISH particularly suitable for evaluating rice farming systems characterized by complex interactions among environmental, socio-economic, and technological factors.

Despite increasing attention to sustainability assessment in agriculture, several important limitations remain in existing research. Previous studies have focused primarily on productivity improvement or economic performance, often neglecting the integrated evaluation of ecological, social, institutional, and technological dimensions required to capture long-term sustainability dynamics (Nawaz et al., 2022). Furthermore, many sustainability assessments have been conducted at national or provincial levels, which may obscure localized variations in sustainability performance (Mariyono, 2024). Agricultural sustainability is inherently location-specific and strongly influenced by local agroecological characteristics, infrastructure availability, farmer capacity and institutional support systems. Consequently,

sustainability conditions may differ significantly across smaller administrative regions even within the same province (Rachman et al., 2022).

A particularly significant research gap exists at the district-level scale, where agricultural development programs and policy implementation are most frequently conducted (Syakirotin et al., 2025). District-level sustainability assessments are essential for generating localized evidence that supports targeted policy interventions and resource allocation. However, in Indonesia, including West Java Province, comprehensive multidimensional sustainability assessments of rice farming systems at the district level remain limited (Ismail et al., 2025). Existing studies often emphasize production trends and productivity improvements rather than integrated sustainability evaluation across multiple dimensions. This limitation results in insufficient empirical evidence regarding the sustainability status of rice farming systems and the identification of sensitive leverage attributes that influence sustainability outcomes at the local level.

This research gap is particularly evident in Pangandaran Regency, a developing agricultural region characterized by significant rice production potential and strong dependence on agriculture as a primary livelihood source. The region benefits from favourable agroecological conditions, including suitable rainfall patterns and fertile soil resources, which support rice cultivation activities. However, Pangandaran Regency also faces increasing sustainability challenges, including land-use pressure driven by tourism development, limited institutional capacity, fluctuating market accessibility, and environmental management constraints related to water resource utilization and soil conservation. Despite the strategic importance of rice farming in the region, comprehensive multidimensional sustainability assessments conducted specifically at the district level in Pangandaran Regency remain scarce. This lack of localized sustainability information limits the ability of local governments to formulate targeted development strategies and implement effective sustainability interventions.

Addressing these limitations requires the application of robust multidimensional analytical frameworks capable of integrating diverse sustainability indicators into a unified evaluation model. In this context, the application of RAPFISH to rice farming systems at the district level represents a novel and valuable contribution to agricultural sustainability research. Unlike previous studies that focus primarily on productivity or economic indicators, this study integrates five sustainability dimensions—ecological, economic, social, institutional, and technological—into a comprehensive assessment framework. The integration of these dimensions enables a more holistic understanding of sustainability performance and provides actionable insights into key leverage attributes influencing sustainability outcomes. Furthermore, by utilizing district-specific data from Pangandaran Regency, this study provides localized empirical evidence that supports evidence-based decision-making and targeted policy formulation.

Therefore, this study aims to evaluate the sustainability status of rice farming systems in Pangandaran Regency using a multidimensional analytical framework based on the Rapid Appraisal for Fisheries (RAPFISH) method. Specifically, this research assesses sustainability performance across ecological, economic, social, institutional, and technological dimensions, calculates sustainability index values using Multidimensional Scaling (MDS), identifies sensitive leverage attributes influencing sustainability outcomes, and formulates strategic recommendations for improving the sustainability of rice farming systems. By bridging the existing research gap at the district level and providing integrated sustainability analysis, this study contributes to strengthening sustainable agricultural development and enhancing food security resilience in Indonesia.

MATERIALS & METHODS

This study employed a stratified random sampling technique to ensure representative participation of rice farmers across different sub-districts in Pangandaran Regency. The stratification was based on geographical distribution and the concentration of rice farming activities within each sub-district. Within each stratum, respondents were selected randomly to minimize sampling bias and enhance the representativeness of the collected data.

The sample size of 258 rice farmers was determined using the Slovin formula, which is widely applied in agricultural and socio-economic research to estimate an appropriate number of respondents from a known population size. The formula is expressed as:

$$n = \frac{N}{1 + N(e)^2}$$

where n represents the sample size, N denotes the total population of rice farmers, and e refers to the acceptable margin of error (set at 5%). This approach ensures that the selected sample size provides statistically reliable estimates while maintaining feasibility in field data collection.

Scoring Criteria and Scale Definition

The scoring of sustainability attributes followed standardized procedures adapted from the RAPFISH (Rapid Appraisal for Fisheries) methodology developed by Kavanagh and Pitcher (2004). Each attribute was evaluated using a five-point ordinal scale ranging from 1 to 5, representing the level of sustainability performance. The scoring criteria were defined as follows:

Score 1 (Very Poor): The attribute condition is highly unsustainable and does not support system sustainability.

Score 2 (Poor): The attribute condition is below acceptable sustainability standards and requires significant improvement.

Score 3 (Moderate): The attribute condition meets minimum sustainability requirements but still requires improvement.

Score 4 (Good): The attribute condition supports sustainability with minor limitations.

Score 5 (Very Good): The attribute condition strongly supports sustainability and represents an optimal state.

This scoring approach ensures consistency in evaluating qualitative and quantitative indicators across multiple sustainability dimensions and has been widely validated in sustainability assessment studies using the RAPFISH framework (Kavanagh & Pitcher, 2004; Pitcher & Preikshot, 2001).

Validation of Sustainability Attributes

The selection and validation of sustainability attributes were conducted through a combined literature review and expert judgment approach. Initially, relevant attributes were identified from previous studies on sustainable rice farming and multidimensional sustainability assessment frameworks. These attributes were subsequently reviewed and validated through consultations with agricultural experts, including agricultural extension officers, academic researchers, and local practitioners with expertise in rice farming systems.

The validation process aimed to ensure that each attribute met three essential criteria: relevance, measurability, and applicability to local farming conditions. Attributes that did not adequately reflect the characteristics of rice farming systems in Pangandaran Regency were refined or excluded. This validation approach enhances the reliability and contextual relevance of the sustainability indicators used in the RAPRF analysis (Kavanagh & Pitcher, 2004).

Research Locations

Research locations based on the administrative division of West Java Province, Indonesia. The study was conducted in selected regencies and cities within the southeastern region of West Java Province, particularly in Tasikmalaya Regency, Ciamis Regency, Banjar City, and Pangandaran Regency (Fig. 1). The numbered blue circles (1–6) indicate specific sampling sites distributed across these administrative areas. Green areas represent regencies, red areas indicate cities, and purple dots denote regency capitals. Neighboring provinces, including Banten Province, Jakarta Special Capital Region, and Central Java Province, are shown to provide regional geographic context.

Multidimensional Scaling (MDS) Analysis

The sustainability status of rice farming in Pangandaran Regency was analysed using the Multidimensional Scaling (MDS) approach developed by the Fisheries Centre of the University of British Columbia. The MDS analysis was employed to assess the sustainability of rice farming systems across five dimensions, namely economic, social, ecological, institutional, and technological dimensions. These dimensions were constructed based on the principles, indicators, and criteria of the Indonesian Sustainable Rice Farming framework. The analysis applied the RAPRF (Rapid Appraisal for Rice Farming) ordination technique, which represents a modification of the RAPFISH (*Rapid Appraisal Technique for Fisheries*) method originally introduced by Kavanagh and Pitcher (2004).

The modification process involved refining and adjusting sustainability indicators within each dimension to ensure alignment with the characteristics, scope, and thematic focus of rice farming systems under investigation (Zega et al., 2025). Such adaptation allows the analytical framework to better capture the specific ecological, socio-economic, and institutional conditions relevant to agricultural sustainability assessment at the regional level.

The RAPRF-based sustainability (Table 1) analysis began with a comprehensive review, identification, and definition of agricultural attributes used in the assessment. Subsequently, each attribute was evaluated through a scoring process following standardized procedures established in the RAPFISH methodology. The scoring results were then processed using RAPFISH software integrated as an add-in within Microsoft Excel. Attribute scores organized in the *RapScores* matrix were analysed within the software environment to generate sustainability index values and ordination results.

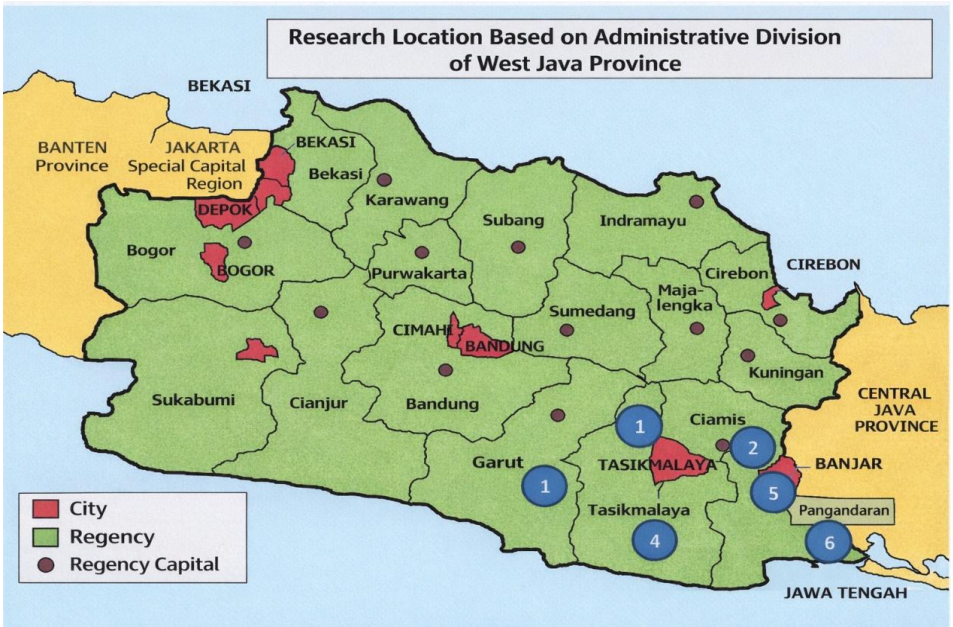

Fig. 1: Research Location.

Table 1: Attributes Employed in Each RAPRF Dimension

Component / Sector	Set of Attributes Used
Economic Dimension	(1) Rice farming productivity; (2) Economic feasibility of rice farming enterprises; (3) Market access for rice sales; (4) Rice price stability; (5) Local labor absorption in rice farming activities; (6) Changes in real wages of agricultural labor; (7) Contribution of rice farming income to household livelihoods
Social Dimension	Farmers' formal education level; Average age of farmers; Availability of agricultural infrastructure supporting farming activities; Access to education services; Access to healthcare services; Land dispute and conflict resolution mechanisms; Legal recognition
Ecology Dimension	Forest degradation or forest burning activities; Land suitability based on agroclimatic conditions for rice cultivation; Total managed rice cultivation area; Implementation of technical practices in rice cultivation and post-harvest transportation; Environmental pollution levels; Presence of buffer or boundary vegetation; Environmental permits and regulatory compliance; Conversion and utilization of forest land for agricultural purposes
Institutional Dimension	(1) Farming households receiving agricultural extension; (2) Participation in farmer groups; (3) Participation in farmer group associations; (4) Farmer group capital capacity; (5) Farmer group accessibility to banking; (6) Farmer access to technology sources; (7) The role of cooperatives in rice farming; (8) Recording of the application of SPPL (environmental management and utilization letter)
Technology Dimension	(1) Agricultural farming system; (2) Use of high quality, certified seeds; (3) Soil processing mechanisms; (4) Planting distance; (5) Use of fertilizer according to recommendations; (6) Time and method of fertilizer application; (7) Weeding; (8) Time and method of harvesting; (9) Management of plant pests (OPT);

To enhance analytical robustness and ensure result reliability, the sustainability assessment was further validated using Leverage Analysis and Monte Carlo Analysis. Leverage analysis was applied to identify sensitive attributes that significantly influence sustainability performance, while Monte Carlo simulation was conducted to evaluate the stability and uncertainty of the MDS estimation results. The set of attributes employed across each sustainability dimension within the RAPRF framework is presented in the following section.

The detailed analysis procedure (Fig. 2) using the RAPRF technique involved several stages, as follows:

1. Collecting data on agricultural conditions at the research site.
2. Interviewing rice farmers in Pangandaran Regency to analyze attribute data and research results.
3. Scoring sustainability aspects.
4. Conducting a Multidimensional Scaling (MDS) analysis using an Excel template to determine ordination and stress values using the ALSCAL algorithm.
5. Rotating rice farms to determine the position of good and bad ordination.
6. Conducting a sensitivity analysis (leverage analysis) and Monte Carlo analysis to account for uncertainty.

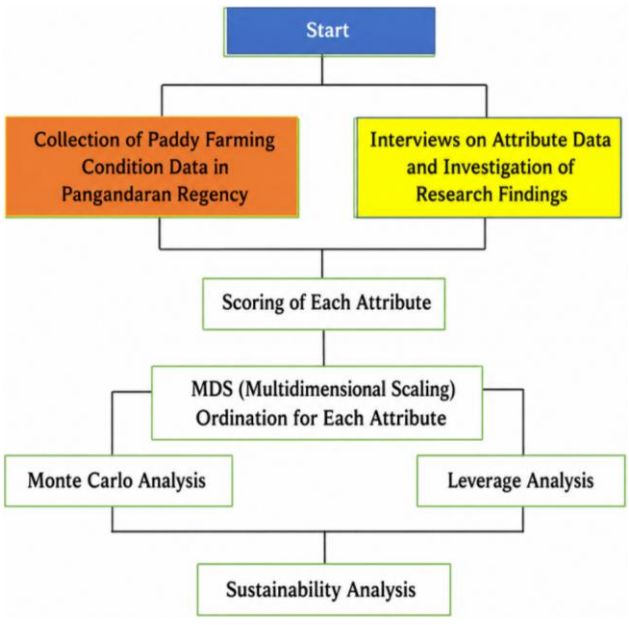

Fig. 2: RAPRF Analysis Stages.

Pitcher & Preikshot (2001) stated that MDS analysis in RAPFISH provides stable results when compared to other multivariate analysis methods. In MDS, two identical points or objects are mapped into one adjacent point. Conversely, dissimilar objects or points are depicted by points that are far apart. The ordination technique or distance determination in MDS is based on the Euclidean distance in n-dimensional space and the equation is as follows:

$$d = \sqrt{(x_1 - x_2|^2 + |y_1 - y_2|^2 + z_1 - z_2|^2 + \cdots)}$$

The ordinates of the object or point are then approximated by regressing the direction *euclidian* (d_{ij}) from point i to point j with origin ($^{\delta_{ij}}$). The equation is as follows:

$$d_{ij} = \propto + \beta\delta ij + \varepsilon$$

To regress the equation above, the method used is last squared alternating based on the Euclidean Distance root (square distance) or called the ALSCAL method.

This method optimizes the squared distance *(squareddistance = d_{ijklm})* to the square data (origin point = O_{ijklm}). In five dimensions (ijklm) it is called S-Stress according to the following equation:

$$S = \sqrt{\frac{1}{m}\sum_{k=1}^{m}[\frac{\sum_t \sum_f (d^2_{ijklm} - 0^2_{ijklm})^2}{\sum_t \sum_f 0^4_{ijklm}}]}$$

The squared distance is the Euclidean distance according to the equation:

$$d^2_{ijklm} = \sum wka(x_{ia} - x_{ja})^2$$

Following the ordination process, a *goodness-of-fit* assessment was conducted to evaluate the distance between the estimated points and the reference origin. The goodness-of-fit value reflects the magnitude of the S-Stress statistic and the coefficient of determination (R^2). According to Kavanagh and Pitcher (2004), a model is considered reliable when the S-Stress value is below 0.25 ($S < 0.25$) and the R^2 value approaches 1 (or 100%), indicating a strong model fit.

The stress value and coefficient of determination (R^2) serve as key indicators in determining whether additional variables are required, ensuring that the selected attributes adequately represent the characteristics of the evaluated

system. These parameters confirm the robustness of the ordination results and the extent to which the variables employed capture the comparative properties of the analysed sustainability objects.

The MDS analysis demonstrates that the sustainability position can be visually represented through horizontal and vertical axes derived from leverage analysis and Monte Carlo analysis. Leverage analysis was conducted to identify sensitive indicators influencing sustainability performance. Within the MDS framework, sensitivity (leverage) analysis aims to determine key indicators that significantly contribute to sustainability outcomes. These key indicators are identified based on leverage results reflected by changes in the Root Mean Square (RMS) values of ordination along the X-axis. Greater RMS changes indicate higher sensitivity of a given indicator in influencing improvements in sustainability status (Kavanagh & Pitcher, 2004).

Subsequently, a Monte Carlo analysis was performed to assess uncertainty within the analytical process. Monte Carlo analysis is employed to estimate the effects of random error occurring during data processing at a 95% confidence interval. In this study, the Monte Carlo approach functions as a simulation method to evaluate the impact of stochastic variability across all sustainability dimensions. The analysis was implemented using a scatter plot method illustrating the ordination distribution of each sustainability dimension. Furthermore, sustainability index values for each dimension were visualized using a kite diagram to provide an integrated representation of multidimensional sustainability performance, as presented in Fig. 3.

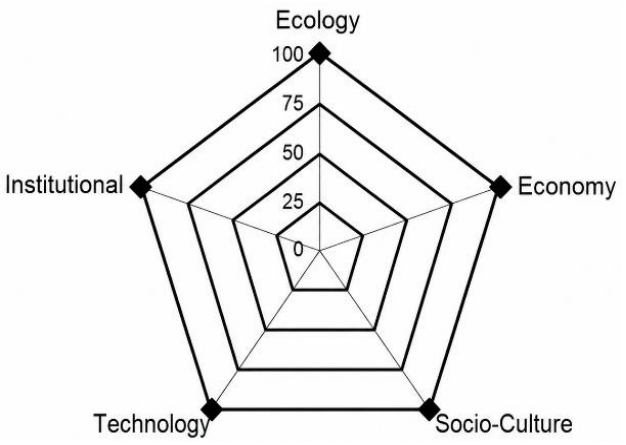

Fig. 3: Kite diagram illustrating the multidimensional sustainability analysis across ecological, economic, socio-cultural, technological, and institutional dimensions. The diagram presents sustainability index values on a scale of 0–100, providing an integrated visualization of the relative performance of each sustainability dimension.

Each indicator within the respective criteria was assigned a score based on the evaluators' scientific judgment. The scoring range varied from 1 (poor) to 5 (good), depending on the condition and performance level of each indicator. The obtained scores were subsequently analysed using a multidimensional approach to determine one or more ordination points representing the sustainability position across the five assessed dimensions, relative to two reference benchmarks, namely the *good* and *bad* anchor points.

The scoring results (Table 2) were processed using the RAPRF analytical framework to determine the sustainability status of rice farming systems, following the methodological approach proposed by Kavanagh and Pitcher, as adapted in Zega et al. (2025). This procedure enables the quantitative interpretation of sustainability performance through multidimensional ordination analysis.

Table 2: Categories Index Values and Sustainability Status

Index Values (%)	Sustainability Status
0 – 25	Bad- (not sustainable)
25 – 50	Less- (less sustainable)
50 – 75	Sufficient- (sufficiently sustainable)
75 – 100	Good- (very sustainable))

RESULTS & DISCUSSION

Characteristics of Respondent Farmers

The respondents in this study consisted of rice farmers engaged in paddy cultivation. Rice farmers are defined as individuals who independently manage rice farming activities, encompassing financial management, production practices, and the marketing of harvested outputs. The farmers included in this study were self-initiated landholders who independently opened and managed their agricultural land and were not affiliated with any specific company or corporate entity. A total of 258 rice farmers participated as respondents in this research.

The characteristics of rice farmers in Pangandaran Regency were analysed using descriptive statistical methods. The data were processed through grouping and tabulation, employing frequency distributions and mean values. These results were subsequently presented in a narrative form to provide an empirical overview of the primary data collected from respondents who were directly involved in rice farming management activities. The characteristics were examined based on four indicators, which are described in greater detail in the following table:

Table 3 presents the characteristics of the respondent farmers, namely rice farmers, which include age, level of formal education, farming experience in rice cultivation, and number of family dependents. Based on the processed data in Table 3, the results indicate that the majority of rice farmers are aged 42–52 years, accounting for 34.11% of respondents. This finding suggests that rice farmers in Pangandaran Regency are generally of productive age.

The majority of rice farmers had completed only primary education, accounting for 56.59% of the respondents. This finding indicates that the formal education level of rice farmers in Pangandaran Regency is relatively low. Therefore, further attention is needed, particularly through the provision of non-formal education programs such as agricultural extension services. In terms of farming experience, most rice farmers had between 11 and 20 years of experience, representing 37.98% of the respondents. Farming experience constitutes an important aspect of rice cultivation practices. The experience possessed by farmers, when complemented by extension services, may facilitate the adoption of improved practices and contribute to increased rice productivity.

Table 3: 1Percentage Distribution of Independent Farmers' Characteristics

Indicators of Independent Farmers' Characteristics	Perceptions of the Components of Independent Farmers' Characteristics	Number of Respondents (Persons)	Percentage (%)
Age (years)	1 = 20 – 30 years	11	4.26
	2 = 31 – 41 years	52	20.16
	3 = 42 – 52 years	88	34.11
	4 = 53 – 64 years	78	30.23
	5 = >64 years	29	11.24
	Total	258	100.00
Formal Education Level (years)	1 = No Formal Education	12	4.65
	2 = Primary School	146	56.59
	3 = Junior Secondary School	49	18.99
	4 = Senior High School	42	16.28
	5 = Tertiary education	9	3.49
	Total	258	100.00
Farming Experience (years)	1 = 0 – 10 years	63	24.42
	2 = 11 – 20 years	98	37.98
	3 = 21 – 30 years	60	23.26
	4 = 31 – 40 years	29	11.24
	5 = >40 years	8	3.10
	Total	258	100.00
Number of Household Dependents (persons)	1 = >4 persons	51	19.77
	2 = 4 persons	58	22.48
	3 = 3 persons	76	29.46
	4 = 2 persons	73	28.29
	5 = <2 persons	0	0
	Total	258	100.00

Source: Primary Data (processed).

The highest proportion of rice farmers in Pangandaran Regency reported having three family dependents, accounting for 29.46% of the respondents. Family dependents in this context include the household head, spouse, and children, referring to family members who remain financially dependent on the farming household head. The number of family dependents constitutes an important factor influencing household income allocation. A larger number of dependents generally implies higher household expenditures. Based on the conditions observed in the study area, it can be inferred that the overall household expenditures of farming families in Pangandaran Regency are relatively low.

Sustainability Status Analysis

Rice farming sustainability represents a framework that describes sustainability status based on predetermined sustainability indicators (Fuhrmann-Aoyagi et al., 2024). The assessment of the sustainability status of rice farming in Pangandaran Regency was conducted using the RAP–Rice Farming (RAPRF) method through a multidimensional approach encompassing five sustainability dimensions: economic, social, ecological, institutional, and technological dimensions. The statistical parameters employed in this study included Monte Carlo analysis, S-Stress values and the coefficient of determination (R^2). The RAPRF analysis generated goodness-of-fit values reflected in the S-Stress and R^2 statistics. According to Kavanagh and Pitcher (2004), a model is considered robust when the S-Stress value is less than 0.25 and the R^2 value approaches 1 (100%). The S-Stress values obtained for each dimension as well as for the multidimensional analysis were all below 0.25. The closer the S-Stress value is to zero, the better the model fit. The resulting S-Stress and R^2 values indicate that all attributes analysed, both dimensionally and multidimensionally, satisfy the statistical criteria and are appropriate for explaining the sustainability status of rice farming (Zega et al., 2025).

Table 4 shows that the S-Stress values range from 0.13 to 0.17, while the R^2 values range from 0.92 to 0.94. These results indicate that the goodness-of-fit criteria of the RAPRF analysis have been satisfactorily met. The difference between the Multidimensional Scaling (MDS) analysis and the Monte Carlo simulation at a 95% confidence level (5% significance level) ranges from 0.01 to 1.65. This finding suggests that the potential error resulting from scoring bias in the analysis is relatively small. Since the difference between the two analytical approaches is less than 5%, the MDS results are considered adequate for estimating the sustainability index, indicating that the rice farming system can be categorized as sustainable.

Table 4: Goodness-of-Fit Results of the RAPRF Analysis and Sustainability Status of Rice Farming in Pangandaran Regency

Criteria	MDS	Monte Carlo	Difference in Sustainability Index	S-Stress	R^2
Multidimensional	52.13	51.47	0.66	0.177	0.927
Economic	44.93	44.86	0.07	0.148	0.942
Social	75.86	76.48	0.62	0.144	0.947
Ecological	47.18	47.19	0.01	0.136	0.941
Institutional	58.15	57.55	0.60	0.147	0.945
Technological	55.65	54.00	1.65	0.147	0.948

Source: Primary Data (processed).

Multidimensional Sustainability Status of Rice Farming

The results of the multidimensional RAPRF analysis using the Multidimensional Scaling (MDS) method indicate that the sustainability index of rice farming in Pangandaran Regency is 52.13. This value falls within the range of 51–75 and is classified as moderately sustainable. The analysis yielded an S-Stress value of 0.177 and an R^2 value of 0.927, as illustrated in the following ordination scale:

Based on the results of the RAPRF analysis presented in Fig. 4, the multidimensional sustainability index of rice farming in Pangandaran Regency is 52.13. This value is derived from a composite analysis

integrating all sustainability dimensions—economic, social, ecological, institutional, and technological—referred to as the multidimensional analysis. From this combined assessment, the economic and ecological dimensions exhibit the lowest index values and therefore exert the greatest influence on the overall multidimensional sustainability result. According to Kavanagh & Pitcher (2004), in MDS analysis, index values within the range of 51–75 are categorized as moderately sustainable. This classification reflects the fact that, among the five sustainability dimensions evaluated in this study, two dimensions—economic and ecological—are categorized as less sustainable. The analysis further indicates that the research hypothesis was not supported; however, the sustainability of rice farming in Pangandaran Regency can still be considered maintained within the applied assessment framework. Therefore, it can be concluded that rice farming in Pangandaran Regency is moderately sustainable.

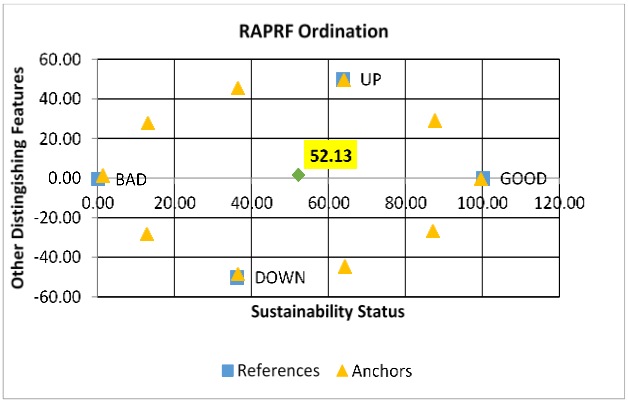

Fig. 4: Sustainability Index of Rice Farming in Pangandaran Regency.

Each dimension comprises specific attributes that serve as parameters for assessing the sustainability of rice farming in Pangandaran Regency. The sustainability index value was derived from the evaluation of 39 sustainability attributes distributed across the respective dimensions. A more detailed description of these attributes is presented in the following Fig. 5.

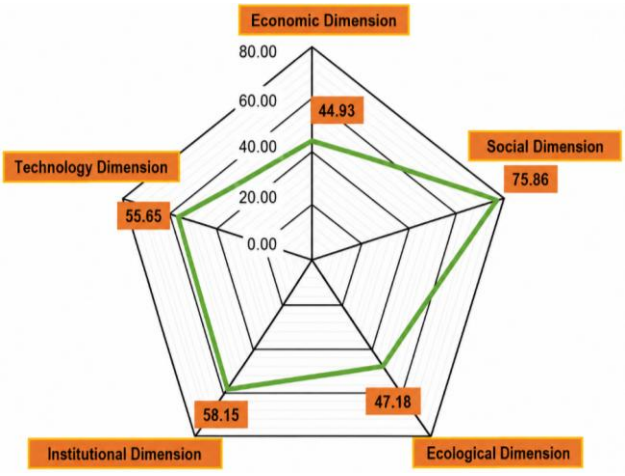

Fig. 5: Radar Chart of the Rice Farming Sustainability Index in Pangandaran Regency.

The sustainability index values of each dimension projected in the kite diagram (Fig. 5) indicate that the farther the sustainability point extends from zero, the higher the sustainability level. Based on the kite diagram, the economic dimension exhibits the lowest sustainability index value, followed sequentially by the ecological, technological, and institutional dimensions, while the social dimension demonstrates the highest index value. The sustainability index values of each dimension, as illustrated in the kite diagram, are not yet well-balanced, suggesting that the implementation of sustainability across the respective dimensions has not been evenly and proportionally achieved. The kite diagram provides an integrated visualization of the sustainability status of rice farming in Pangandaran Regency across multiple sustainability dimensions.

Economic Dimensions

The economic dimension represents one of the most critical criteria in assessing the sustainability of rice farming in Pangandaran Regency (Fig. 6). According to Zega et al. (2025), the economic dimension refers to the capacity of rice farming systems to sustainably meet the needs of rice farmers. Rice farming is considered sustainable when it contributes to improving the economic welfare of the farming community. The economic dimension is also a fundamental responsibility within the concept of sustainable development. As stated by Zboroń (2020), economic success implies the prudent utilization of financial resources to enhance societal welfare. In this study, seven attributes were employed to measure the economic dimension using the RAPRF analysis, namely: (a) rice farming productivity; (b) feasibility of rice farming enterprises; (c) market access for rice; (d) rice prices; (e) local labour absorption; (f) changes in real wages of local labour; and (g) the contribution of rice income to household income.

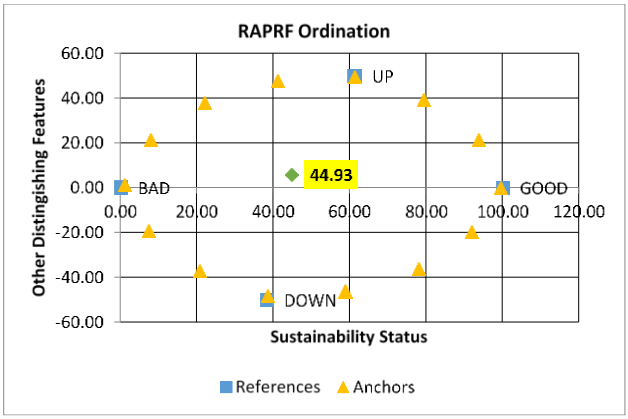

Fig. 6: Position of the Economic Dimension Sustainability Status.

RAP–Rice Farming (RAPRF) Analysis

The results of the Economic Dimension analysis of rice farming sustainability in Pangandaran Regency, conducted using the RAPRF software across all relevant attributes, indicate that the sustainability index value for the Economic Dimension is 44.93. This value falls within the range of 26–50 and is therefore classified as "less

sustainable," in accordance with the categorization proposed by Kavanagh & Pitcher (2004).

The ordination analysis of the Economic Dimension, conducted with two iterations, produced an R^2 value of 0.9426 and an S-Stress value of 0.14 (14%). These results indicate that the goodness-of-fit of the Economic Dimension analysis in this study can be categorized as fair. According to Kavanagh & Pitcher (2004), Multidimensional Scaling (MDS) analysis is considered acceptable when the S-Stress value is less than 25% (<0.25) and the R^2 value approaches 1 (100%). These findings suggest that the attributes tested within the Economic Dimension adequately explain the model, approaching a near-perfect fit relative to the original model

Sensitivity (Leverage) Analysis

The sensitivity analysis of the Economic Dimension, conducted using the leverage analysis method in the RAPRF software, indicates that among the seven evaluated attributes (Fig. 7), two attributes are particularly sensitive and exert the greatest influence on the sustainability of rice farming in Pangandaran Regency: (1) local labour absorption (RMS = 5.38) and (2) paddy grain prices (RMS = 5.35).

Nguyen et al. (2024) argue that the higher the leverage value, the more sensitive the attribute is in influencing the sustainability of rice farming systems.

These findings indicate that efforts to enhance the sustainability status of the Economic Dimension in rice farming management in Pangandaran Regency should prioritize and carefully consider these two key attributes. The first attribute exerting the greatest influence on the sustainability of rice farming in Pangandaran Regency within the Economic Dimension is local labour absorption. Based on field observations, the results suggest that the absorption of local labour in rice farming activities in Pangandaran Regency has not yet been optimized.

The second attribute that most significantly influences the sustainability of smallholder rice farming in Pangandaran Regency within the Economic Dimension is the price of paddy grain. Field observations revealed that all rice farmers in Pangandaran Regency sell their harvest directly to middlemen (local traders) at a price of IDR 6,500 per kilogram (the prevailing price at the time of the study). The price difference between rice mills and middlemen ranges from IDR 4,500 to IDR 5,500, representing approximately 80%–85%. This situation occurs because rice farmers in Pangandaran Regency do not have cooperative institutions to support and facilitate collective rice marketing. As a result, rice farmers in Pangandaran Regency function primarily as price takers rather than price makers within the market structure.

Monte Carlo Analysis

The Monte Carlo analysis was conducted to assess the stability of the ordination results obtained through 25 iterations. The results of the Monte Carlo simulation for the Economic Dimension are presented in Fig. 8. Based on the Monte Carlo simulation, the ordination points do not exhibit significant dispersion, indicating that the ordination results are stable. This stability suggests that the model reliably represents the sustainability status of rice farming in Pangandaran Regency.

Social Dimension

The social aspect constitutes an essential criterion in achieving sustainable rice farming. It represents one of the key pillars of sustainable development, contributing to rural development and poverty alleviation (Ogbari et al., 2024). The social aspect is also one of the three primary dimensions of sustainability, referring to the continuous fulfilment of basic human needs, including security, justice, freedom, education, employment, and recreation.

According to Yan et al. (2025), sustainability within the Social Dimension reflects the capacity of rice farming systems to function as a medium for social interaction.

In this study, seven attributes were employed to assess the sustainability of the Social Dimension of rice farming in Pangandaran Regency, namely: (a) farmers' formal education level; (b) average age of farmers; (c) availability of agricultural infrastructure; (d) access to education; (e) access to healthcare services; (f) resolution of land dispute conflicts; and (g) legal recognition and protection of land rights and community welfare.

1) RAP–Rice Farming (RAPRF) Analysis

Based on the RAPRF analysis using seven attributes within the Social Dimension, the sustainability index value of the Social Dimension of rice farming in Pangandaran Regency is 75.86. This value falls within the range of 51–75 and is therefore classified as "moderately sustainable. The sustainability position of the Social Dimension is illustrated in greater detail in Fig. 9.

The RAPRF analysis indicates that the sustainability position of the Social Dimension of rice farming in Pangandaran Regency falls at a value of 75.86. This result demonstrates that the Social Dimension sustainability index is higher than that of the Economic Dimension.

The ordination analysis, conducted with two iterations, shows a goodness-of-fit categorized as fair, with a coefficient of determination (R^2) of 0.947 and an S-Stress value of 0.14 (14%). These results satisfy the statistical criteria for Multidimensional Scaling (MDS) analysis

Leverage-Based Sensitivity Analysis

Based on the results of the sensitivity (leverage) analysis conducted on the seven attributes of the Social Dimension, one attribute was identified as having the highest leverage value, as shown in Fig. 10. This attribute is the farmers' formal education, with an RMS (Root Mean Square) value of 5.9%. The leverage analysis was performed to determine which attributes are most sensitive in influencing the sustainability of the Social Dimension of rice farming in Pangandaran Regency. According to Zega et al. (2025), the greater the change in the RMS value, the more sensitive the attribute is in contributing to the improvement of sustainability status.

The most sensitive attribute influencing the sustainability status of the Social Dimension of rice farming in Pangandaran Regency is the formal education of farmers. Education is a key indicator of human resource quality development. The level of education typically affects the ability to adapt to new technologies, and

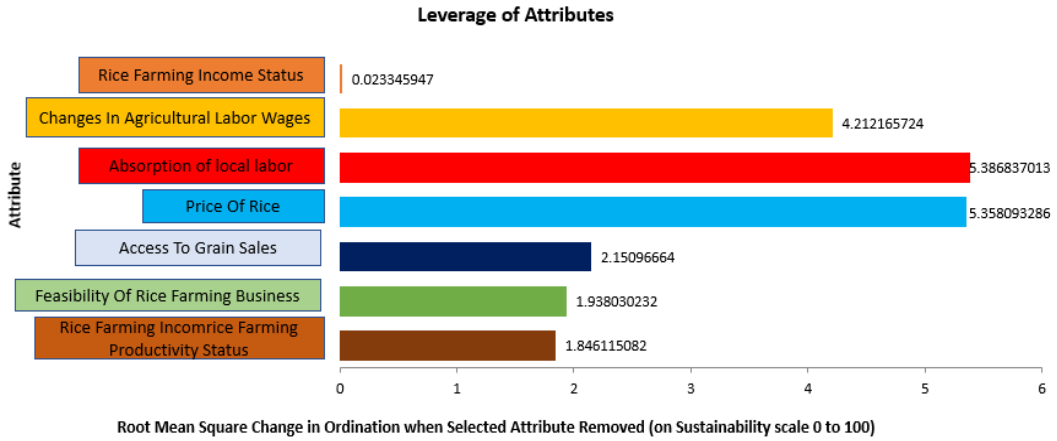

Fig. 7: Leverage Analysis Results for the Economic Dimension.

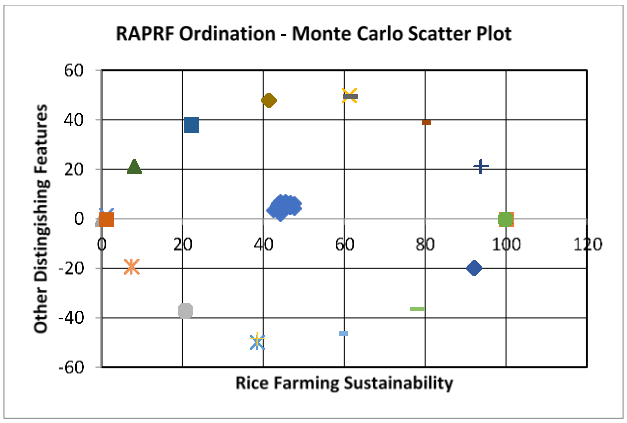

Fig. 8: Stability of RAPRF Ordination Results in the Economic Dimension.

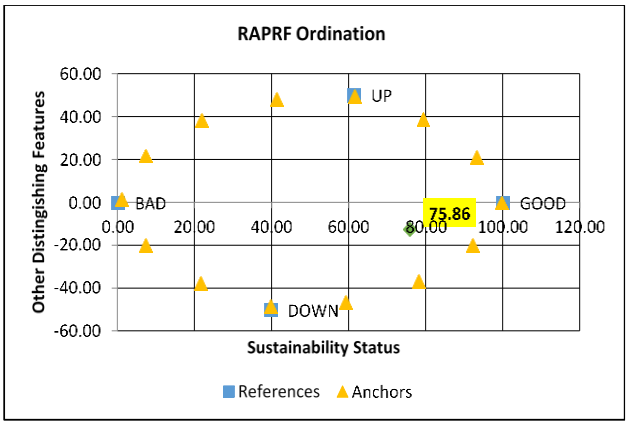

Fig. 9: Sustainability Position of the Social Dimension.

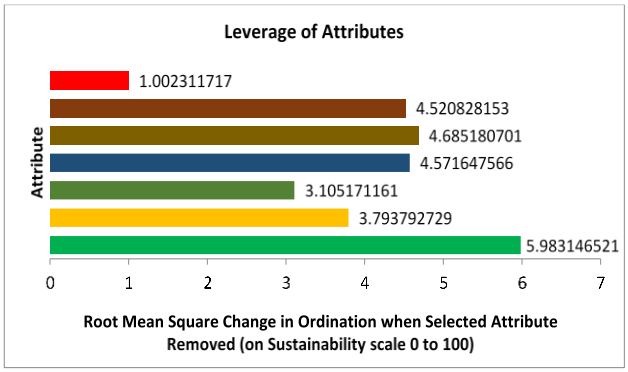

Fig. 10: Leverage Analysis Results for the Social Dimension.

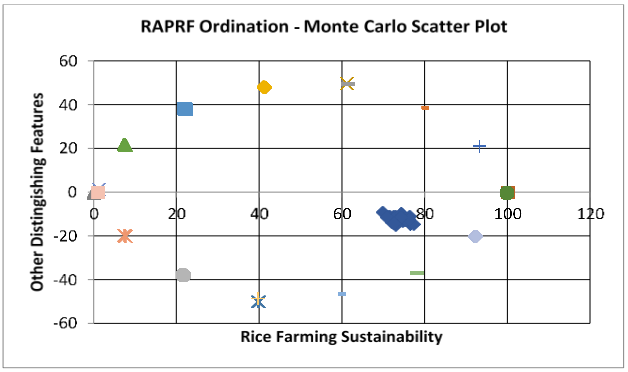

Fig. 11: Stability of RAPRF Ordination Results in the Social Dimension.

farmers' educational background can indirectly influence the adoption of sustainable practices. Field observations indicate that the formal education level of rice farmers in Pangandaran Regency is relatively low, with the majority having completed only primary school (SD). Among the 258 rice farmers who participated as respondents, 146 individuals (56.59%) were primary school graduates. Several farmers reported that education was not considered very important at the time they were pursuing schooling, while others indicated that economic factors played a role in limiting their educational attainment. Many farmers chose to work directly on managing their land rather than continuing formal education.

This finding also indicates that efforts to improve the sustainability status of the Social Dimension of rice farming in Pangandaran Regency should prioritize the formal education of farmers. Low educational attainment may negatively impact the sustainable management of rice farming. According to Soekartawi (1988), education is considered a key means of enhancing knowledge about new technologies. However, the relationship between education and the adoption of agricultural innovations may be indirect, except for those who have received specific training on new innovations.

Monte Carlo Analysis

The Monte Carlo analysis was conducted to assess the stability of the ordination results. Monte Carlo analysis, also referred to as uncertainty analysis, is used to estimate the influence of random errors in the analysis process within a 95% confidence interval. This method accounts for uncertainty in the modelling process. Based on the Monte

Carlo analysis, which was performed with 25 iterations, the ordination points show no significant dispersion and remain concentrated at a single location, indicating that the ordination is stable, as illustrated in Fig. 11.

Ecological Dimension

One of the key requirements for sustainable natural resource management (NRM) is the maintenance of the original functions of natural resources. In addition, management practices should meet the criteria of eco-efficiency, meaning they must be efficient both economically and ecologically. Kospa (year) emphasizes that sustainable rice farming must consider the surrounding natural resources at all stages: prior to land management, during land clearing, and throughout ongoing farming operations.

The ecological dimension is a key factor, as it determines the balance between the utilization of natural resources and the provision of ecosystem services. Ecological attributes were selected to reflect how natural resource and environmental management impacts sustainability from an ecological perspective. Inefficient allocation of natural resources can compromise future growth and development.

In this study, the sustainability of the Ecological Dimension of rice farming in Pangandaran Regency was assessed using eight measurement attributes, analysed through the RAPRF method: (a) forest damage or burning; (b) agroclimatic suitability for rice cultivation; (c) area of rice fields managed; (d) implementation of rice cultivation and transportation techniques; (e) environmental pollution; (f) presence of legume cover crops (LCC); (g) environmental permits and legal compliance; and (h) use of forest land conversion.

RAP–Rice Farming (RAPRF) Analysis

Based on the RAPRF analysis, the sustainability index of the Ecological Dimension of rice farming in Pangandaran Regency is 47.18, which falls into the "less sustainable" category, as shown in Fig. 12. This indicates that the sustainability status of the Ecological Dimension is similar to that of the Economic Dimension. This condition is attributed to the limited awareness and understanding among rice farmers in Pangandaran Regency regarding the importance of maintaining environmental conservation, which is essential for ensuring the sustainability of rice production.

Ecological Dimension Sustainability Analysis

The ordination analysis of the ecological sustainability dimension was conducted using two iterations, resulting in a coefficient of determination value of (R^2 = 0.941) and an S-Stress value of 0.13 (13%). These results indicate that the ecological sustainability analysis of rice farming systems in Pangandaran Regency demonstrates an acceptable (*fair*) level of goodness of fit and satisfies the statistical requirements of a reliable Multidimensional Scaling (MDS) analysis. The relatively high (R^2) value and low stress level confirm that the model adequately represents the multidimensional relationships among ecological sustainability attributes.

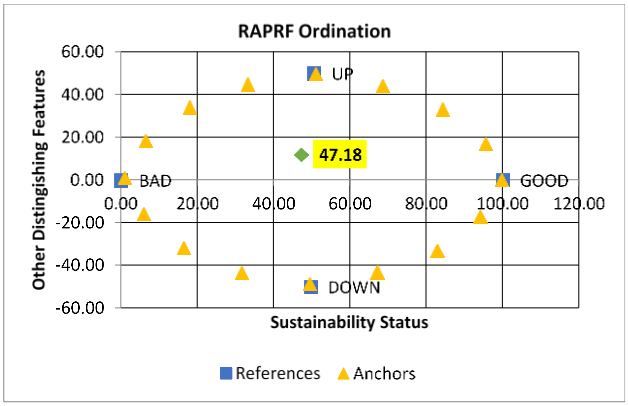

Fig. 12: Position of Ecological Dimension Sustainability Status.

Sensitivity Analysis (Leverage Analysis)

Leverage analysis represents an advanced analytical stage following the RAPRF assessment and is intended to identify the most sensitive attributes influencing the ecological sustainability dimension. Fig. 13 shows the results of the leverage analysis, which reveal three key attributes that exert the strongest influence on the ecological sustainability of rice farming in Pangandaran Regency. These include: (1) environmental licensing and regulatory compliance, with a Root Mean Square (RMS) value of 7.7; (2) environmental pollution, with an RMS value of 7.1; and (3) the presence of legume cover crops (Legume Cover Crop/LCC), which demonstrates the highest sensitivity with an RMS value of 8.3.

These findings indicate that environmental governance, ecological management practices, and biological soil conservation strategies play a critical role in strengthening the sustainability performance of rice-based agroecosystems at the regional level.

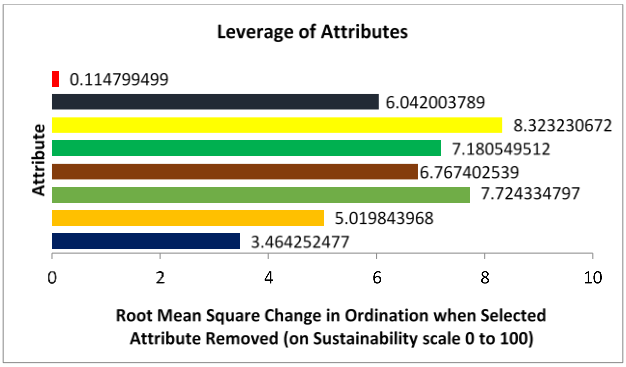

Fig. 13: Results of the Ecological Dimension Leverage Analysis.

The first attribute influencing the sustainability of the ecological dimension of rice farming in Pangandaran Regency is environmental licensing and land legality. One of the fundamental principles required to achieve sustainable rice agriculture is secure land tenure, which is demonstrated through legally recognized land ownership documents such as land certificates, land sale and purchase agreements (*Akta Jual Beli*), and other valid ownership evidence. Field observations indicate that the

majority of farmers already possess legally certified land ownership, while a smaller proportion are currently undergoing administrative processes to formalize land legality. Secure land tenure contributes positively to ecological sustainability, as it encourages farmers to adopt long-term land management practices and sustainable resource utilization.

The second attribute affecting ecological sustainability is environmental pollution, particularly pollution resulting from improper pesticide application. The study identified that several rice farmers still maintain the perception that higher pesticide dosages accelerate weed and pest mortality while preventing regrowth. Consequently, pesticide applications are sometimes conducted excessively and without adherence to recommended timing, including spraying during the rainy season. Such practices raise concerns regarding environmental contamination, especially surface water pollution, considering that Pangandaran Regency is traversed by a major watershed, namely the Citanduy River. These findings highlight the need for strengthened farmer capacity-building programs and continuous education on appropriate pesticide management aligned with Integrated Pest Management (IPM) principles to minimize ecological risks and promote environmentally responsible farming practices (Abdullahi et al., 2026; Rasool & Qadir, 2026).

Monte Carlo Analysis

Monte Carlo analysis was conducted to evaluate the stability and robustness of the ordination results obtained from the Multidimensional Scaling (MDS) analysis through 25 simulation iterations. The Monte Carlo simulation results for the ecological dimension are presented in Fig. 14. The analysis indicates that the ordination points are closely clustered and do not exhibit significant dispersion, demonstrating a high level of stability in the ordination configuration. These results confirm that the MDS analysis for the ecological dimension is statistically reliable and that the sustainability assessment outcomes can be considered robust and consistent.

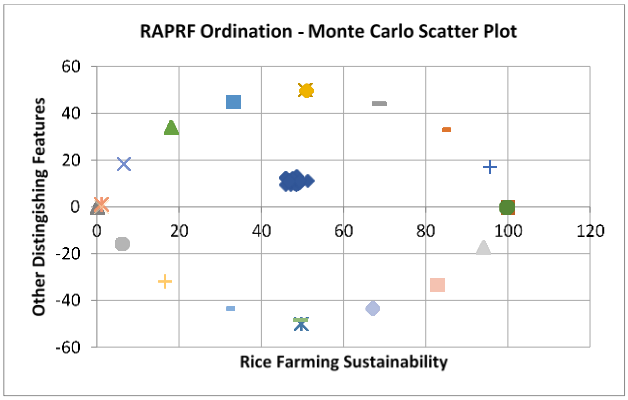

Fig. 14: Stability of RAPRF Ordination Values in the Ecological.

Institutional Dimension

The institutional dimension constitutes a fundamental component in assessing the sustainability of rice farming systems. Institutional sustainability reflects the capacity of farmer organizations to integrate and effectively perform institutional functions that facilitate agricultural production activities. Institutional parameters serve as indicators of the availability of regulatory frameworks and organizational structures that support the sustainable utilization of natural resources. From an institutional perspective, the absence or limited functionality of farmer organizations—such as agricultural cooperatives, efficient marketing networks, and village-level financial institutions—reduces motivational and structural incentives for farmers to expand production scale through the adoption of modern and value-added agricultural technologies.

The success of rice-based agribusiness systems largely depends on strong institutional support. Institutional arrangements represent a critical prerequisite for ensuring efficiency, coordination, and continuity in rice farming operations, thereby contributing to long-term sustainability. Effective institutions also play a vital role in improving farmers' access to government assistance programs, financial services, technological innovation, and capacity-building initiatives.

The sustainability assessment of the institutional dimension of rice farming in Pangandaran Regency was conducted using eight measurement attributes: (a) farmer households receiving agricultural extension services; (b) participation in farmer groups; (c) participation in farmer group associations; (d) financial capacity of farmer organizations; (e) accessibility of farmer groups to banking institutions; (f) farmers' access to technological resources; (g) the role of cooperatives in rice farming activities; and (h) documentation and implementation of Environmental Management and Monitoring Statements (*SPPL*).

RAP–Rice Farming (RAPRF) Analysis

Based on the RAPRF analysis results for the institutional dimension, the sustainability index value of rice farming in Pangandaran Regency reached 58.15, which falls within the range of 51–75, indicating a "moderately sustainable" category. The ordination point position is illustrated in Fig. 15. These findings suggest that although institutional performance has contributed positively to sustainability, significant improvements and strengthening efforts remain necessary to enhance institutional effectiveness and support future sustainable rice farming development.

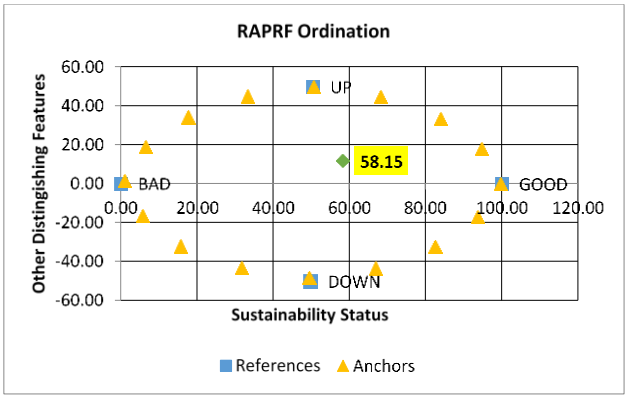

Fig. 15: Institutional Dimension Sustainability Status Position.

The RAPRF analysis within the institutional dimension was conducted through two iterations, resulting in a coefficient of determination value of R^2 = 0.945 and an S-Stress value of 0.147 (14.7%). These results indicate that the goodness-of-fit of the sustainability analysis for the institutional dimension of rice farming in Pangandaran Regency falls within a fair and acceptable category, thereby satisfying the statistical requirements of a reliable Multidimensional Scaling (MDS) analysis. The obtained stress value demonstrates that the ordination model adequately represents the multidimensional data structure used to assess institutional sustainability performance.

Sensitivity (Leverage) Analysis

Sensitivity analysis was performed to identify the most influential attributes affecting the sustainability of the institutional dimension of rice farming in Pangandaran Regency. The leverage analysis results revealed two key sensitive attributes that significantly contribute to institutional sustainability performance: (1) the role of agricultural cooperatives in rice farming activities, and (2) documentation and implementation of Environmental Management and Utilization Permits (SPPL — *Environmental Management and Monitoring Statement Letter*). These attributes represent critical leverage factors that determine institutional effectiveness in supporting sustainable rice farming systems, as illustrated in Fig. 16.

The first attribute identified as the most sensitive factor influencing the sustainability of the institutional dimension, with a Root Mean Square (RMS) value of 3.8, is the role of cooperatives in rice farming systems. This finding indicates that improving the sustainability status of the institutional dimension of rice agriculture in the future requires strengthening cooperative institutions within rice farming activities. The study results revealed the absence of formal agricultural cooperatives in Pangandaran Regency. Currently, rice farmers in the region are primarily organized under farmer groups (*Kelompok Tani*) and farmer group associations (*Gapoktan*), which function as the main institutional structures supporting farming activities. The lack of cooperative institutions limits farmers' access to collective economic services, financing mechanisms, and market strengthening initiatives. Therefore, stronger policy intervention and institutional facilitation from the Pangandaran Regency Government are required to promote the establishment and development of agricultural cooperatives in the region.

The second most sensitive attribute affecting institutional sustainability is the documentation and implementation of SPPL (*Environmental Management and Monitoring Statement Letter*), with an RMS value of 3.04. Field findings indicate that farmer groups in Pangandaran Regency generally lack awareness regarding SPPL obligations and have never received formal dissemination or technical guidance related to its implementation and reporting procedures. This condition reflects institutional and regulatory gaps in environmental governance at the farm level. Consequently, enhancing the sustainability of the institutional dimension requires systematic socialization programs, training, and technical assistance on SPPL compliance facilitated by local government authorities to improve farmers' environmental management capacity.

Monte Carlo Analysis

Monte Carlo analysis was conducted to evaluate the stability and reliability of the ordination results obtained from the Multidimensional Scaling (MDS) analysis, using 25 simulation iterations. The Monte Carlo simulation results for the institutional dimension of rice farming sustainability in Pangandaran Regency demonstrate that the ordination points converge within a single cluster, indicating a high level of stability in the ordination configuration. This outcome confirms that the sustainability index generated through the MDS approach is statistically robust and minimally affected by scoring uncertainty or random variation (Fig. 17).

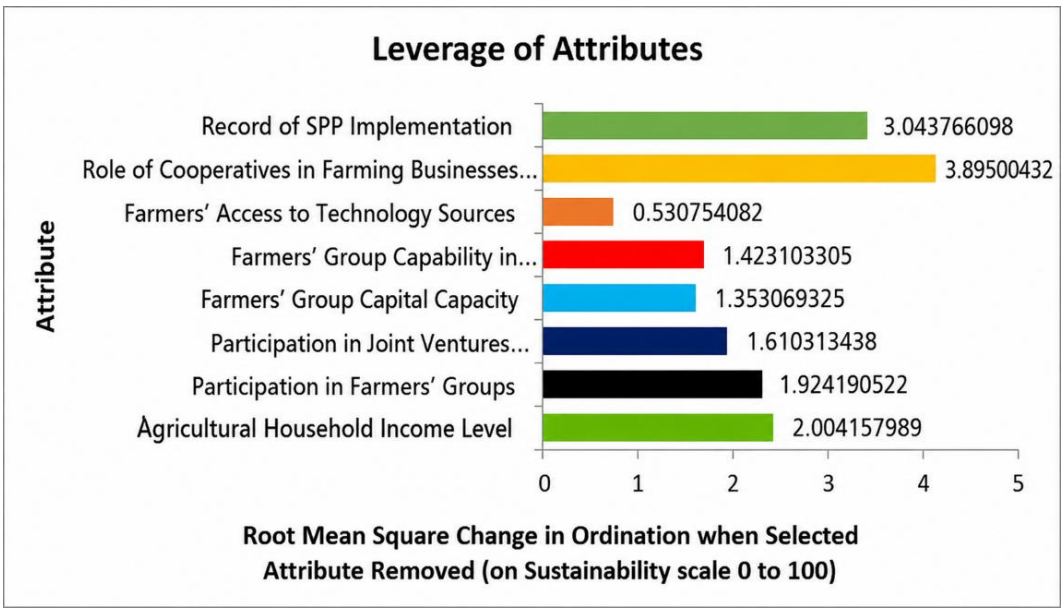

Fig. 16: Results of Institutional Dimension Leverage Analysis.

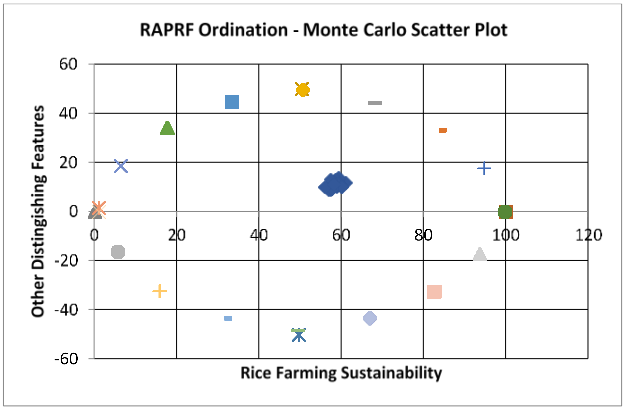

Fig. 17: Stability of RAPRF Ordinance Values in the Institutional Dimension.

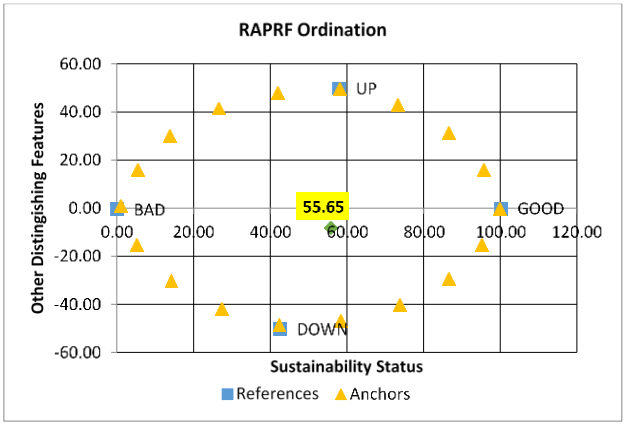

Fig. 18: Position of Sustainability Status of Technology Dimension.

Technological Dimension

The technological sustainability dimension reflects the utilization and adoption of agricultural technologies in rice farming systems to improve farming efficiency and operational performance. Technological advancement represents a critical prerequisite for achieving efficient and sustainable rice production. The availability and proper implementation of technological components significantly contribute to maintaining the long-term sustainability of rice farming systems. Sustainable rice cultivation should prioritize the application of appropriate agricultural technologies in accordance with Good Agricultural Practices (GAP) standards.

To meet market quality requirements, efforts to enhance productivity must be supported by policies promoting standardized quality management in rice farming practices. Such standardization is essential to ensure the production of high-quality agricultural outputs capable of competing in international markets. The adoption of improved agricultural technologies is therefore expected to generate higher value-added benefits for farmers while strengthening the competitiveness of rice-based agricultural systems.

The assessment of technological sustainability in rice farming in Pangandaran Regency was conducted using nine evaluation attributes, namely: (a) farming system management; (b) use of certified high-quality improved seeds; (c) land preparation mechanization; (d) planting spacing; (e) fertilizer application based on recommended standards; (f) timing and methods of fertilizer application; (g) weed management practices; (h) harvesting time and techniques; and (i) pest and disease management (*Plant Pest Organism Management*).

RAP–Rice Farming (RAPRF) Analysis

The RAPRF analysis results indicate that the technological sustainability index of rice farming in Pangandaran Regency reached a value of 55.65, which falls within the "moderately sustainable" category. The ordination point position is presented in Fig. 18. This finding suggests that the level of technological implementation among smallholder rice farmers in Pangandaran Regency remains suboptimal and requires further improvement.

The RAPRF analysis for the technological dimension was performed through two iterations, producing a coefficient of determination value of R^2 = 0.948 and an S-Stress value of 0.147 (14.7%)**.** These results indicate that the technological dimension analysis achieved an acceptable (*fair*) level of goodness of fit, confirming that the MDS ordination adequately represents the sustainability condition of technological practices within the studied rice farming system.

Sensitivity (Leverage) Analysis

Leverage analysis was conducted to identify key attributes or the most sensitive factors influencing the sustainability of the technological dimension of rice farming in Pangandaran Regency. Among the nine evaluated attributes, two were identified as having the highest sensitivity in determining technological sustainability performance, as presented in Fig. 19. These attributes include: (1) the use of high-quality and certified superior seeds, with a Root Mean Square (RMS) value of 2.9; and (2) planting spacing management, with an RMS value of 3.6.

These findings indicate that efforts to improve the sustainability status of the technological dimension should prioritize the optimization of these two critical attributes. Enhancing the adoption of certified superior seed varieties and implementing appropriate planting spacing practices are therefore essential strategic interventions for strengthening technological sustainability in rice farming systems within Pangandaran Regency.

The first sensitive attribute influencing the sustainability of the technological dimension of rice farming in Pangandaran Regency is the use of high-quality and certified superior seeds. Seed quality represents a critical determinant in rice farming systems, as crop productivity is strongly influenced by the genetic and physiological quality of planting materials. The use of certified seeds has been widely recognized as a key factor in ensuring stable and high-quality rice production. A reliable seed quality control and certification system plays an essential role in maintaining varietal authenticity and genetic purity, both at the production and farm-utilization levels. High-quality seeds contribute significantly to increased production, improved productivity, enhanced product competitiveness, and ultimately to higher farmer income and welfare.

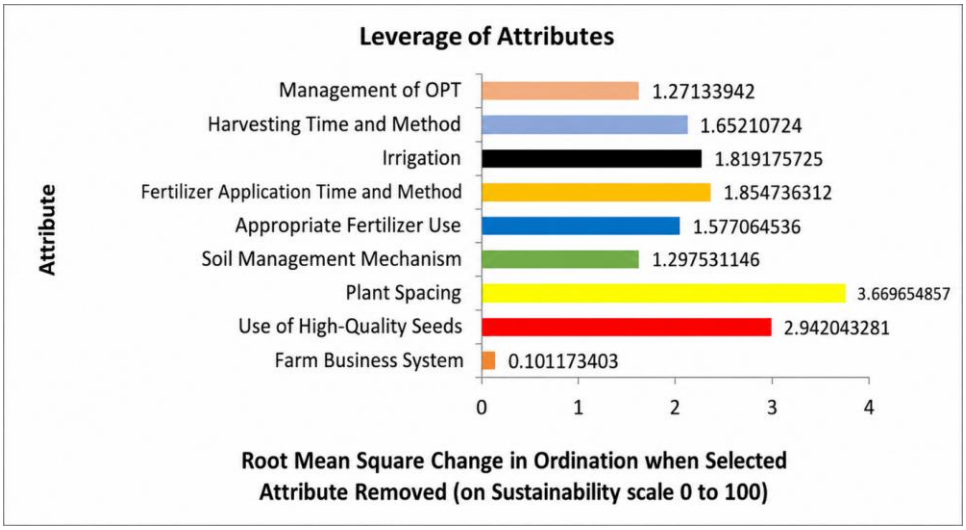

Fig. 19: Results of Technology Dimension Leverage Analysis.

Field findings in Pangandaran Regency indicate that many rice farmers still rely on seeds obtained from local seed growers who frequently reuse derivative or second-generation seeds as planting materials. This practice potentially results in reduced productivity and increased susceptibility of rice crops to pests and diseases. Therefore, strengthening extension programs and implementing certified seed distribution support through local agricultural agencies are necessary to encourage farmers to adopt high-quality certified seeds, thereby enhancing the long-term sustainability of the technological dimension of rice farming in Pangandaran Regency.

The second sensitive attribute affecting technological sustainability is planting spacing, with a Root Mean Square (RMS) value of 3.6. In rice cultivation, determining appropriate planting distance constitutes a fundamental management practice to ensure optimal crop growth and productivity. Excessively wide spacing increases light penetration to the soil surface, which may promote weed proliferation and reduce crop efficiency. The study results reveal that 50 farmers applied irregular planting distances, 137 farmers used varying spacing practices, and only 71 farmers implemented planting distances consistent with Good Agricultural Practice (GAP) guidelines. Plant spacing is a significant determinant of rice productivity, consistent with findings reported by Hayata et al. (2020). Furthermore, Asghar et al. (2021) demonstrated that rice planted at a spacing of 18 × 18 cm produced denser grain formation and higher productivity compared to alternative spacing arrangements. Accordingly, the adoption of standardized planting spacing aligned with GAP guidelines is expected to substantially improve the sustainability status of the technological dimension of rice farming in Pangandaran Regency.

Monte Carlo Analysis

Monte Carlo analysis was conducted to evaluate the stability and robustness of the ordination results obtained from the Multidimensional Scaling (MDS) analysis through 25 simulation iterations. The Monte Carlo simulation results for the technological dimension (Fig. 20) indicate that the ordination points are closely clustered without significant dispersion, demonstrating a high level of analytical stability. These findings confirm that the MDS estimation for the sustainability assessment of the technological dimension is reliable and statistically robust, indicating that the technological sustainability status of rice farming in Pangandaran Regency can be considered well-established.

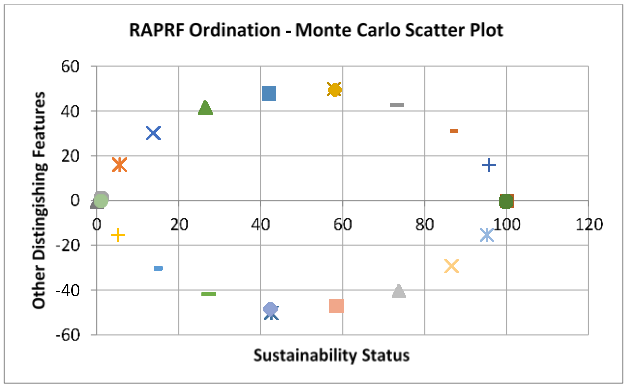

Fig. 20: Stability of RAPRF Ordination Values in the Technology Dimension.

Conclusion

This study evaluated the sustainability of rice farming systems in Pangandaran Regency using the RAP–Rice Farming (RAPRF) approach based on Multidimensional Scaling (MDS), encompassing economic, social, ecological, institutional, and technological dimensions. The results indicate that the multidimensional sustainability index reached 52.13, categorizing the system as moderately sustainable. The analytical model demonstrated strong reliability and robustness, as reflected by an S-Stress value below 0.25 and an R^2 value exceeding 0.90, confirming that the model adequately represents the sustainability conditions of rice farming systems in the study area. Among the evaluated dimensions, the social dimension exhibited the highest performance (75.86), followed by institutional (58.15) and technological dimensions (55.65). In contrast, the economic (44.93) and ecological dimensions (47.18) remained within the less sustainable category, indicating their role as primary constraints limiting overall system sustainability improvement.

Leverage analysis further revealed that paddy price

stability and local labour absorption were the most sensitive attributes within the economic dimension. Meanwhile, environmental legality compliance, pesticide-related pollution, and the adoption of certified superior seeds emerged as key determinants within the ecological and technological dimensions. These findings highlight the necessity for integrated policy interventions aimed at strengthening farmers' economic institutions, stabilizing commodity prices, promoting environmentally sustainable cultivation practices, and accelerating the adoption of Good Agricultural Practices (GAP) to enhance the long-term sustainability of rice farming systems.

DECLARATIONS

Funding: This research was financially supported by Universitas Muhammadiyah Sukabumi through the Internal Research Grant Program. The funding covered research implementation, data collection, data analysis, and manuscript preparation.

Acknowledgement: The authors would like to express their sincere gratitude to Universitas Muhammadiyah Sukabumi, Indonesia, for providing financial support through the Internal Research Grant Program. The authors also extend their appreciation to the rice farmers in Pangandaran Regency for their willingness to participate in this study, as well as to the local agricultural extension officers and related stakeholders for their valuable assistance during the data collection process. The constructive comments provided by the anonymous reviewers are also gratefully acknowledged, as they have significantly improved the quality of this manuscript.

Conflict of Interest: The authors declare no conflicts of interest regarding the publication of this paper.

Data Availability: The data that support the findings of this study are available from the corresponding author upon reasonable request.

Ethics Statement: The author certifies that this article is an original work and has not been previously published, nor is it currently under consideration for publication in any other journal.

Author's Contribution: R.S.: Conceptualization, methodology, investigation, formal analysis, writing—original draft, supervision. M.F.N.: Methodology, validation, formal analysis, writing—review and editing. S.A.A.: Investigation, data curation, resources, writing—review and editing. W.O.A.Z.: Investigation, validation, resources, writing—review and editing. M.N.Y.: Conceptualization, supervision, funding acquisition, project administration, writing—review and editing. All authors have read and approved the final version of the manuscript.

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

Publisher's Note: All claims stated in this article are exclusively those of the authors and do not necessarily represent those of their affiliated organizations or those of the publisher, the editors, and the reviewers. Any product that may be evaluated/assessed in this article or claimed by its manufacturer is not guaranteed or endorsed by the publisher/editors.

REFERENCES

Abeysekara, I., & Rathnayake, I. (2024). *Global trends in rice production, consumption and trade*. SSRN. https://doi.org/10.2139/ssrn.4948477

Abdullahi, S., Sani, L.A., Bichi, B.I., Shehu, A.M., & Auwal, A.M. (2026). Impact of arbuscular mycorrhizal fungi on the growth and yield of rice (*Oryza sativa* L.) affected by *Magnaporthe oryzae* (B. Couch). *Trends in Animal and Plant Sciences, 7*, 24–30. https://doi.org/10.62324/TAPS/2026.004

Aljaafreh, O.M. (2026). The impact of sustainable food supply chain on food security: case study of jordanian food companies. International Journal of Agriculture and Biosciences, 15(2), 831- 839. https://doi.org/10.47278/journal.ijab/2025.233

Anam, M.H., Sulaiman, A., Othman, A.K., & Jamaludin, N.F. (2025). Sustainability criteria for rice farmer practices based on environmental, economic and social dimensions. In *IOP Conference Series: Earth and Environmental Science*, 1535(1), 012017. https://doi.org/10.1088/1755-1315/1535/1/012017

Asghar, M., Hassan, T.-U., Arshad, M., Aziz, A., & Latif, M. T. (2021). Effect of plant spacing on incidence of rice planthoppers in transplanted rice crop. *International Journal of Tropical Insect Science, 41*, 575–585. https://doi.org/10.1007/s42690-020-00242-4

Ashfaq, A., Jamil, R., Waheed, A., & Anwar, A.S. (2023). Association of quantitative attributes in rice genotypes. *Trends in Animal and Plant Sciences, 1*, 1–6. https://doi.org/10.62324/TAPS/2023.001

BPS - Statistics Indonesia (2023). *Statistical yearbook of Indonesia 2023*. Badan Pusat Statistik. https://www.bps.go.id/id/publication/2023/02/28/18018f9896f09f03580a614b/statistik-indonesia-2023.html

BPS - Statistics Indonesia (2025). *Statistical yearbook of Indonesia 2025*. Badan Pusat Statistik. https://www.bps.go.id/id/publication/2023/02/28/18018f9896f09f03580a614b/statistik-indonesia-2025.html

Chang, S.H.E., Benjamin, E.O., & Sauer, J. (2024). Factors influencing the adoption of sustainable agricultural practices for rice cultivation in Southeast Asia: A review. *Agronomy for Sustainable Development, 44*, 27. https://doi.org/10.1007/s13593-024-00960-w

Fitriani, R., Bulkis, S., Jamil, M.H., & Lakare, H. (2025). Institutional sustainability of organic rice farmers in South Sulawesi: A multidimensional scaling analysis. *Nongye Jixie Xuebao/Transactions of the Chinese Society of Agricultural Machinery, 56*, 10. https://doi.org/10.62321/issn.1000-1298.2025.10.3

FAO. (2023). Food and Agriculture Organization of the United Nations. Global food outlook. https://openknowledge.fao.org/server/api/core/bitstreams/a00ef752-f070-40d8-958f-832fc5084b44/content

Fuhrmann-Aoyagi, M.B., Miura, K., & Watanabe, K. (2024). Sustainability in Japan's agriculture: An analysis of current approaches. *Sustainability, 16*(2), 596. https://doi.org/10.3390/su16020596

Hibatullah, F.H., Raidasari, F., Triana, A.P., Siagian, V.K.L., & Simarmata, T. (2024). Revealing food fulfillment threads and innovative technology for enhancing rice productivity and ensuring food security in Indonesia. *International Journal on Food, Agriculture and Natural Resources, 5*(3), 45–51. https://doi.org/10.46676/ij-fanres.v5i3.316

Imbiri, S., & Wambrauw, L.T. (2025). Farmers' attitudes towards fertilizer and pesticide use in enhancing agricultural yields. *The Journal of Academic Science, 2*(4), 1066–1076. https://doi.org/10.59613/96xbdp66

Islam, R., Rahman, A.M., Thierry, H., & Sivakumar, M. (2025). *Climate change mitigation and adaptation to improve food security in South Asia* (1st ed.). CRC Press. https://doi.org/10.1201/9781032628691

Ismail, R., Revida, E., Lubis, S., Kardhinata, E.H., Sutatminingsih, R., Manurung, R., Hafi, B., Harahap, R.H., & Sihotang, D. (2025). Climate change adaptation knowledge among rice farmers in Lake Toba Highland, Indonesia. *Sustainability, 17*(13), 5715. https://doi.org/10.3390/su17135715

Kavanagh, P., & Pitcher, T.J. (2004). *Implementing Microsoft Excel software for RAPFISH: A technique for the rapid appraisal of fisheries status* [Report]. Fisheries Centre. University of British Columbia. https://doi.org/10.14288/1.0074801

Khatri, P., Kumar, P., & Shakya, K.S. (2024). Understanding the intertwined nature of rising multiple risks in modern agriculture and food system. *Environment, Development and Sustainability, 26*, 24107–24150. https://doi.org/10.1007/s10668-023-03638-7

Mariyono, J. (2024). Sustainable intensification practices of fish-rice co-culture in Java, Indonesia: Technical, socio-economic and environmental features. *Journal of Agribusiness in Developing and Emerging Economies, 14*(5), 1015–1032. https://doi.org/10.1108/JADEE-09-2022-0208

Naik, S.K., Shinde, R., Mali, S.S., Sarkar, P.K., & Das, A. (2025). Land degradation: A global challenge to environmental sustainability and livelihood security. In S. Babu, A. Das, S. S. Rathore, R. Singh, & R. Singh (Eds.), *Ecological solutions to agricultural land degradation* (pp. 1–24). Springer. https://doi.org/10.1007/978-981-96-3392-0_1

Naqvi, S.Z.H., Maqbool, B., Arshad, M.I., Aderibigbe, A., & Gul, S.T. (2025). Food security and livestock: a comprehensive review of sustainability, challenges and innovative solutions. Agrobiological Records, 20, 50-58. https://doi.org/10.47278/journal.abr/2025.019

Nawaz, A., Rehman, A.U., Rehman, A., Ahmad, S., Siddique, K.H.M., & Farooq, M. (2022). Increasing sustainability for rice production systems. *Journal of Cereal Science, 103*, 103400. https://doi.org/10.1016/j.jcs.2021.103400

Nguyen, L.L.H., Khuu, D.T., Halibas, A., & Nguyen, T.Q. (2024). Factors that influence the intention of smallholder rice farmers to adopt cleaner production practices: An empirical study of precision agriculture adoption. *Evaluation Review, 48*(4), 692–735. https://doi.org/10.1177/0193841X23120077

Nguyen-Thi-Kim, N., Nguyen-Anh, T., Nguyen-Phuong, T., Lai-Minh, H., & Pham-Anh, T. (2024). Adoption of sustainable farming practices in Vietnam: A discourse of the determining factors. *Heliyon, 10*(11), e31792. https://doi.org/10.1016/j.heliyon.2024.e31792

Ogbari, M.E., Folorunso, F., Simon-Ilogho, B., Adebayo, O., Olanrewaju, K., Efegbudu, J., & Omoregbe, M. (2024). Social empowerment and its effect on poverty alleviation for sustainable development among women entrepreneurs in the Nigerian agricultural sector. *Sustainability, 16*(6), 2225. https://doi.org/10.3390/su16062225

Pitcher, T.J., & Preikshot, D. (2001). RAPFISH: A rapid appraisal technique to evaluate the sustainability status of fisheries. *Fisheries Research, 49*(3), 255–270. https://doi.org/10.1016/S0165-7836(00)00205-8

Prabhakar, S.V.R.K. (2021). A succinct review and analysis of drivers and impacts of agricultural land transformations in Asia. *Land Use Policy, 102*, 105238. https://doi.org/10.1016/j.landusepol.2020.105238

Rachman, B., Ariningsih, E., Sudaryanto, T., Ariani, M., & Septanti, K.S. (2022). Sustainability status, sensitive and key factors for increasing rice production: A case study in West Java, Indonesia. *PLOS ONE, 17*(12), e0274689. https://doi.org/10.1371/journal.pone.0274689

Rasool, G., & Qadir, F. (2026). Precision genome editing for smarter, inclusive, and nutritious crops: Emerging tools, omics integration, and global perspectives. *Trends in Animal and Plant Sciences, 7*, 38–51. https://doi.org/10.62324/TAPS/2026.006

Rupasinghe, S. (2024). Innovative sowing and seedbed management for resilient maize, rice, and wheat production in arid zones. *Trends in Animal and Plant Sciences, 4*, 106–111. https://doi.org/10.62324/TAPS/2024.052

Santoso, A. B., Girsang, S. S., Raharjo, B., Pustika, A. B., Hutapea, Y., Kobarsih, M., Suprihatin, A., Manurung, E. D., Siagian, D. R., Hanapi, S., Purba, T., Parhusip, D., Budiarti, S. W., Wanita, Y. P., Hatmi, R. U., Girsang, M. A., Haloho, L., Waluyo, Suparwoto, Yustisia, Sudarmaji. (2023). Assessing the challenges and opportunities of agricultural information systems to enhance farmers' capacity and target rice production in Indonesia. *Sustainability, 15*(2), 1114. https://doi.org/10.3390/su15021114

Shah, T.M., Tasawwar, S., Bhat, M.A., & Otterpohl, R. (2021). Intercropping in rice farming under the system of rice intensification—An agroecological strategy for weed control, better yield, increased returns, and social–ecological sustainability. *Agronomy, 11*(5), 1010. https://doi.org/10.3390/agronomy11051010

Soekartawi (1988). *Basic principles of agricultural communication*. Faculty of Agriculture, Brawijaya University.

Syakirotin, M., Sulistyowati, L., & Noor, T.I. (2025). Sustainable livelihood strategy approach for farmer households in expansion areas: A bibliometric analysis. *Discover Sustainability, 6*, 983. https://doi.org/10.1007/s43621-025-01912-4

Yan, F., Chen, M., Huang, Q., Yan, Z., Liu, Y., & Zhang, F. (2025). Social networks and farmers' low-carbon rice farming intention and behavioral discrepancies under the social embedding perspective. *Journal of Cleaner Production, 491*, 144814. https://doi.org/10.1016/j.jclepro.2025.144814

Zboroń, H. (2020). Economic success or social well-being. In K. Bachnik, M. Kaźmierczak, M. Rojek-Nowosielska, M. Stefańska, & J. Szumniak-Samolej (Eds.), *CSR in contemporary Poland* (pp. 1–18). Palgrave Macmillan. https://doi.org/10.1007/978-3-030-42277-6_1

Zega, U., Hanani, N., & Rosihan Asmara, S. (2025). Assessment of rice farming sustainability with the MDS-RAPFISH approach: A case study in South Nias Regency, Indonesia. *Nongye Jixie Xuebao/Transactions of the Chinese Society of Agricultural Machinery, 56*(8). https://doi.org/10.62321/issn.1000-1298.2025.8.6