MULTIDIMENSIONAL SUSTAINABILITY ASSESSMENT OF RICE FARMING SYSTEMS INBALI: ATRIHITAKARANA-BASED APPROACH FORTRADITIONAL AGRICULTURAL DEVELOPMENT

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ABSTRACT
Tabanan Regency, Bali's primary rice-producing region, faces critical sustainability challenges including accelerated agricultural land conversion (2.92% annually) and demographic transitions with 70% of farmers exceeding 60 years of age. This study evaluates rice farming sustainability and develops evidence-based strategies grounded in the Tri Hita Karana (THK) philosophical framework. The research employed Multidimensional Scaling methodology through the Rapid Appraisal for Farm approach to assess sustainability across ecological, economic, social, technological, and institutional dimensions. Data were collected through structured interviews with 15 key informants and field observations in two subaks within the Yeh Empas irrigation system. Results indicate an overall sustainability index of 66.50% (moderately sustainable). Dimensional analysis revealed ecological (63.42%) and social (63.59%) as most vulnerable, while technological dimension achieved highest performance (71.42%). Leverage analysis identified five critical determinants: price stability (4.88), irrigation efficiency (4.53), intergenerational knowledge transfer (4.50),spatialplanningclarity(4.49),andawig-awigcontinuity(4.39).Monte Carlo validation confirmedmodelreliabilitywithdeviationsbelow2%. Five integrated strategies are proposed based on THK principles: institutional strengthening through spatial planning integration, youth engagement with traditional knowledge preservation, formal recognition of customary governance, market stabilization with digital cooperatives, and irrigation modernization with participatory management. This study contributes novel insights by demonstrating balanced sustainability in traditional systems, establishing economic centrality in multidimensional frameworks, and providing replicable methodology for integrating indigenous knowledge with scientific assessment.

Keywords: sustainability assessment, rice farming, Tri Hita Karana, subak system, traditional agriculture, Bali

INTRODUCTION

Sustainability is a dynamic concept that evolves according to natural and social conditions, including agricultural sustainability. It is anticipated that agricultural sustainability will lead to in dynamic development and sustainable production (Connor et al., 2021). The five dimensions of sustainability are ecological, economic, social, technological, and institutional (Yusuf et al., 2022). According to Roy et al. (2014), agriculture is essential for regional development, especially for the welfare of the community. In Bali, the subak plays a crucial role in ensuring food security and agricultural sustainability by successfully fusing traditional methods with contemporary farming techniques. This demonstrates how indigenous systems can adapt and flourish in the face of contemporary pressures, highlighting the close connection between cultural heritage and economic stability.

Agriculture has a complex connection to the socioeconomic stability and nutritional security of many social groups in Bali. This link is especially important because of the subak system, a traditional irrigation and agricultural management system that UNESCO has designated as part of the world's intangible cultural heritage. The subak not only promotes sustainable agricultural practices, but it also reflects the complex socio-religious dynamics of Balinese society, thereby contributing to the preservation of food security through sustainable water management and rice output (Pradana, 2023; Jayendra et al., 2021; Ardana et al., 2024).

The notion of Tri Hita Karana (THK), which serves as the cornerstone for subak philosophy, emphasizes the necessity of harmony among the environment, the divinity, and humanity. This philosophy is expressed through the three principles of palemahan, pawongan, and parhyangan. Subak's operations are directed by these principles, which ensure that agricultural techniques are preserved in their natural nature while still meeting contemporary socioeconomic needs. Research has shown that the subak system preserves community resilience by integrating sustainable practices and ceremonial customs that honor agricultural deities, thereby ensuring a balance between ecological preservation and agricultural output (Ardana et al., 2024; Hirakawa et al., 2024).

In the past few years, the government has implemented programs that are specifically intended to diversify production and support rural economies, thereby enhancing food security. This has been accomplished by encouraging sustainable agriculture techniques, primarily through the Ministry of Defense. However, the fundamental work of subak demonstrates how local farmers have historically maintained food reserves and grown commodities in accordance with cultural beliefs, contributing to a resilient food system long before the development of these governmental strategies (Sedana, 2024; Putri, 2020). The ceremonial regard for dewa nini highlights the strong cultural values that are strongly embedded in Balinese farming systems, where food security is linked to spiritual and communal identities rather than just agriculture (Wahyuni et al., 2023).

In addition, the importance of subak is not limited to its influence on agriculture; it is a socioeconomic framework that strikes a balance between environmental responsibility and collective endeavors. The preservation of traditional techniques, such as subak, is becoming increasingly important in order to protect both ecological integrity and food security as Bali addresses current issues such as urbanization and tourism-related land conversion (Sriartha et al., 2015; Liu et al., 2023). By safeguarding these historical practices, Bali can maintain its agricultural heritage, address contemporary environmental challenges, and guarantee food security at all social levels (Lansing et al., 2023).

The primary rice-producing area in Bali Province, Tabanan Regency, possesses substantial agricultural potential due to the fact that rice cultivation is the cornerstone of regional economic stability and food security. Recent production data show a 0.15 percent increase from 169,265 tons in 2022 to 169,512 tons in 2023 (BPS-Statistics Bali Province, 2024). Nevertheless, this slight increase in production is starkly contrasted with a 60% increase in productivity in 2023, which highlights the underlying structural issues that are hampering the long-term sustainability of rice cultivation. Throughout Bali Province, the food security equilibrium is directly influenced by the agricultural policies that regulate rice yield in Tabanan Regency (Paramarta, 2024).

Accelerated agricultural land conversion is the most serious threat to the region, with a worrying fall in harvested area from 29,039 hectares in 2022 to 28,190 hectares in 2023—a net loss of 849 hectares per year, or a 2.92% annual decline rate. Eastern Tabanan, where development pressures exacerbate land-use conflicts, exemplifies this pattern. According to historical studies, Kediri District lost 127 hectares at an average rate of 31.7 hectares between 2015 and 2018, with the most dramatic conversion rates.

Beyond numerical land losses, the area has qualitative issues as a result of inadequate spatial planning coordination. Urban development projects often choke irrigation channels, causing cascade effects throughout the water supply network. These infrastructural disruptions put downstream farmers into water scarcity situations, motivating delayed land conversion as agricultural viability declines (Paramarta & Karyati, 2024). This interrelated pattern of land transformation, infrastructure disturbance, and reduced agricultural viability poses a systematic challenge to the sustainability of rice farming systems in Tabanan Regency.
The agriculture industry has significant challenges due to rice growing issues in Tabanan Regency, particularly in terms of farmer regeneration. A large proportion of Tabanan's rice farmers are now 60 years or older, indicating a lack of younger individuals entering the profession. Scholarly studies by Sulaeman et al. (2020) suggest that newer generations' preference for the service sector—where they see more promising earning potential—contributes to the decline in farmer regeneration.

Tabanan Regency, which covers an area of around 38,535 hectares, has set a rice growing aim in its agricultural plans for 2024. Ten districts cover 38,713 hectares, with the expected yield spread between them. With recent estimates of yields of around 6 tons of dry harvested grain per hectare, compared to historical averages of roughly 5.7 tons per hectare, average rice productivity has increased. Though these come from specific, ideal locations, numerous sites have recorded peak yields of up to 7-8 tons per hectare (Suastika et al., 2023). Appropriate irrigation water availability, proper fertilizer distribution, and pest control strategies (Hirakawa et al., 2024) all contribute to this productivity increase.
Although rice cultivation pays less than other businesses, it allows farmers to seek alternative work, like as commerce and constructing, producing additional revenue during maintenance periods (Hirakawa et al., 2024). As Tabanan is refining its agricultural practices to face the difficulties of the aging farmer demographic will play a vital role in ensuring the region's rice crop sustainability and future viability.

Using a five-dimensional sustainability assessment framework that includes ecological (environmental resource management and conservation), economic (financial viability and market dynamics), social (community engagement and knowledge transfer), technological (innovation adoption and infrastructure efficiency), and institutional (governance structures and policy frameworks) dimensions, the research This comprehensive approach aids in the identification of key sustainability factors and the development of integrated strategies that align traditional Balinese agricultural knowledge with modern sustainability demands, allowing for the preservation and improvement of rice farming systems critical to regional food security and cultural legacy protection.

METHODOLOGY

Research Location and Time

This study was conducted in Tabanan Regency,Bali Province, Indonesia, selected as the primary research site due to its status as the province's largest rice-producing region,contributing169,512 tonsannuallywithproductivityratesof6.0tonsperhectare(BPS-StatisticsBaliProvince,2024). Within Tabanan Regency, Kediri District was purposively selected as the focal area based on its experience of extensive agricultural land conversion, totaling 127 hectares during the study reference period (Paramarta, 2024).

The research employed a strategic sampling approach focusing on two subaks (traditional irrigation communities) within the Yeh EmpasIrrigation System to examine the cascading effects of land conversion along the water distribution network. Subak Sanggulan was selected as the upstream study site, representing a subakexperiencing significant land conversion pressure with a 30% reduction in agricultural area from 107hectares in 2005 to 75 hectares in 2020, including 35 hectares of recent conversion within Kediri District. Located at the terminus of the Yeh Empas irrigation network, Subak Bengkel was selected as the downstream counterpart, where it serves as the ultimate water recipient from upstream subaks. This subak is a suitable example for investigating the downstream effects of upstream land-use changes because it underwent a 40-hectare land conversion in 2022 (Dananjaya et al., 2024).

The comparative analysis of sustainability challenges across the irrigation gradient is facilitated by this paired sampling design, which offers insights into the propagation of land conversion pressures through traditional water management systems. The study was carried out over three months, from January to March 2025, during the post-harvest season, to allow for in-depth interviews with subak officials and farmer representatives when agricultural activity were less active.

Data Collection

A mixed-method qualitative approach was implemented in this investigation, which combined direct field observations and in-depth interviews to obtain a comprehensive understanding of the sustainability of rice cultivation. Semi-structured questionnaires with open-ended questions were employed to conduct in-depth interviews with stakeholders, enabling a comprehensive examination of their perspectives, experiences, and contextual knowledge with respect to sustainability challenges and conventional management practices (Sanchez-Rodriguez et al.,2023). In particular, this method was advantageous for comprehending intricate socio-cultural dynamics within subak systems that were not adequately captured by standardized surveys.

Interview data was supplemented by field observations, which documented the actual farming practices, irrigation infrastructure conditions, and social interactions within their natural contexts (Althubaiti, 2023). By incorporating both expressed opinions and observed behaviors, this dual approach facilitated the triangulation of data sources, thereby improving the reliability and validity of the data (Wittekind et al., 2023).

The study employed purposive sampling to identify 15 key informants pursuant to their institutional positions and areas of expertise. The subak governance institutions were represented by ten informants, which included traditional leaders (pekaseh and vice pekaseh), administrative officers (treasurer and secretary), and water management specialists (juru arah). An additional five informants, including agricultural extension officers and leaders of the agriculture, culture, and public works departments, represented government institutions. Comprehensive coverage of both traditional knowledge systems and formal institutional perspectives was guaranteed by this informant composition, which is crucial for comprehending the sustainability dynamics in rice cultivation systems.

Data Analysis

This study implemented a quantitative analytical framework that implemented Multidimensional Scaling (MDS) methodologies to evaluate the sustainability of rice cultivation in five distinct domains: ecological, economic, social, technological, and institutional. A systematic three-stage process was implemented to conduct the analysis, which included data acquisition, processing, and statistical analysis (Sanchez-Rodriguez et al., 2023).

The Rapid Appraisal for Fisheries (RAPFISH) framework was modified to create the Rapid Appraisal for Farm (RAP-Farm) methodology, which was used in the main analytical procedure (Fekih-Romdhane et al., 2023). By analyzing dissimilarity matrices and generating point configurations in Euclidean space, MDS simplifies multidimensional data, thereby facilitating the visualization of sustainability relationships across dimensions (Lim & Mémoli, 2024). This technique determines important features within each sustainability dimension and informs strategy creation based on THK principles (Piłat-Rożek et al., 2023).

Table1.SustainabilityIndexand Status

No	SustainabilityIndex	Sustainability Status
1	0 - <25	Poor(unsustainable)
2	25 ≥ IndexValue <50	Less(lesssustainable)
3	50 ≥ IndexValue <75	Moderate(moderatelysustainable)
4	75 ≥ IndexValue ≤ 100	Good(sustainable)

Source:Kavanagh(2001) inLinda,etal(2018)

RESULTS AND DISCUSSION

1. Research Area Description

Tabanan Regency is strategically located in south-central Bali, covering 849.31 km² with diverse topographical features ranging from coastal plains to mountainous regions, with elevations spanningfromsealevelto2,276metersabovesealevel(BPS-StatisticsBaliProvince,2025).The regency is bounded by Buleleng Regency to the north, Badung Regency to the east, the Indian Oceantothesouth,andJembranaRegencytothewest.Thisgeographicaldiversitycreatesvaried microclimates and agricultural zones that support intensive rice cultivation, earning Tabanan recognition as Bali's primary rice-producing region with the highest concentration of traditional irrigation communities (subaks) in the province.

Subak Bengkel: Downstream Study Site

Subak Bengkel, located in Bengkel Village, Kediri District, is the downstream unit of the Yeh Empas irrigation system. Among the largest subaks in the region, this traditional irrigation cooperative oversees 329 hectares that are distributed across Bengkel Village (210 ha) and Pangkung Tibah Village (119 ha). UNESCO has recognized Subak Bengkel as an Ecohydrology Demonstration Site for its effective amalgamation of traditional water management and contemporary agricultural technologies, achieved through the collaboration of the Tabanan Regency Government and Muhammadiyah University of Malang (Paramarta & Karyati, 2024). This designation emphasizes the subak's role as a sustainable agriculture model that addresses contemporary challenges while preserving cultural heritage. Subak Bengkel, being the terminal water recipient in the Yeh Empas system, provides critical insights into the water management experiences of downstream communities.

Subak Sanggulan: Upstream Study Site

The upstream component of this comparative study is Subak Sanggulan, which spans approximately 55 hectares in Banjar Anyar Village, Kediri District. This subak is situated in a strategic location within the Yeh Empas irrigation network, with Banjar Anyar Village to the east, Banjar Pangkung Prabu to the west, Gatot Subroto Road to the north, and Banjar Demung to the south (Fig. 1).

The Subak Museum is a comprehensive repository of traditional agricultural knowledge and practices, exemplifying the cultural and educational significance of the subak. The museum is home to a vast collection of educational materials, historical documentation, and traditional agricultural implements that document the development of Bali's irrigation systems (Paramarta, 2024). This facility further solidifies Subak Sanggulan's dual function as a center for cultural preservation and intergenerational knowledge transmission, as well as an active agricultural community.

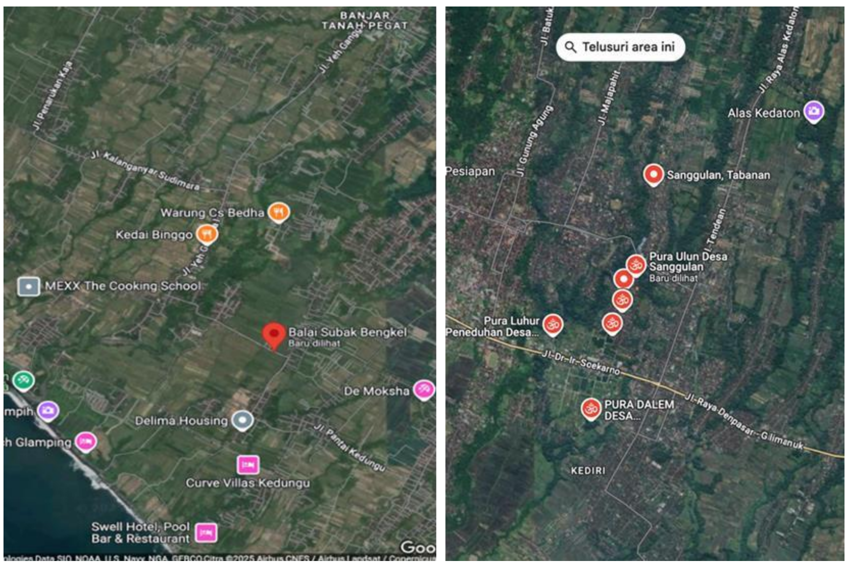

Figure1. The mapped regions of Subak Bengkel (on the left) and Subak Sanggulan (on the right)
Source:GoogleMap2025

2. Informant Characteristics

The selection of key informants was determined by their institutional knowledge, practical experience, and strategic roles within rice farming systems, thereby facilitating access to diverse perspectives on sustainability challenges and traditional management practices (Demastus & Landrum, 2024). This purposive sampling method improves data validity and reinforces analytical interpretations by integrating diverse stakeholder perspectives (Golob et al., 2023; Walker et al., 2023).

The demographic analysis of subak officials indicates a farming community with significant experience, yet it encounters challenges related to generational transition. The majority of informants (79%) are mature farmers who are approaching retirement age and possess substantial agricultural expertise. They are aged 55 to 59. This demographic pattern is further supported by farming experience data, which indicates that 40% of participants have been involved in rice cultivation for more than two decades. This data demonstrates a profound institutional memory of traditional practices and environmental changes.

The educational profiles of the farmer informants indicate that they have moderate literacy levels, with 45% of them having completed secondary education. It is possible that this educational foundation may restrict engagement with intricate agricultural innovations that necessitate advanced technical knowledge, despite its support for information processing and fundamental technology adoption. Resource constraints may potentially impact the investment capacity for sustainability enhancements, as 40% of farmers manage 0.25-0.5 ha plots, indicating that land ownership patterns are predominantly small-scale.

Agricultural extension officers with field-level implementation experience and department leaders with policy-making authority are some of the government informants who represent complementary institutional perspectives. Comprehensive coverage of both grassroots agricultural realities and institutional policy frameworks is guaranteed by this diverse informant composition.

A farming community that possesses valuable traditional knowledge but requires targeted support to navigate modernization challenges is indicated by the demographic profile. The aging farmer population, coupled with moderate educational attainment and small-scale operations, highlights the necessity for accessible extension services, financial support mechanisms, and intergenerational knowledge transfer programs to promote sustainable agricultural development (Zhou, 2023).

3.3Rice Farming Sustainability Analysis in Tabanan Regency

By utilizing the RAP-Farm approach, the Multidimensional Scaling (MDS) analysis produced exhaustive sustainability assessments across five dimensions, resulting in the production of two critical outputs: leverage values and sustainability indices. Sustainability indices are quantitative measures (0-100 scale) that illustrate the performance level of each dimension, with higher values indicating greater sustainability (Mohamed & Godon, 2020; Riffel et al., 2023). In order to ascertain the factors that have the most significant impact on the overall sustainability performance, leverage values are used to identify the most influential attributes within each dimension. A summary of the multidimensional sustainability performance of rice cultivation operations in Tabanan Regency is provided in Table 2.

The analytical framework visualizes results through coordinate systems where the x-axis represents sustainability performance (0% indicating poor conditions, 100% indicating optimal conditions) and the y-axis displays attribute score variations within each dimension (Shedden-Mora et al., 2023). Additional reference points (anchors) surrounding the primary sustainability indicators provide analytical context for interpretation (Knezek et al., 2023).

Table2.Rice Farming Sustainability Index and Statusin Tabanan Regency

No	Dimension	Index	SustainabilityStatus
1	Ecological	63.42	Moderate(moderately sustainable)
2	Economic	70.42	Moderate(moderately sustainable)
3	Social	63.69	Moderate(moderately sustainable)
4	Technological	71.42	Moderate(moderately sustainable)
5	Institutional	63.53	Moderate(moderately sustainable)
	Multidimensional	66.50	Moderate(moderately sustainable)

Dimensional analysis reveals notable performance variations, with technological (71.42%) and economic (70.42%) dimensions demonstrating the highest sustainability levels, while ecological (63.42%) and social (63.69%) dimensions show the lowest performance, requiring prioritized intervention strategies (Pascual et al., 2023).

Monte Carlo Analysis
Monte Carlo analysis was conducted to address uncertainty aspects by performing 25 repetitions on each dimensional data (Piscicelli,2023).Monte Carlovalues were compared with MDS values in each dimension. Comparison differences between MDS and Monte Carlovalues preferably have values <5% (Table 3).

Table3.MDSandMonte CarloValue Differences forRAP-FarmValues

Dimension	MDS (%)	MonteCarloAnalysis (%)	Difference(%)
Ecological	63.42	62.34	1.08
Economic	70.42	68.76	1.66
Social	63.69	62.65	1.04
Technological	71.42	69.56	1.86
Institutional	63.53	62.65	0.88

Table 3 demonstrates strong methodological reliability, with Monte Carlo values ranging from 62.34%to69.56%acrossall dimensions. The deviation between MDS and Monte Carloanalyses ranges from 0.88% to 1.86%, well below the acceptable threshold of 5%, confirming the robustness of the RAP-Farm methodology for sustainability assessment in rice farming systems (Golob et al., 2023).

These minimal deviations validate three critical aspects of data quality: (1) attribute scoring accuracy—errors in individual attribute assessments are negligible; (2) analytical stability—repeated iterations through Monte Carlosimulation demonstrate consistent results despite inherent variability in expert opinions; and(3) data integrity—the low variance indicates minimal data entry errors and reliable information processing. The consistency between MDS and Monte Carlo results establishes confidence in the sustainability indices and supports the validity of subsequent strategic recommendations based on these findings.

Goodness of Fit Assessment
Model validation through goodness of fit assessment is essential to ensure that the MDS analysis accurately represents the original sustainability data, This assessment determines whether the multidimensional scaling transformation maintains the genuine relationships within the data or introduces substantial distortions that could potentially undermine the reliability of the results.

To assess the sustainability of rice cultivation in Tabanan Regency, the goodness of fit evaluation utilizes two critical statistical measures, as illustrated in Table 4. The degree of distortion in the MDS model is evaluated by S-stress values, which must be less than 0.25 in order to achieve satisfactory performance (Walker et al., 2023).

The proportion of the original data variance captured by the model is quantified by determination coefficients (R^2), with higher values indicating greater representation.

Table4.S-StressValuesandRAP-FarmDetermination Coefficients

Dimension	MDS (%)	S-Stress	R-Square
Ecological	63.42	0.1462725	0.9654321
Economic	70.42	0.1487631	0.9765332
Social	63.69	0.1453624	0.9476853
Technological	71.42	0.1476263	0.94099870
Institutional	63.53	0.1461428	0.94287453

S-stress analysis indicates that the model performs exceptionally in all dimensions, with values ranging from 0.1453 to 0.1488, which are significantly lower than the 0.25 threshold. This confirms that the sustainability indices accurately preserve the original data relationships, as there is minimal distortion during the MDS transformation process.

All dimensions exhibit exceptional explanatory power, with R^2 values ranging from 94.1% to 97.7%. The MDS model effectively captures the vast majority of sustainability information with minimal data loss, as the economic dimension obtains the highest variance explanation (97.7%) and all dimensions exceed 94%. These statistics, when combined, substantiate the reliability of the RAP-Farm methodology and provide assurance that the sustainability assessment accurately represents the actual conditions of the rice cultivation systems in Tabanan Regency (Mikhail et al., 2023).

Kite Diagram

A comprehensive visual representation of multidimensional sustainability performance is provided by the kite diagram, which allows for the immediate identification of strengths and deficits across all five sustainability dimensions. By converting numerical sustainability indices into a geometric pattern, this radar-style visualization enables the identification of strategic priorities and comparative analysis of rice cultivation systems in Tabanan Regency.

Utilizing a coordinate system, the kite diagram displays sustainability index values (0-100%) on five axes that correspond to ecological, economic, social, technological, and institutional dimensions. The sustainability profile is revealed by the resulting polygon shape, with larger areas suggesting improved overall performance and irregular shapes emphasizing dimensional imbalances (Charfeddine & Umlai, 2023). The critical boundary between sustainable (≥50%) and unsustainable (<50%) performance levels is determined by the 50% threshold (Jiang et al., 2023).

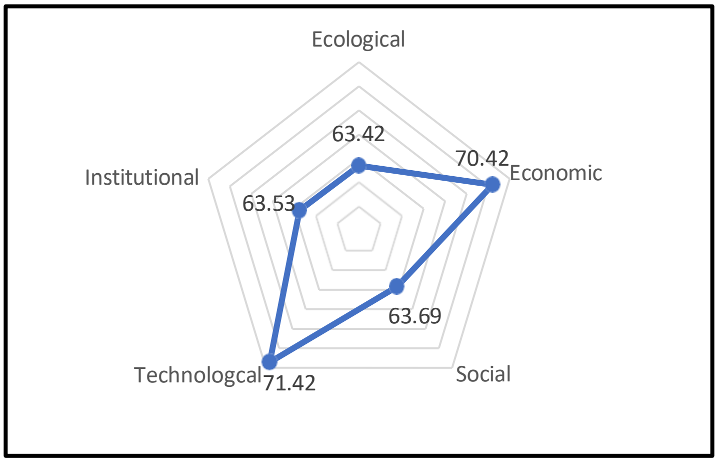

Figure2.SustainabilityKite DiagramforRice Farmingin Tabanan Regency

The five dimensions of the kite diagram (Figure 2) indicate that the rice cultivation system is moderately sustainable, with all five dimensions exceeding the 50% sustainability threshold. The polygon demonstrates relatively balanced development across dimensions, with performance indices ranging from 63.42% (ecological) to 71.42% (technological), indicating consistent moderate-level sustainability achievement without extreme variations. The diagram clearly illustrates a performance hierarchy with technological dimension (71.42%) forming the most extended vertex, followed by economic dimension (70.42%). These leading dimensions create the diagram's most prominent features, reflecting successful implementation of efficient irrigation systems, particularly the one inlet-one outlet system, and relatively stable economic conditions within the rice farming sector (Dananjaya et al., 2024).

The three remaining dimensions—social (63.69%), institutional (63.53%), and ecological (63.42%)—form the more constrained portions of the kite shape, indicating priority areas for sustainabilityimprovement(seeFigure3).Therelativelycompressedverticesinthesedimensions suggest systematic challenges in community engagement, governance effectiveness, and environmental management that require targeted intervention strategies (Rosalina et al., 2023).

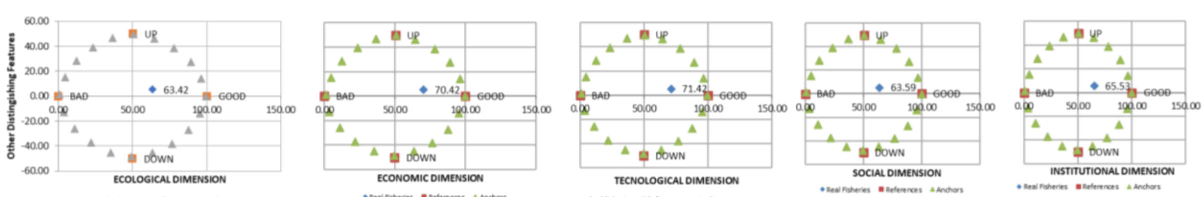

Figure 3. Sustainability index value of ecological, economic, technological, social, and institutional dimensions of rice farming systems at Tabanan Regency

The kite diagram's shape reveals a sustainability profile characterized by technological strength butrequiringcoordinatedenhancementacrosssocial,institutional,andecologicaldimensions.The moderate expansion in all directions indicates that while the rice farming system maintains basic sustainability, significant potential exists for advancement toward high sustainability status (≥75%) through strategic interventions addressing the lower-performing dimensions. This visual analysis confirms that the rice farming systems of Tabanan Regency have a strong sustainability foundation and clear directions for development, particularly in the areas of social, institutional, and ecological performance, by utilizing technological strengths.

Leverage Analysis

In order to identify the most influential attributes within each sustainability dimension that have a substantial impact on the overall system performance, leverage analysis is a critical component of the RAP-Farm methodology. The sensitivity of sustainability indices to changes in specific attributes is quantified by this analytical technique, which allows for the prioritization of strategic interventions based on their potential impact magnitude. Through the identification of the factors that have the most significant impact on sustainability outcomes, leverage analysis facilitates the formulation of evidence-based policies and the allocation of resources to optimize their effectiveness.

The leverage analysis quantifies the extent to which each attribute contributes to the fluctuations in the sustainability index by estimating the root mean square (RMS) ordination changes along the sustainability scale. Attributes that exhibit higher leverage values are more sensitive, which means that changes in these factors will result in more significant changes in the performance of the overall sustainability. The analysis evaluates ten attributes across each dimension, employing selection criteria that prioritize attributes with leverage values surpassing fifty percent of the maximum observed value, thereby identifying the most significant factors (Angelino et al., 2023). The leverage analysis identifies five key determinants of rice farming sustainability in Tabanan Regency, each reflecting the most sensitive attribute within its respective dimension.

(1) Economic Dimension - Price Stability (Leverage: 4.88)
With a leverage value of 4.88, the sustainability of rice and grain price stability is the most influential factor across all dimensions. This discovery suggests that price fluctuations have the most extensive influence on the overall sustainability performance, which underscores the critical significance of market stability for the economic security and long-term viability of farmers (Kubontubuh, 2023).

(2) Technological Dimension: Irrigation Efficiency (Leverage: 4.53).
Sustainable irrigation system efficiency is the second most influential factor (4.53), emphasizing the critical role of water management in the success of rice cultivation. This high leverage value illustrates the fundamental dependency of rice agriculture on reliable, efficient water distribution infrastructure and the significant influence that irrigation improvements can have on overall sustainability (Shedden-Mora et al., 2023).

(3) Social Dimension - Knowledge Transfer (Leverage: 4.50):
The sustainability of intergenerational knowledge transfer is significantly influenced (4.50), underscoring the significance of preserving and transmitting traditional agricultural wisdom while evolving to meet contemporary challenges. This leverage factor highlights the importance of human capital development and cultural continuity in sustaining farming practices.

(4) Ecological Dimension - Spatial Planning (Leverage: 4.49):
The ecological sustainability is significantly influenced by the coherence of land-use policy, as evidenced by the high sensitivity (4.49) of the quality of general plans and spatial planning. This result is indicative of the influence of planning decisions on the preservation of agricultural areas, environmental protection, and land conversion pressures (Riffel et al., 2023).

(5) Institutional Dimension - Traditional Governance Leverage: 4.39

The substantial influence of awig-awig (traditional regulations) on the sustainability of institutional sustainability is evident (4.39), underscoring the ongoing significance of customary governance systems. In the context of contemporary agricultural sustainability, this leverage value emphasizes the importance of community-based management structures and traditional knowledge systems (Golob et al., 2023).

The leverage analysis reveals a balanced distribution of critical factors across all five dimensions, with leverage values clustering between 4.39 and4.88. This narrow range (0.49differencebetween highest and lowest) suggests that sustainable rice farming requires coordinated attention to economic stability, technological efficiency, social continuity, ecological planning, and institutional governance. The identification of these high-leverage factors provides clear targets for policy intervention and resourceal location to achieve maximum sustainability improvements.

Based on leverage magnitudes, the analysis suggests prioritizing economic price stabilization mechanisms, followed by irrigation system modernization, intergenerational knowledge transfer programs, spatial planning reforms, and traditional governance strengthening. However, the similar leverage values across dimensions indicate that integrated approaches addressing multiple factors simultaneously may yield superior results compared to single-dimension interventions.

DISCUSSION

The overall sustainability index of 66.50% (moderately sustainable) represents a novel finding demonstrating that traditional subaksystems, whenintegrated with modern agricultural practices, can maintain balanced sustainability performance despite contemporary challenges (Sanchez-Rodriguezetal.,2023).Thenarrowperformancerangeacrossdimensions(7.99percentagepoints) provides new evidence that traditional agricultural systems can achieve balanced development across multiple sustainability aspects.

The technological dimension's leadership (71.42%) reveals an unexpected finding—traditional irrigationsystemscontributesignificantlytotechnologicalsustainabilitywhileenvironmentaland social vulnerabilities require targeted interventions. This challenges conventional assumptions about traditional agricultural systems' technological capacity. The identification of price stability as the most influential factor across all dimensions (leverage: 4.88) represents a novel finding demonstrating economic security's centrality in multidimensional sustainability frameworks (Paramarta & Karyati, 2024).

Ecological sustainability faces critical challenges through spatial planning clarity (leverage:4.49), providing new evidence for policy coherence's critical role in maintaining environmental sustainability within traditional systems (Riffel et al.,2023). The vulnerability of the social dimension in intergenerational knowledge transmission (leverage: 4.50) provides a novel perspective on the specific mechanisms that threaten agricultural continuity, illustrating that knowledge degradation poses both technical and socio-cultural risks (Walker et al., 2023).

Scientific sustainability assessment is systematically integrated with THK philosophy to establish a novel methodology for agricultural development that is culturally appropriate. This methodology presents the most innovative perspectives on the empirical validation and improvement of indigenous knowledge systems. A new approach that connects traditional water management with contemporary governance systems is represented by the ecological strategy, which combines formal spatial planning with subak institutional strengthening. The integration of cross-sectoral policies offers innovative methods for the preservation of cultural heritage values and the prevention of conflicts. The integration of digital-based cooperatives with minimal price policies promotes economic sustainability and is consistent with THK's pawongan principles. This approach offers new perspectives on the enhancement of traditional cooperative values through contemporary platforms while preserving social solidarity (Pratama et al., 2021). The social strategy, which prioritizes youth engagement while maintaining traditional practices, provides innovative solutions to the issues of generational transitions in agriculture. New methods of modernizing conventional water management systems while maintaining cultural values are represented by technological advancements that enhance irrigation efficiency (Asrika et al., 2023). This institutional strategy for the formal legal recognition of awig-awig is an innovative measure of institutional strengthening that serves as a bridge to 2023.

There are four substantial innovations to sustainability science that this study contributes, which challenge existing theoretical frameworks and introduce new methodological approaches. The research initially establishes a balanced sustainability model that contradicts the assumption that traditional agricultural systems inevitably lag in comprehensive sustainability performance. This model demonstrates that traditional agricultural systems can maintain equilibrium across multiple sustainability dimensions despite modernization pressures. Secondly, the results exhibit an economic centrality framework in which price stability is the most critical factor across all sustainability dimensions, thereby challenging traditional multi-dimensional approaches that treat economic factors as separate considerations rather than central organizing principles. Thirdly, the investigation establishes a THK integration methodology that validates traditional wisdom scientifically, thereby establishing replicable frameworks for culturally appropriate development strategies that connect indigenous knowledge with modern sustainability science. Fourthly, the research illustrates traditional-modern synthesis pathways, which illustrate how indigenous agricultural systems can achieve sustainable modernization without cultural compromise. This offers new models for development that respect traditional values while enhancing technological and economic performance. These contributions collectively advance sustainability science by establishing practical models for culturally sensitive agricultural development, producing new theoretical frameworks that acknowledge the centrality of economic stability in multidimensional sustainability, and providing evidence-based approaches for integrating traditional knowledge systems with scientific assessment methodologies. The narrow leverage value range (4.39-4.88) serves as new evidence that sustainable rice farming necessitates coordinated interventions rather than single-dimension interventions. This supports the THK philosophy's emphasis on balanced harmonies and provides empirical validation for traditional wisdom approaches.

These discoveries have substantial implications for the development of policy in regions with traditional agricultural systems, as they illustrate how scientific evaluation can validate and improve indigenous knowledge systems while simultaneously addressing modern sustainability challenges. The incorporation of formal policy frameworks with traditional governance provides replicable models for sustainable agricultural development that respects cultural heritage while achieving modernization objectives.

Tabanan Regency's rice cultivation demonstrates a dedication to environmental preservation, as evidenced by its ecological dimension sustainability index of 63.42 (moderately sustainable). Ecological dimension sustainability of rice farmingin Tabanan Regency includes soil and water conservation, more efficient agricultural input use, and biodiversity maintenance. The attribute with highest sensitivity value is clarity of general plans and spatial planning with leverage score of 4.49. Clarity in spatial planning plays important roles in providing legal certainty and directed, sustainable agricultural development directions, including allocation of permanent agricultural land and intersectoral integration. Conversely, spatial planning unclear can cause land use conflicts, uncontrolled land conversion, and inefficiency in agricultural production management risking productivity decline.

The sustainability index of 70.42 places the economic dimension of rice farming in Tabanan Regency in moderately sustainable category. This status indicates that economic activities supporting rice farming have been running quite well but have not reached optimal conditions (Charfeddine&Umlai,2023). Leverage analysisresults show the most sensitive attribute affecting economic sustainability index is sustainability ofrice and grain price stability with leverage score of 4.88. This value illustrates that rice and grain price fluctuations greatly affect economic sustainability levels in rice farming systems in this region. Price stability becomes a key factor because it determines income certainty for farmers,encourages investment feasibility infarming, and maintains balance between production Costs and received results(Paramarta&Karyati,2024).

The social dimension also contributes to quite sustainable status with sustainability index of 63.59, shown by strong social solidarity, active farmer participation in farmer groups, and acceptance of local value sin agricultural systems. The existence of mutual cooperation traditions and agricultural knowledge inheritance from generation to generation becomes strengthening factors in social sustainability. Leverage results show the most sensitive attribute is sustainability of intergenerational knowledge transfer with leverage score of 4.50. This value indicates that knowledge transfer from older to younger generations plays very important roles in maintaining rice farming practice continuity in Tabanan Regency (Walker et al., 2023). When younger generations are less involved or uninterested incontinuing agricultural activities, then knowledge of provenlocal practices in resource management will experience degradation. This phenomenon not only threatens agricultural sector sustainability technically but also socially and culturally considering agricultural activities in Tabanan Regency are inseparable from local values such as mutual cooperation and agrarian rituals deeply rooted in community life.

Meanwhile, technological dimension sustainability index of 71.42 (moderately sustainable category) is the highest sustainability index compared to four other dimensions. Existingly, rice farming in Tabanan Regency has utilized some modern agricultural technologies such as agricultural machinery use and superior varieties. However, technology dissemination is not evenly distributed and therearestillobstaclesinnewinnovationadoption,especiallyamongsmall farmers and those less exposed to training (Pratama et al., 2021; Wicaksana et al., 2020). Sustainable appropriate technology extension and training are greatly needed to improve rice farming efficiency and productivity. Leverageanalys is results show the most sensitive attributeis irrigation system efficiency with value 4.53. This value indicates that efficient irrigation systems have great influences on sustainability in technological dimensions. Irrigation system efficiency not only impacts water use savings and land productivity improvements but also determines successinothertechnologyadoptionssuchasusingsuperiorvarietiesrequiringmoreprecisewater regulation (Anindita et al., 2020).

Institutional dimension sustainability includes subak existence, farmer cooperatives, and local government support that have provided quite strong institutional foundations in supporting sustainability.However,institutionaleffectivenessstillneedsstrengtheningthroughmanagement capacity improvements, transparency, and access to information and more inclusive regulatory support. Institutional dimension ordination value of 65.53 shows institutional dimensions in rice farming in Tabanan Regency are moderately sustainable. Institutional dimensions play strategic rolesinsustainableagriculturaldevelopmentbecausetheyarecloselyrelatedtolocalregulations, farmer organization existence, financing access, inter-institutional coordination, and distinctive traditional institutional roles such as subak and awig-awig in Bali. The most sensitive attribute is awig-awigexistencesustainabilitywithleveragescore4.39(Aninditaetal.,2020).Awig-awigare written rules traditionally implemented by subak member farmers in regulating resource governance such as irrigation water, land use, and social relationships among farmers.

Based on sustainability indices, ecological dimensions (63.42) and social dimensions (63.59) are relatively similar and occupy the two lowest indices. Therefore, in formulating rice farming sustainabilitystrategiesinTabananRegency,thesetwodimensionsneedmoreattentiontoprevent sustainability status decline. However, to maintain or even improve rice farming sustainability status in Tabanan Regency, all dimensions need strengthening.

Rice farming sustainability strategy in Tabanan Regency through strategies in ecological, economic, social, technological, and institutional dimensions based on THK concepts. This concept consists ofthree main harmonies: *parahyangan* (harmonious relationshipbetween humans and God), *pawongan* (harmonious relationship among humans), and *palemahan* (harmonious relationship between humans and nature).

Strategyinecologicaldimensionsconsideringthehighestsensitivityattributeofgeneralplanand spatial planning clarity is subak institutional strengthening strategy through mentoring and subak integration into spatial planning and regional development as well as cross-sectoral approaches. Related to other sensitive attributes, namely land processing and water resource management, more consistent and integrated sustainable agriculture principle applications are needed. This strategy represents systematic approaches in maintaining food security and environmental sustainability, particularly in subak context as world cultural heritage. Cross-sectoral approaches aim to synergize intersectoral policies such as agriculture, environment, spatial planning, and tourism to prevent overlapping or counter-productive policies.

Strategy in economic dimensions considering rice and grain prices as sensitive attributes is minimum price policy intervention (Pratama et al., 2021) and local market and value chain strengthening through digital-based farmer cooperative strengthening. This approach aligns with THK principles, particularly*pawongan*aspectsbecauseitprioritizeseconomicjusticeandsocial solidarity among agricultural and market actors, encourages farmer economic literacy improvements, and creates equality in accessing opportunities.

Strategy to encourage sustainability in social dimensions with sensitive attribute of intergenerational knowledge transfer sustainability is active young generation involvement in farmer groups, extension services based on local wisdom, social incentives, and preservation of traditional agricultural practices adaptive tochangingtimes. This strategy represents strategic steps in maintaining agricultural system sustainability while answering farmer regeneration challenges.

Irrigation system efficiency becomes the most sensitive attribute in technological dimensions. Therefore, irrigation system efficiency improvement efforts must be prioritized in sustainable agricultural development planning. Applicable strategies are irrigation channel revitalization, modern irrigation technology applications such as drip or sprinkler irrigation modified for rice fields, and farmer group training and empowerment in participatory water management (Asrikaet al., 2023).

The most sensitive attribute in institutional dimensions is awig-awig existence sustainability. Therefore, policy intervention strategies supporting local institutional strengthening through formal legal recognition of awig-awig are needed. By strengthening awig-awig existence sustainability, institutional dimensions in rice farming systems in Tabanan Regency can continue supporting agricultural sector sustainability more robustly and resiliently, bridging traditional values and modernization needs, and strengthening Bali's community and environment-based agricultural identity (Darmawan et al., 2023).

CONCLUSION

Rice farming sustainability in Tabanan Regency achieves an overall index of 66.50%, classified as moderately sustainable across all five dimensions.Theecological(63.42%)andsocial(63.59%) dimensionsshowthelowestperformance,indicatingpriorityareasforimprovement.Fivecritical factors most significantly influence sustainability: spatial planning clarity, price stability, intergenerational knowledge transfer, irrigation efficiency, and traditional governance (awig-awig) continuity.

Based on the THK frame work, five integrate dstrategies are recommended: (i)strengthening subak institutions through spatial planning integration and cross-sectoral coordination; (ii) engaging youth in farmer groups while preserving traditional practices through local wisdom-based extension services; (iii) providing formal legal recognition for traditional governance systems (awig-awig); (iv) implementing minimum price policies and developing digital-based farmer cooperatives; and (v) modernizing irrigation systems through technology adaptation and participatory water management. These strategies address identified vulnerabilities while building on existing strengths to enhance overall sustainability performance. Therefore, research recommendations are for stakeholders to revitalizesubak systems based on THK values in realizing sustainable rice farming in Tabanan Regency and Bali Province.

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