

Restoring the Meratus: A Permaculture-Based Nexus Supporting Adaptive Practice in Indigenous Communities

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ABSTRACT

This study investigates the role of permaculture-based agroforestry in strengthening ecosystem restoration, food security, and community resilience within the indigenous Dayak Meratus population in South Kalimantan, Indonesia. Following a major flash flood in 2021, an integrated landscape management initiative was implemented in Hinas Kiri village. From January to June 2025, data from 100 respondents collected through modified snowball sampling revealed measurable improvements in ecological and socio-economic indicators. The implementation of agroforestry systems based on permaculture principles resulted in increased plant diversity, improved soil conditions, and positive trends in tree growth. Biophysical assessments showed increased tree canopy cover and trunk diameter (5.7–7.1%) across *Shorea* sp., *Peronema canescens*, and *Hevea brasiliensis*, while crop yields rose for banana (+8.0%), taro (+8.9%), and rattan (+12.5%). Grounded theory analysis indicated a perceptual shift among farmers, who increasingly viewed permaculture as a climate adaptation strategy and pathway to economic diversification. A digital monitoring prototype and preliminary policy brief were developed to support adaptive management and evidence-based decision-making. The findings provide empirically grounded insights and demonstrate the value of an integrative nexus-based approach for climate-resilient landscape governance in rural area.

Keywords: Adaptive landscape management, Circular economy, Indigenous knowledge, Permaculture, Sustainable agriculture

INTRODUCTION

The growing frequency and intensity of climate-related disasters in the Global South, particularly in ecologically fragile regions, underscore the urgent need for integrated, community-based approaches to land and resource management. In Indonesia, the 2021 flash floods that devastated the Meratus Mountains region were not merely natural events, but symptoms of deeper structural and ecological dysfunctions resulting from deforestation, unsustainable land conversion, and the erosion of traditional ecological knowledge (TEK). Flood

events have triggered significant socio-economic and socio-cultural transformations, including changes in livelihoods, social roles, and environmental perceptions (Normaulida et al., 2023). Furthermore, the decline of TEK has been identified as a critical factor weakening community resilience, as such knowledge systems play a central role in anticipating, predicting, and mitigating flood hazards (Bwambale et al., 2018). These phenomena reflect a global pattern wherein vulnerable communities face the compounded risks of environmental degradation, social inequality, and climate volatility (Adger et al., 2013; IPBES,

2019). This shift in perception has occurred due to external influences, modernization, and government policies. Previously, the Meratus people viewed themselves as having a spiritual bond (oneness) with nature, in which humans care for the land and the land sustains life (Gumelar, 2024). Such realities necessitate rethinking development paradigms through nature-based solutions (NbS) that restore ecological functions while reinforcing socio-economic resilience (Raymond et al., 2017).

Permaculture has emerged as a powerful alternative paradigm within the broader agroecological movement, offering both a design system and a philosophical orientation for sustainable living. Its emphasis on regeneration, biodiversity, and ethical land stewardship aligns with global calls for just transitions and ecologically sound livelihoods (Ferguson & Lovell, 2014). In contrast to conventional agricultural intensification, which often prioritizes yield at the expense of ecosystem health, permaculture emphasizes circular resource use, low external inputs, and the integration of human systems within local ecological processes, contributing to improved biodiversity, soil quality, and system resilience (Krebs & Bach, 2018; Reiff et al., 2024; Williamson et al., 2024). Holmgren (2002) and Mollison (1988) recent studies indicate that permaculture systems can enhance soil fertility, water retention, and crop diversity, especially in smallholder contexts across the tropics (de Molina & Guzmán Casado, 2017; Yang et al., 2023).

The adoption of permaculture by Indigenous communities such as the Dayak Meratus of South Kalimantan signals a meaningful convergence of global innovation with local wisdom. Rather than passive recipients of external interventions, these communities are co-creating agroecological knowledge systems grounded in place-based ethics

and collective memory. Yet, empirical research on the outcomes of such community-led initiatives remains scarce. What is needed is a framework that not only evaluates biophysical indicators but also captures the socio-cultural and epistemological dimensions of agroecological transitions (Altieri & Nicholls, 2017; Anderson et al., 2019). Without such integration, policies risk reinforcing technocratic biases and undermining the relational worldviews central to Indigenous stewardship.

This study addresses that gap by developing and applying a nexus framework. The nexus is not conceptualized as a broad multi-sectoral framework, but rather as an empirically grounded set of linkages between vegetation structure, crop productivity, and farmer practices within a permaculture-based agroforestry system in Hinas Kiri village. These components are treated as interacting elements, where changes in vegetation structure may influence agricultural output and shape farmer decision-making. Integrating nexus with sustainable livelihoods enables the development of a more holistic Environmental Livelihood Security (ELS) framework that balances human demands with the supply of natural resources (Hoff, 2011). Although interest in climate-resilient agriculture and agroecological approaches is growing, existing studies remain fragmented; they often examine climate adaptation, food security, or the circular economy in isolation rather than as an integrated system. Research on permaculture-based agroforestry systems, particularly in disaster-prone mountainous areas inhabited by indigenous communities, remains limited, and few studies combine socio-cultural analysis with biophysical assessments to capture overall system dynamics. This study develops and applies a multidimensional nexus framework within a permaculture-based agroforestry system in Hinas Kiri Village,

integrating grounded theory derived from field observations, biophysical measurements, and scenario modeling to evaluate system interactions. The findings provide actionable insights for climate-resilient landscape governance in mountainous and biodiversity-rich regions, while contributing to discussions on participatory knowledge co-production, adaptive management, and digital monitoring for evidence-based decision-making (Clark & Harley, 2025; Holland et al., 2022).

The novelty of this study lies not only in its empirical contributions but also in its epistemic stance: it challenges reductionist metrics of success and foregrounds the lived realities of Indigenous farmers navigating socio-ecological change. It argues that permaculture, when contextualized through local cosmologies and institutional support, can function as a dynamic strategy for climate resilience and regenerative economies. As global crises deepen, such integrative and reflexive models are no longer optional—they are essential.

RESEARCH METHOD

Designing a methodology that accurately captures both ecological dynamics and socio-cultural transformation requires the integration of interdisciplinary tools, participatory approaches, and rigorous empirical protocols. This study employed a mixed-methods framework that triangulates biophysical field measurements, structured social inquiry, and qualitative narrative analysis to assess the ecological and socio-economic impacts of permaculture-based agroforestry in Hinas Kiri village, South Kalimantan. Acknowledging the complexity of socio-ecological systems, the research design aimed to balance quantitative robustness with contextual depth, in alignment with

sustainability science approaches (Lang et al., 2012).

1. *Sampling Strategy and Respondent Selection*

The study adopted a modified snowball sampling method to identify and engage 100 respondents across three ecological zones within the research site (Figure 1). Unlike random sampling, snowball sampling was chosen for its effectiveness in reaching knowledge-rich participants embedded within tight-knit Indigenous farming communities (Kissinger et al., 2021; Noy, 2008). The sampling process began with key informants, including community leaders and experienced farmers, and expanded through referral networks. To reduce selection bias, inclusion criteria were applied at each stage, including involvement in agroforestry practices, land-use diversity, and residence within specific ecological zones. Sampling continued until thematic saturation was achieved. Respondent selection was further guided by spatial criteria, such as proximity to watershed areas, slope gradients, and historical land-use practices, as well as socio-demographic diversity. This purposive approach ensured coverage across key agroecological functions and socio-demographic variations, rather than statistical representativeness (Etikan, 2016; Noy, 2008).

2. *Field-Based Biophysical Assessments*

To assess ecological recovery and land productivity, in situ measurements were conducted over two seasonal cycles (January–June 2025). Biophysical indicators included tree growth parameters (canopy diameter, trunk circumference), soil pH and organic carbon levels, water infiltration rates, and microclimatic variability. These variables were measured using calibrated instruments (e.g., Yamayo Million Diameter Tape, Soil Analyzer 3 in 1, 4 in

1 Environment Meter) and standard forestry protocols (FAO, 2017). Tree species observed included *Shorea sp.*, *H. brasiliensis*, and *P. canescens*, selected due to their relevance to both ecological

restoration and local livelihoods. These data were cross-referenced with remote sensing imagery to validate changes in vegetation cover (Wang et al., 2010).

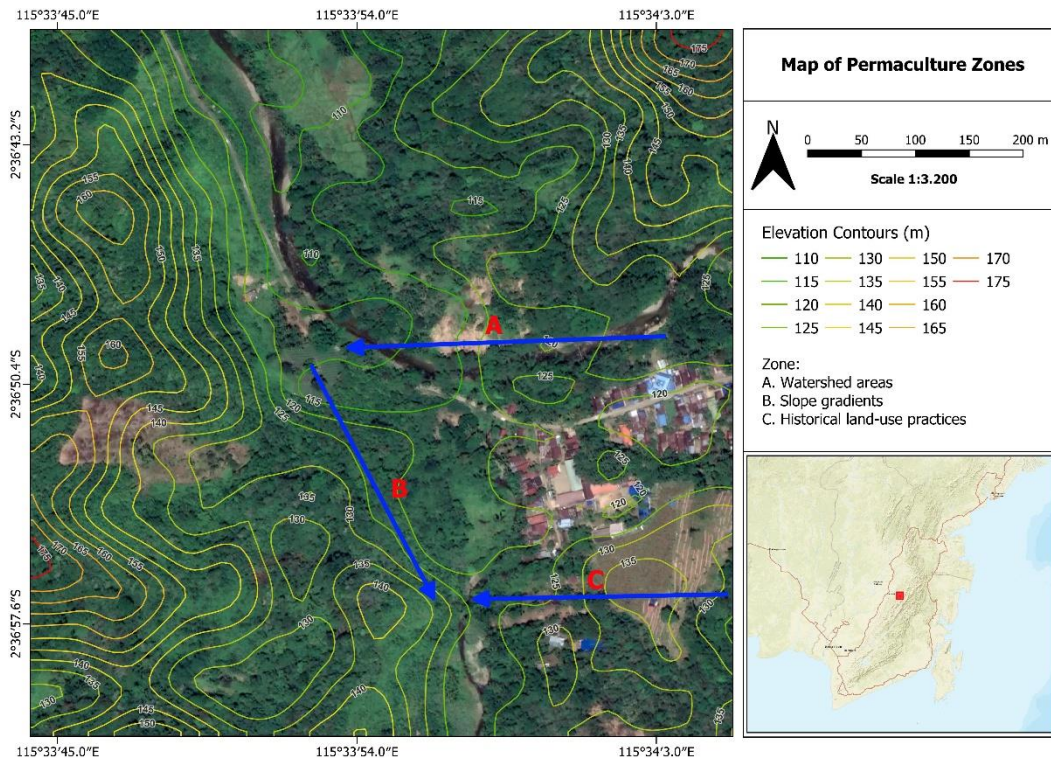


Figure 1
Map of Permaculture Zone in Hinas Kiri

3. Structured Surveys and Perception Mapping

Structured questionnaires were administered to all 100 respondents, covering five thematic domains: agroforestry practices, water-use efficiency, renewable energy awareness, income diversification, and adoption of sustainable agriculture. Each domain consisted of 4–6 items measured using a five-point Likert scale (1 = strongly disagree to 5 = strongly agree). The instrument was adapted from validated tools in agroecology and climate adaptation studies (Gie Yong & Pearce, 2013).

In addition to surveys, five community dialogue sessions were conducted using

participatory rural appraisal (PRA) (Ali et al., 2023; Krisdianto et al., 2025) tools to contextualize survey responses and deepen understanding of community values, motivations, and constraints.

4. Grounded Theory and Qualitative Narrative Analysis

To analyze local perceptions, behavioral changes, and emerging farmer identities, grounded theory methodology was employed. This approach allowed for inductive coding and theory generation from the narratives of farmers engaged in permaculture transitions (Charmaz, 2006; Charmaz 2024). Interviews and group discussions were recorded, transcribed, and coded using NVivo 14 software. The

process followed an open–axial–selective coding sequence (Corbin & Strauss, 2008), ensuring the identification of key categories such as ecological ethics, intergenerational knowledge transfer, and adaptive strategies under climate stress. During open coding, interview transcripts and field observations were systematically analyzed on a line-by-line basis to generate initial concepts related to farmer behavior and the implementation of permaculture practices. Subsequently, axial coding was employed to organize these concepts into higher-order categories by examining relationships among conditions, actions/interactions, and consequences, while selective coding facilitated the integration of these categories into core themes that provide a coherent explanation of how permaculture practices shape farmer behavior and broader socio-ecological outcomes. Attention was given to the epistemological richness of local expressions, which often blended spiritual and ecological meanings.

5. Data Integration and Scenario Modeling

Quantitative survey data were further analyzed using Principal Component Analysis (PCA) to reduce dimensionality and identify dominant patterns in respondents' perceptions across thematic domains. Based on the PCA scores, cluster analysis was conducted to classify respondents into distinct groups representing varying levels of engagement, knowledge, and consistency in sustainable agriculture practices. The final analytical layer involved integrating biophysical and social data into a participatory scenario modeling tool. The model simulated three landscape governance scenarios—status quo, agroecological transition, and hybrid technocratic intervention—using

stakeholder-informed assumptions and system dynamics logic (Sterman, 2000). In line with established ecosystem service assessment frameworks such as Millennium Ecosystem Assessment (2005), the scenarios were designed to evaluate trade-offs among ecological functions, livelihood outcomes, and long-term sustainability. This approach is consistent with recent global assessments emphasizing the importance of integrating traditional knowledge systems in addressing land degradation and enhancing conservation outcomes (Bizikova et al., 2009; IPBES, 2019). Such a reflexive and participatory framework enables a more inclusive understanding of resilience trade-offs and long-term socio-ecological viability (Bizikova et al., 2009).

RESULTS AND DISCUSSION

Results

Integration of Farmer Behavior for Conservation and Sustainable Production within the Circular Economy Framework

Preliminary analysis results for 2025 indicate positive trends in the growth of forest trees (Meranti, Lurus, and Rubber) and an increase in the production of agroforestry products, including bananas, taro, and rattan. The increase in tree trunk diameter and canopy area, ranging from 5.7% to 7.1% in two quarters (Table 1), demonstrates the success of the agroforestry strategy in combining the ecological and productive functions of the land.

On the other hand, the transition to permaculture-enhanced agroforestry systems significantly increased the productivity of key food and non-food crops. In two quarters, yields of bananas, taro, and rattan increased by 8.0%, 8.9%, and 12.5%, respectively (Table 1).

Table 1
Growth Rate of Permaculture Crops

Commodities	Unit	Quarter 1 2025	Quarter 2 2025	Growth Rate (%)
Meranti Tree	Trunk Diameter (cm) / Canopy Area (m ²)	35 cm / 12 m ²	37 cm / 13 m ²	5.7
Lurus Tree	Trunk Diameter (cm) / Canopy Area (m ²)	30 cm / 10 m ²	32 cm / 11 m ²	6.7
Rubber Tree	Trunk Diameter (cm) / Canopy Area (m ²)	28 cm / 9 m ²	30 cm / 9.5 m ²	7.1
Banana Production	Bunch (100 Tree)	250 kg	270kg	8
Taro Production	Kg (400 Tree)	900 kg	980kg	8.9
Rattan Production	Stems (20 ha)	1200	1350	12.5

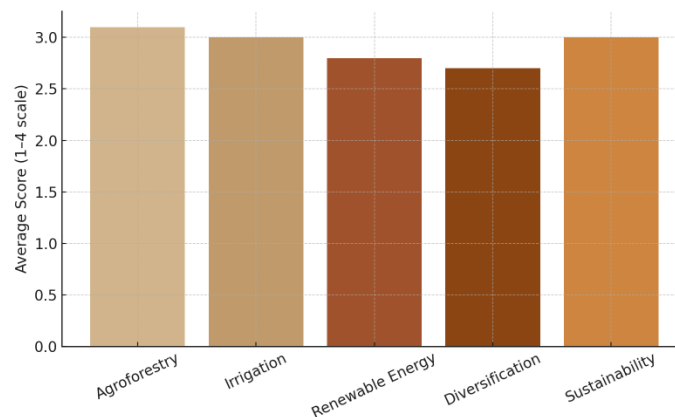
Source: Primary data analysis, 2025

In line with the circular economy concept, the observed increases in productivity were associated with improved resource utilization efficiency and enhanced internal nutrient recycling. Farmers adopted practices such as organic waste composting, crop residue reutilization, and integration of livestock inputs, resulting in approximately 60–75% of biomass being reintegrated into the system as compost or mulch. These practices contributed to increased soil organic matter and reduced reliance on external inputs. Concurrently, diversification of agroforestry outputs (including timber, food crops, and non-timber forest products such as rattan) facilitated value circulation within local markets, thereby reducing production risks and enhancing income stability. Preliminary estimates indicate a 15–20% reduction in external input costs and a 10–

18% increase in net household income, underscoring the role of permaculture-based management in strengthening circular economy dynamics through resource recirculation, waste minimization, and diversified livelihood systems (Anderson et al., 2019).

Social Response and Farmers' Perceptions of Agroforestry, Efficient Irrigation, Renewable Energy, Income Diversification, and Sustainable Agriculture

Data were collected using a questionnaire distributed to 100 participants, covering 25 questions grouped into five main topics, namely Agroforestry, Efficient Irrigation, Renewable Energy, Income Diversification, and Sustainable Agriculture. The average scores for each of these topics are present in Figure 2.



Source: Primary data analysis, 2025

Figure 2
Average Score per Topic

Survey responses and cluster analysis indicated moderate uptake of water-efficient irrigation and renewable energy technologies. While awareness of these practices was high, their application remained uneven mainly due to cost barriers and limited technical assistance.

Respondent Clustering: Support Segmentation

Clustering respondents based on scores for all topics shows that groups with high scores also tend to give high scores on the topic of sustainable agriculture. Conversely, groups with low or moderate scores show inconsistency in their understanding or application of these practices (Figure 3)

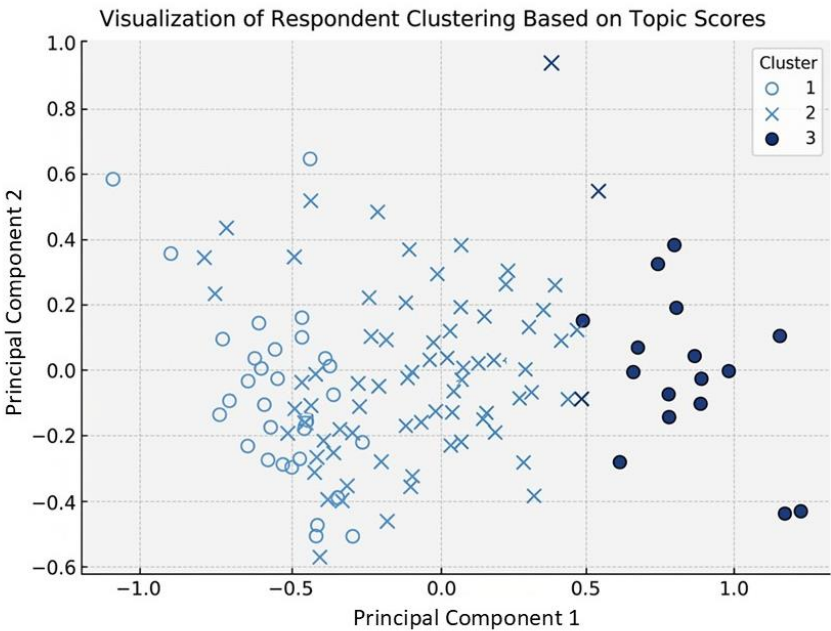
Cluster analysis revealed three respondent typologies, where Cluster 1 emerged as the most prominent group: (1) Transitional Farmer Group (moderate supporters with inconsistent implementation); (2) Progressive Farmer Group (proactive agents of change); and (3) Constrained Farmer Group (hesitant adopters with limited access to resources). The average score for each topic was calculated on a 1-4 scale. The visualization of farmer clusters shows that there are three groups with different characteristics, as described in the following table

Discussion

Integrating Farmer Behavior for Conservation and Sustainable Production within a Circular Economy Framework

In the vulnerable terrain of the Meratus Mountains, expansive tree canopies serve as vital hydrological buffers against heavy rainfall, minimizing soil erosion and improving local hydrology, demonstrating that adaptive landscape management can significantly strengthen ecosystem resilience to climate change (Asyiqin & Ong, 2025). Building on this ecological stability, farmers apply circular economy practices by recycling organic matter to maintain soil health. This synergy makes crop diversification highly effective, directly linking ecosystem restoration with increased economic output and food security (Tittonell et al., 2020). This diagram (Figure 4) illustrates how integrating circular economy principles into agrifood systems minimizes waste, enhances resource efficiency, and supports ecological restoration. According to Jurgilevich et al. (2016) and Alami et al., (2024) upcycling agricultural residues like biomass, the sector transitions from a linear to a circular model, improving soil health and mitigating environmental degradation. Ultimately, this synergistic

closed-loop system fosters eco-friendly production, long-term food security, and local economic resilience through sustainable land management (Zhang et al. 2022;Tittonell et al., 2020)



Source: Primary data analysis, 2025

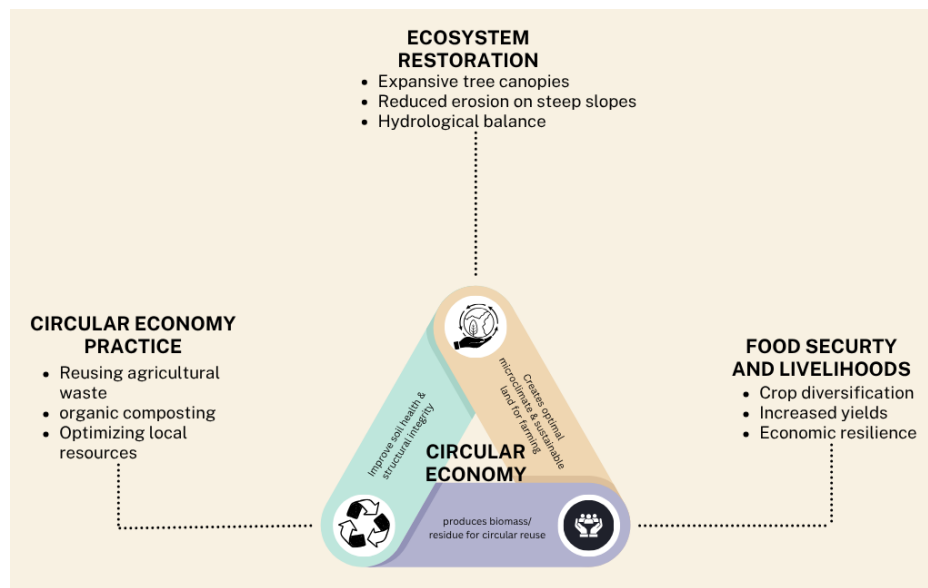
Figure 3
Visualization of Respondent Clustering based on the average score for each topic (Agroforestry, Irrigation, Renewable Energy, Diversification, and Sustainability).

Table 3
Clustering of Respondents

Cluster	Agroforestry	Irrigation	Renewable Energy	Diversification	Sustainability	Number of Respondents
1	3.01	2.83	2.99	2.62	2.82	49
2	3.16	3.07	3.08	2.81	3.23	36
3	2.71	2.63	2.69	2.47	2.33	15

Source: Primary data analysis, 2025

The positive correlation between farmers' land management practices and production outcomes reflects the success of the permaculture approach, which combines ecosystem regeneration with productivity optimization. Farmers who are actively involved not only increase the capacity of ecosystems to provide environmental services, but also strengthen the socio-economic resilience of their communities. Integrating social and ecological dimensions into landscape management produces a double impact: improving environmental quality while strengthening social cohesion (Kim et al., 2023).



Source: Primary data model design, 2025

Figure 4

Conceptual model of the Agroforestry Nexus in the Meratus Mountains, illustrating the interrelationships among the circular economy, ecosystem restoration, and food security.



Source: Primary data analysis, 2025

Figure 5

The community-based organic composting cycle in the Meratus agroforestry system

From a circular economy perspective, this model provides long-term benefits, namely a) Waste-free resource management, The local community actively implements circular economy principles by recycling biomass

residues from tree pruning and banana and taro harvesting. Through established community composting initiatives, these organic wastes are systematically processed into compost to return essential nutrients to the soil, reducing

reliance on external inputs. b) Diversification of income sources, Forest products such as rattan and rubber can be marketed alongside food products, reducing dependence on a single commodity. c) Strengthening of local supply chains, Agroforestry products can be processed at the community level, increasing their added value before being marketed. The composting process is shown in Figure 5.

The significance of these research findings for adaptive living in harmony with nature is that productivity does not have to be achieved at the expense of ecology. Instead, by combining local knowledge, scientific innovation, and community collaboration, a dual-function agricultural system is created: preserving nature and providing a decent livelihood. Bezner Kerr et al., (2019) and von Cossel et al. (2025) that regenerative systems based on agroecology are the main pathway for climate adaptation and long-term sustainability

Integrated Agroforestry Farmers' Efforts Based on Permaculture

This approach is in line with the findings (Jabbar et al., 2023b) which confirms that the integration of trees, food crops, and non-timber forest products in large landscapes can build resilient and equitable food systems.

Despite these successes, integrating high-canopy trees like *Shorea* sp. with understory crops like taro presents a significant challenge regarding sunlight competition. An increase in tree canopy density can potentially impede taro growth due to reduced solar radiation reaching the ground layer. However, the permaculture approach addresses this through strategic spatial zoning and periodic canopy management (pruning). By implementing a multi-strata design, farmers ensure that light-sensitive crops are positioned in areas with optimal filtered light, while regular pruning of the Meranti and Rubber trees provides a dual

benefit: preventing excessive shading and generating high-quality biomass for the community's composting initiatives. This managed synergy ensures that the ecological goal of increased tree cover does not compromise the productivity of food crops (Burggraaf et al., 2020; Toop et al., 2017)

Farming communities increasingly acknowledge that economic success depends on ecological sustainability. According to Bopp et al., (2019) and Gao et al., (2023) this approach builds climate resilience by optimizing biodiversity, resource utilization, and risk distribution. This climate-resilient model fosters a harmonious human-ecosystem relationship, proving that prosperity can be achieved through environmental stewardship rather than destruction.

Social Response and Farmers' Perceptions of Agroforestry, Efficient Irrigation, Renewable Energy, Income Diversification, and Sustainable Agriculture

Thematically, the aggregation of average scores per topic reinforces these findings. The first topic, Agroforestry, received a relatively high average score compared to other topics, indicating a relatively strong level of acceptance and experience among respondents in applying agroforestry principles on their land. The second group of topics concerns irrigation. The average scores for the questions in this group range from 2.63 to 3.07, which means that respondents generally agree with and support efficient irrigation systems. This level of support reflects the belief that drip irrigation technology does indeed bring tangible benefits.

The third topic group is perceptions of renewable energy and carbon emissions. Analysis of the average score per question shows relatively moderate values, ranging from 2.6 to 3.0. This indicates that most respondents are familiar with and have started to

implement renewable energy, but have not yet fully felt its maximum impact in their daily practices. Some respondents have started using renewable energy, or at least have plans to adopt it. They recognize its potential benefits, such as cost efficiency and carbon emission reduction, but these benefits have not been widely felt. Access to renewable energy technology remains an obstacle, both in terms of infrastructure and the initial cost of implementation. Nevertheless, respondents still consider renewable energy to be important for the future of sustainable agriculture.

The fourth topic group is income diversification and economic welfare. The income diversification and economic welfare domain achieved an average score from 2.47 to 2.81, indicating that respondents 'quite often' engage in activities such as ecotourism and honey production. The consistent scoring across items (Q16–Q20) suggests that these strategies are being adopted evenly as a means to reduce dependence on single-source income. Similar to findings in Pakistan, such diversification reduces household vulnerability and promotes the adoption of conservation practices (Jabbar et al., 2023). These results confirm that farmers increasingly recognize the synergy between economic stability and environmental sustainability, though significant potential for further integration remains (Jabbar et al., 2023)

High diversification scores reflect a robust household resilience strategy against market fluctuations, climate change, and crop failure. By stabilizing cash flow, diversification improves family welfare; however, its success is not automatic. As noted by Igwe et al. in Nigeria, education is a primary driver for innovation and non-agricultural shifts, highlighting that human resource development remains essential for sustainable and inclusive growth.

Beyond economic gains, diversification drives social

transformation. Engaging in ventures like agro-ecotourism and non-timber forest products (NTFPs) expands social networks and fosters environmental stewardship, as these businesses depend on ecological health. Integrating income diversification with ongoing training can enhance village independence and quality of life (Flores-Tapia et al., 2022). Consequently, diversification serves as a socio-ecological empowerment mechanism for sustainable rural development.

To optimize this potential, the following actions are recommended: (1) integrate diversification with conservation efforts like community-based ecotourism; (2) provide technical and market support to increase profitability; and (3) adopt cluster-based strategies to scale impact among respondents showing intent but yet to begin (Igwe et al., 2020). The fifth topic group is sustainable agriculture. This topic group explores aspects of knowledge, training, support, and access to information related to sustainable agricultural practices. The average score per question in this group generally ranges from 2.7 to 3.1, indicating that respondents' perceptions of sustainable agriculture tend to be positive, but not yet fully strong or consistent. This shows that respondents support the idea of sustainable agriculture and recognize the importance of these practices in the long term. However, the variation in scores also indicates differences in the level of access and direct involvement among respondents.

Respondent Clustering: Support Segmentation

The cluster profile table clearly shows the average score per topic Agroforestry, Irrigation, Renewable Energy, Diversification, and Sustainable Agriculture as well as the number of respondents in each cluster. These results provide a critical segmentation, as each cluster shows different patterns of

support and understanding of sustainable agricultural innovation. With this approach, we can understand not only the general level of acceptance among respondents, but also which groups are most ready to become agents of change, which groups are moderate, and which groups still need additional intervention.

Respondents in Cluster 2 (high scores) can be categorized as progressive farmers who are ready to become agents of change. In contrast, Cluster 3 (low scores) requires additional support in the form of training, information, or policy incentives.

Cluster 1 (Transitional Farmer Group) represents a transitional segment characterized by positive attitudes toward innovation but inconsistent implementation, indicating high potential for adoption if supported by targeted incentives and capacity-building programs. Cluster 2 (Progressive Farmer Group) represents progressive farmers with the highest scores across all indicators, reflecting strong readiness to adopt innovation and act as local change agents within diffusion processes. Cluster 3 (Constrained Group), consisting of 15 respondents, exhibits the lowest adoption levels and faces significant structural constraints, including limited access to resources and technical support. This hesitation is strongly associated with environmental vulnerability, particularly among farmers whose land was affected by the 2021 flood events, indicating that risk exposure plays a critical role in limiting innovation uptake.

Although respondents demonstrate generally positive perceptions of sustainable agriculture, a gap persists between awareness and implementation, primarily due to limited access to training, infrastructure, and institutional support. Limited active participation in training and policy support among some respondents reveals structural challenges that need to be addressed immediately. Recent research confirms that the effectiveness

of continuous training, combined with farmers' intrinsic motivation to learn and innovate, is key to the successful adoption of sustainable agriculture (Jansirani & Krishnan, 2024; Sseguya et al., 2018). These findings are relevant to the conditions of respondents who, despite having positive perceptions, still need external support to take risks in adopting new technologies and practices. By strengthening the training system, expanding access to information, and providing appropriate incentives, the government can reduce the psychological and structural barriers that hinder adoption. Reflection on these results emphasizes the importance of designing human-centered policies that not only facilitate technology transfer but also build the capacity of farmers as active subjects in the transformation towards sustainable agriculture. With such an approach, the hope for the practical implementation of sustainable agriculture is no longer just a vision but can be realized in the field.

The convergence of empirical findings underscores the necessity of integrating scientific inquiry with participatory governance. While the ecological and social gains are promising, their long-term viability depends on institutional support, inclusive policy frameworks, and knowledge democratization. Current top-down agricultural policies often overlook the nuanced realities of smallholder innovation, undermining the transformative potential of community-led practices (Oteros-Rozas et al., 2015). These findings highlight the need for adaptive, multi-level governance frameworks that integrate scientific evidence, local knowledge, and participatory approaches. In particular, the institutionalization of digital monitoring systems and targeted policy support can enhance the scalability and long-term sustainability of permaculture-based agroforestry systems.

CONCLUSION

Permaculture-based agroforestry enhanced vegetation growth, increased crop productivity, and strengthened farmer adaptive practices, demonstrating measurable socio-ecological improvements within Indigenous farming systems. These outcomes reveal a functional nexus linking vegetation structure, production performance, and farmer behavior, where circular resource flows through biomass recycling, organic input reuse, and reduced external dependency contribute to both ecological recovery and livelihood resilience. While these findings highlight the integrative potential of permaculture-based systems within a circular economy framework, their applicability remains context-specific; therefore, further longitudinal and policy-level studies are required to evaluate scalability and long-term sustainability across broader landscapes.

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