

Article

Ecological, Economic, and Social Sustainability of the Puspa and Cardamom Agroforestry System in Gunung Walat Educational Forest (HPGW), Indonesia

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Abstract

This study aims to assess the sustainability of an agroforestry system integrating *Schima wallichii* (puspa) and *Amomum cardamomum* (cardamom) within the Gunung Walat Educational Forest—IPB University Educational Forest (HPGW), Indonesia, by applying the RAP-AFS (Rapid Appraisal Technique for Evaluating Agroforestry Sustainability) approach. The assessment was conducted across four key dimensions: ecological, economic, social, and institutional. The findings suggest that the overall sustainability of the agroforestry system in HPGW is moderately good, with a sustainability index value of 55.94. The social and ecological dimensions performed particularly well, scoring 67.51 and 61.43, respectively. The economic dimension achieved an index score of 55.45, although price fluctuations and reliance on middlemen continue to pose challenges. Meanwhile, the institutional dimension showed the lowest performance, with an index value of 39.37, underscoring the need to enhance institutional support, capacity building, and extension services to strengthen sustainability. In light of these findings, it is recommended to prioritize strengthening institutional frameworks, stabilizing market prices, and expanding soil conservation practices, alongside promoting greater social participation, to ensure the long-term sustainability of the agroforestry system in this region.

Keywords: agroforestry; cardamom; Gunung Walat Educational Forest; puspa; sustainability



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1. Introduction

The increasing frequency of forest fires in the Gunung Walat Educational Forest (HPGW), IPB University, reflects serious challenges in land management that directly threaten environmental sustainability. At the same time, population growth and increasing demand for space have reduced available agricultural land, intensifying competition for land use in surrounding areas. These pressures encourage local communities to seek alternative production spaces, including forest areas, to meet household food and economic needs. Consequently, the HPGW area has become vulnerable to land-use expansion, particularly in the absence of effective law enforcement governing forest utilization [1]. Such conditions have accelerated forest land conversion, leading to soil degradation manifested

by declining soil organic matter, reduced soil biota diversity, and deterioration of water quality and carbon storage capacity [2–5]. These impacts not only degrade forest ecosystems but also weaken the region's essential environmental functions.

Agroforestry systems have been widely recognized as a viable approach to addressing these challenges by balancing agricultural production with forest conservation. Agroforestry integrates woody perennials with agricultural crops and/or livestock within a single land-use unit, enabling mutually beneficial interactions between ecological and economic processes [6]. By enhancing food security while maintaining forest cover, agroforestry offers a strategic pathway for sustainable land management in areas experiencing land-use pressure.

The long-term effectiveness of agroforestry systems depends on their sustainability across multiple dimensions. Previous studies indicate that agroforestry sustainability extends beyond biophysical productivity and must incorporate social and institutional factors that shape implementation and outcomes [7,8]. Weak market structures, limited farmer group participation, and inadequate institutional support have frequently been identified as major constraints, particularly in tropical agroforestry systems. Price volatility and reliance on intermediaries for crops such as cardamom often undermine economic stability, while insufficient institutional capacity limits knowledge transfer and collective action among farmers [6–8].

Despite growing recognition of these challenges, existing agroforestry studies have largely emphasized ecological and economic aspects, with less attention given to the interrelationships between social participation, institutional support, and market access. Although some research has acknowledged institutional and social constraints, comprehensive assessments that integrate these dimensions remain limited. As a result, there is still an incomplete understanding of how coordinated improvements in social engagement, institutional frameworks, and market mechanisms can enhance agroforestry sustainability.

This study addresses these gaps by conducting a multidimensional sustainability assessment of the puspa–cardamom agroforestry system in the Gunung Walat Educational Forest (HPGW). The assessment integrates four key dimensions: ecological, economic, social, and institutional, using a unified analytical framework. Unlike previous studies that focused on isolated dimensions, this research emphasizes the role of institutional strengthening and market access, alongside social participation, as critical factors for overcoming sustainability constraints.

The integration of puspa (*Schima wallichii*) and cardamom (*Amomum cardamomum*) represents a promising agroforestry model for tropical regions such as HPGW. Puspa, a high-value timber species, contributes to soil conservation, biodiversity enhancement, and microclimate regulation, while cardamom provides a commercially valuable understory crop that supports farmer income diversification [9,10]. Cardamom, a tropical spice, is known for its aromatic seeds and is used both in culinary and medicinal applications. It is a high-value crop that can be sold in both domestic and international markets. The combination of these species enables more efficient land use, improves ecological functions, and strengthens food security by reducing dependence on single-crop systems.

This study aims to evaluate the sustainability of the puspa–cardamom agroforestry system in HPGW using the RAP-AFS (Rapid Appraisal Technique for Evaluating Agroforestry Sustainability) approach. RAP-AFS is an adaptation of the RAPFISH method originally developed for fisheries sustainability assessment, modified to accommodate agroforestry contexts. By applying a multidimensional framework encompassing ecological, economic, social, and institutional aspects, RAP-AFS provides a comprehensive evaluation of agroforestry sustainability [11,12]. Through this approach, the study seeks to

generate evidence-based insights to support sustainable agroforestry development for both local communities and forest ecosystems in HPGW.

2. Materials and Methods

2.1. Study Area and Time

This study was conducted from August to September 2023 in the Gunung Walat Educational Forest (HPGW), located in Cibadak District, Sukabumi Regency, West Java, Indonesia. HPGW covers an area of approximately 359 ha and functions as an educational forest managed by IPB University, while simultaneously supporting agroforestry activities practiced by local communities.

Geographically, the study area lies between $6^{\circ}54'23''$ – $6^{\circ}55'35''$ S and $106^{\circ}48'27''$ – $106^{\circ}50'29''$ E, at elevations ranging from 460 to 726 m above sea level. According to the Schmidt and Ferguson climate classification, the area belongs to climate type B, characterized by high annual rainfall ranging from 1600 to 4000 mm. The average day-time temperature is approximately 30°C , while nighttime temperatures average around 19°C . HPGW is bordered by Hegarmanah, Cicantayan, Lembursawah, Batununggal, and Karangtengah villages. The location of the study area is presented in Figure 1.

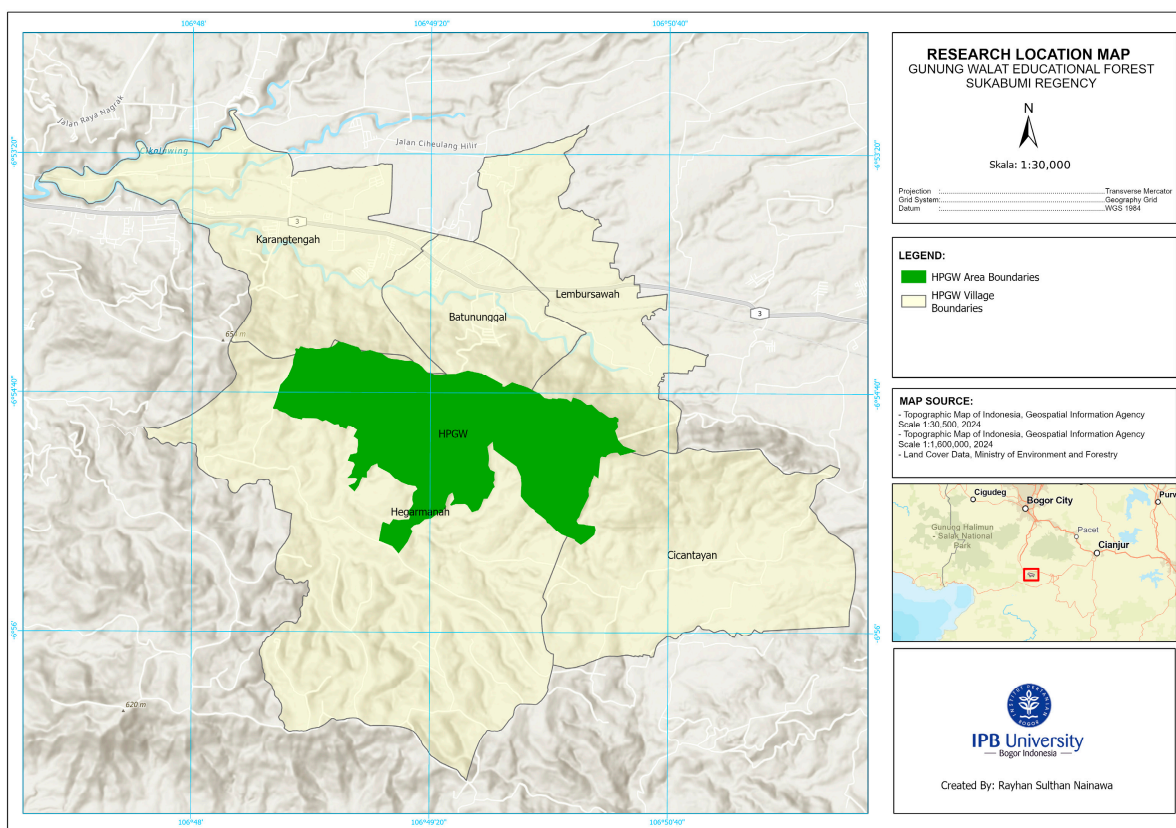


Figure 1. Research location of HPGW.

Agroforestry practices in HPGW are dominated by the integration of puspa (*Schima wallichii*) and cardamom (*Amomum cardamomum*). Farm sizes generally range from 1 to 5 ha, with smaller plots primarily managed by subsistence farmers. Cardamom yields typically range from 200 to 500 kg ha^{−1} year^{−1}, while puspa is cultivated as a long-rotation timber species, providing long-term ecological and economic benefits rather than short-term returns.

2.2. Research Design

This study employed a multidimensional sustainability assessment framework to evaluate the puspa–cardamom agroforestry system in HPGW. The assessment was conducted using the RAP-AFS (Rapid Appraisal Technique for Evaluating Agroforestry Sustainability) method, which is adapted from the RAPFISH approach originally developed for fisheries sustainability assessment. RAP-AFS extends conventional sustainability evaluations by integrating four dimensions: ecological, economic, social, and institutional.

Both qualitative and quantitative data were collected through structured questionnaires and interviews with agroforestry farmers, forest managers, and relevant stakeholders. Sustainability indicators for each dimension were assessed using a Likert-scale scoring system. The indicator scores were subsequently aggregated to generate dimensional sustainability indices.

Multidimensional Scaling (MDS) was applied as the primary analytical tool to ordinate sustainability attributes and calculate sustainability index values. MDS allows the visualization of relationships among attributes while reducing data dimensionality without losing relative information. Model robustness was evaluated using a Monte Carlo simulation to assess potential random errors in the MDS results, with acceptable model performance indicated by a coefficient of determination (R^2) greater than 0.80 [13,14].

Sustainability attributes were further examined using leverage analysis to identify key influencing factors. A comparative analysis was conducted between the cardamom agroforestry system in HPGW and a comparable system in Mount Kendeng, selected due to similarities in cultivation and management practices under differing ecological and social contexts.

Finally, model reliability and conformity were ensured through Monte Carlo validation, and the results were presented as sustainability scores and strategic recommendations to support evidence-based agroforestry management and decision-making (Figure 2)

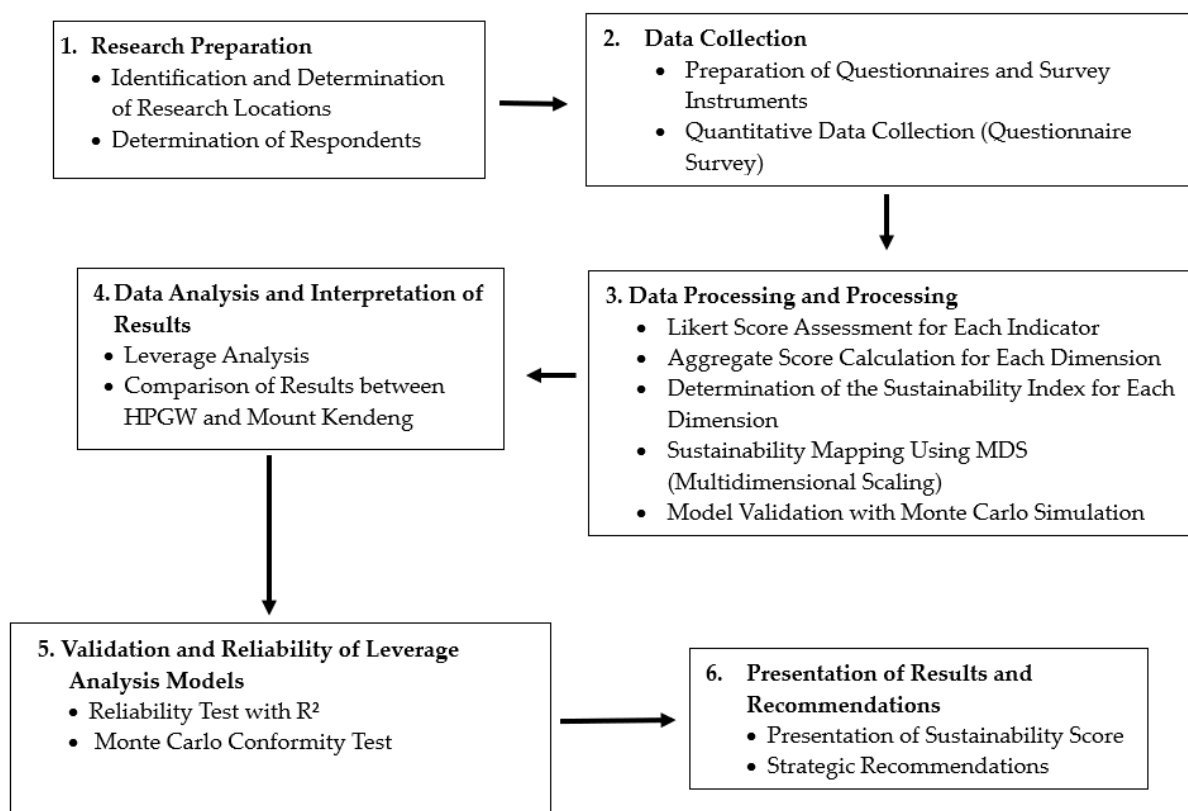


Figure 2. Research workflow diagram.

2.3. Data Collection

Primary data were collected through field observations, structured interviews, questionnaires, and focus group discussions (FGDs) involving agroforestry farmers and HPGW management authorities. Similar data collection procedures were applied in the Mount Kendeng study area to ensure comparability between sites.

Respondents were selected using expert judgment [15], targeting individuals with direct experience and in-depth knowledge of agroforestry practices in the study areas. Selection criteria were clearly defined to include farmers actively involved in agroforestry management, community representatives, and institutional actors. Although this approach may introduce selection bias, it ensured that respondents possessed sufficient expertise to provide reliable information relevant to sustainability assessment.

The collected data included information on farm size, crop yields, land ownership, marketing channels, sources of capital, farmer group participation, and institutional support mechanisms. These data formed the basis for evaluating sustainability across the four dimensions.

2.4. Sustainability Dimensions and Indicators

The sustainability of the puspa–cardamom agroforestry system was evaluated across four dimensions, with indicators adapted to local conditions and informed by previous studies [16–18]:

1. Ecological Dimension: Soil productivity, erosion control, soil fertility level, soil conservation practices, irrigation availability, presence of pests or disturbances, water conservation activities, and suitability of agroforestry application.
2. Economic Dimension: Stability of crop selling prices, sources of business capital, effectiveness of farm business value, land ownership status, and marketing systems.
3. Social Dimension: Community knowledge of agroforestry, effectiveness of program socialization, community participation, farmer group involvement, conflict avoidance, and skill development through local institutions.
4. Institutional Dimension: Existence and functionality of farmer groups, supporting institutions or agencies, marketing institutions, frequency of extension services, role of forestry extension officers, and conformity with existing regulations.

2.5. Data Analysis

Data analysis was conducted using Multidimensional Scaling (MDS) with a non-metric Kruskal approach to generate sustainability indices for each dimension. The goodness-of-fit of the MDS model was evaluated using stress values, with stress values below 0.10 indicating an acceptable representation of the data structure.

Sustainability index values ranged from 0 to 100 and were classified into four categories: highly unsustainable (0–25), unsustainable (26–50), moderately sustainable (51–75), and highly sustainable (76–100) [19–21] (Table 1). Leverage analysis was performed using Root Mean Square (RMS) values to identify the most sensitive attributes influencing sustainability outcomes. Attributes with higher RMS values were considered to have a stronger effect on sustainability improvement. A Monte Carlo analysis was subsequently applied to estimate random errors and assess the stability and reliability of the MDS results. A difference of less than 5% between the MDS and Monte Carlo outputs was considered acceptable.

Table 1. Sustainability status categories by index value.

Index Value	Sustainability Status
0–25	Highly Unsustainable
26–50	Not Sustainable
51–75	Medium Sustainable
76–100	High Sustainability

Additionally, leverage analysis was used to identify the attributes with the greatest influence on the sustainability level of agroforestry businesses. Measurements were taken using Root Mean Square (RMS) to determine which attributes are sensitive to change. The Monte Carlo analysis was used to estimate the random error rate in the MDS model results to ensure their accuracy. The difference between the MDS and Monte Carlo analysis results should be less than 5% for the model to be considered reliable.

3. Results

3.1. MDS Stress Value and Model Fit

The reliability of the RAP-AFS analysis was evaluated using Multidimensional Scaling (MDS) stress values and goodness-of-fit statistics. The MDS results indicate that the stress values obtained for the multidimensional sustainability model are below the acceptable threshold of 0.10. These low stress values suggest that the ordination adequately represents the multidimensional structure of the sustainability attributes and that distortion in the configuration space is minimal.

In addition to stress values, model fit was assessed using the coefficient of determination (R^2). The R^2 values exceed 0.80, indicating a strong correspondence between the ordinated configuration and the original data matrix. This result confirms that the MDS model explains a substantial proportion of the variance in sustainability attributes across the evaluated dimensions.

Monte Carlo simulation was applied to further assess model stability and the influence of random errors on the ordination results. The differences between the sustainability index values generated by the MDS analysis and those obtained through Monte Carlo simulation are small, remaining within the acceptable tolerance range.

Overall, the combination of low stress values, high R^2 values, and minimal differences between MDS and Monte Carlo results confirms that the RAP-AFS model provides a reliable and statistically sound representation of the multidimensional sustainability status of the puspa–cardamom agroforestry system. The validated model performance supports the subsequent analysis of sustainability dimensions presented in the following sections.

3.2. Sensitivity Analysis of Attribute Weights

A sensitivity analysis was conducted to identify key attributes that exert the strongest influence on the sustainability performance of the puspa–cardamom agroforestry system. The analysis was performed using leverage analysis based on Root Mean Square (RMS) values derived from the RAP-AFS ordination. Attributes with higher RMS values were considered more sensitive, as changes in their scores resulted in larger shifts in the sustainability index.

The results indicate that sensitivity levels vary across sustainability dimensions. In the ecological dimension, attributes related to soil conditions and conservation practices exhibit relatively high RMS values, indicating their dominant role in shaping ecological sustainability. Soil fertility status, erosion control measures, and the suitability of agroforestry application are among the most influential ecological attributes, reflecting the importance of land management practices in maintaining ecosystem functions.

Within the economic dimension, attributes associated with market mechanisms and financial stability demonstrate the highest sensitivity. In particular, crop price stability and marketing systems show elevated RMS values, suggesting that fluctuations in market access and price structures strongly affect economic sustainability. Access to business capital also contributes substantially, highlighting the dependence of agroforestry performance on financial support mechanisms.

The social dimension is primarily influenced by attributes related to community engagement and organizational participation. Farmer group involvement and community participation emerge as sensitive attributes, indicating that collective action and social cohesion play a crucial role in sustaining agroforestry practices. Knowledge dissemination and program socialization also contribute to sensitivity, although to a lesser extent.

In the institutional dimension, the most sensitive attributes are linked to institutional presence and functionality. The existence and effectiveness of farmer organizations, frequency of extension services, and the role of extension officers exhibit relatively high RMS values. These findings underscore the significance of institutional support in facilitating coordination, knowledge transfer, and long-term system sustainability.

Overall, the sensitivity analysis demonstrates that sustainability outcomes are not driven by a single dominant attribute but rather by a combination of ecological, economic, social, and institutional factors. Attributes with high RMS values represent critical leverage points for improving sustainability performance and provide a quantitative basis for prioritizing management interventions.

3.3. Sustainability Status by Dimension

The sustainability status of the puspa–cardamom agroforestry system was evaluated separately for each dimension to identify variations in performance across ecological, economic, social, and institutional aspects (Table 2). The dimensional sustainability indices derived from the RAP-AFS analysis reveal differing levels of sustainability between the Gunung Walat Educational Forest (HPGW) and the Mount Kendeng (GK) reference site (Figure 3).

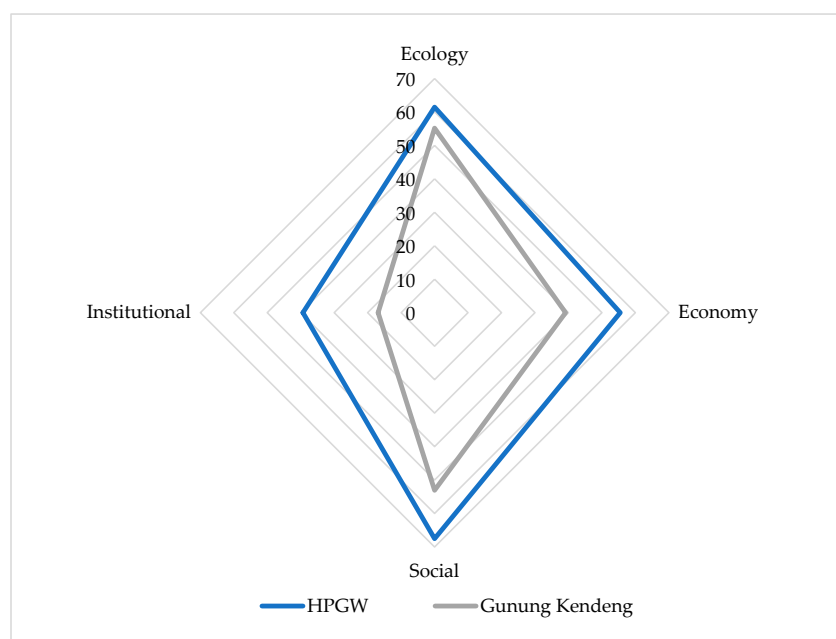


Figure 3. Diagram of the dimensions of agroforestry sustainability in the Gunung Walat (HPGW) and Mount Kendeng (GK) Education Forests.

Table 2. Comparison of results between MDS and Monte Carlo analyses for sustainability indices in HPGW.

Dimensions	Sustainability Index (MDS Value)	Coefficient of Determination (R^2)	Monte Carlo Value	Value Differences Monte Carlo and MDS
Ecological	61.43	0.94	60.73	0.70
Economic	55.45	0.86	54.89	0.56
Social	67.51	0.94	66.90	0.61
Institutional	39.37	0.89	40.14	0.77
Average	55.94	0.91	55.67	0.66

3.3.1. Ecology Dimension

The ecological sustainability index of the agroforestry system in HPGW falls within the moderately sustainable category. This result indicates that, from an ecological perspective, the system maintains acceptable environmental functions, although certain constraints remain. Key ecological attributes contributing to the index include soil productivity, erosion control, and land suitability for agroforestry application.

In comparison, the ecological sustainability index at the GK site is relatively higher, reflecting more favorable ecological conditions and management practices. Despite similarities in crop composition, differences in soil conservation measures and site characteristics contribute to the observed variation between the two locations.

3.3.2. Economic Dimension

The economic sustainability index for HPGW is categorized as less sustainable to moderately sustainable, indicating economic vulnerabilities within the agroforestry system. This condition reflects instability in crop prices, limited market access, and dependence on intermediaries for product marketing. Although agroforestry provides an additional income source for farmers, economic performance remains constrained by market-related factors.

Conversely, the GK agroforestry system demonstrates a higher economic sustainability index. The stronger economic performance at this site is associated with more stable marketing systems and better access to economic support mechanisms, resulting in a more resilient agroforestry-based livelihood structure.

3.3.3. Social Dimension

The social sustainability index of the agroforestry system in HPGW is classified as moderately sustainable. This result suggests that community awareness and participation in agroforestry activities are generally adequate, although not yet optimal. Farmer involvement in group activities and access to capacity-building programs vary across the study area.

The GK site exhibits a higher social sustainability index, indicating stronger social cohesion and more active participation in farmer organizations. Differences in the effectiveness of group-based activities and community engagement contribute to the contrasting social sustainability outcomes between the two sites.

3.3.4. Institutional Dimension

The institutional sustainability index represents one of the weakest dimensions in HPGW and is classified as less sustainable. This result reflects limited institutional support, infrequent extension services, and suboptimal functioning of farmer organizations. Institutional arrangements related to agroforestry management and market facilitation remain insufficient to fully support sustainable system development.

In contrast, the GK agroforestry system shows a substantially higher institutional sustainability index. The stronger institutional performance at this site is characterized by more active extension services, better-organized farmer groups, and clearer institutional roles in supporting agroforestry practices.

4. Discussion

4.1. Reliability of the RAP-AFS Model for Agroforestry Sustainability Assessment

The results of the Multidimensional Scaling (MDS) analysis demonstrate that the RAP-AFS approach provides a reliable framework for evaluating agroforestry sustainability. The low stress values and high coefficients of determination indicate that the ordination accurately represents the multidimensional structure of the sustainability attributes. In addition, the minimal differences between the MDS and Monte Carlo outputs confirm the robustness of the model against random errors. These findings are consistent with previous applications of RAP-based methods in natural resource sustainability assessments, which have reported strong model performance when evaluating complex socio-ecological systems [11,12].

The reliability of the RAP-AFS model is particularly important in agroforestry contexts, where sustainability outcomes are shaped by interactions between biophysical conditions and socio-institutional factors. The validated model performance supports its applicability for assessing agroforestry systems in educational forests and other managed forest landscapes with multiple stakeholders.

4.2. Key Leverage Attributes Influencing Sustainability Performance

The sensitivity analysis highlights that sustainability outcomes are driven by a set of key leverage attributes rather than by a single dominant factor. Across all the dimensions, attributes related to soil management, market access, community participation, and institutional support exhibit high sensitivity. This finding underscores the inherently integrated nature of agroforestry systems, where improvements in one dimension are closely linked to changes in others.

The results of the ecological dimension sustainability analysis (Figure 4) show that the sustainability index in HPGW of 61.43 is higher than the reference index of 55.16 in GK. Based on the results, the ecological dimension's sustainability status in HPGW is categorized as quite sustainable. These results align with several practices [19–21]. Ecological leverage attributes, particularly those related to soil fertility and conservation practices, play a critical role in maintaining long-term productivity and ecosystem stability. Similar findings have been reported in tropical agroforestry systems, where soil quality and erosion control are essential for sustaining both tree and understory crop performance [22,23]. The prominence of these attributes indicates that ecological sustainability remains a foundational requirement for overall system resilience (Figure 5).

Based on the results of several studies that have been conducted, it shows that the agroforestry system plays a significant role in enhancing agricultural production and soil fertility [23], maintains soil organic matter, and promotes nutrient cycling. The system also has high levels of organic matter, nitrogen (N), phosphorus (P), and potassium (K) in the soil, and increases the cation exchange capacity (CEC) [24].

Good conservation practices are integral to land management in HPGW. These practices include using litter to cover the soil as organic mulch, which maintains soil moisture, increases nutrients and organic matter, and prevents erosion [25]. These techniques maintain soil productivity and ensure the sustainability of the applied agroforestry system [22]. Adding organic matter is an effective way to overcome the low nutrient level in agroforestry systems [9].

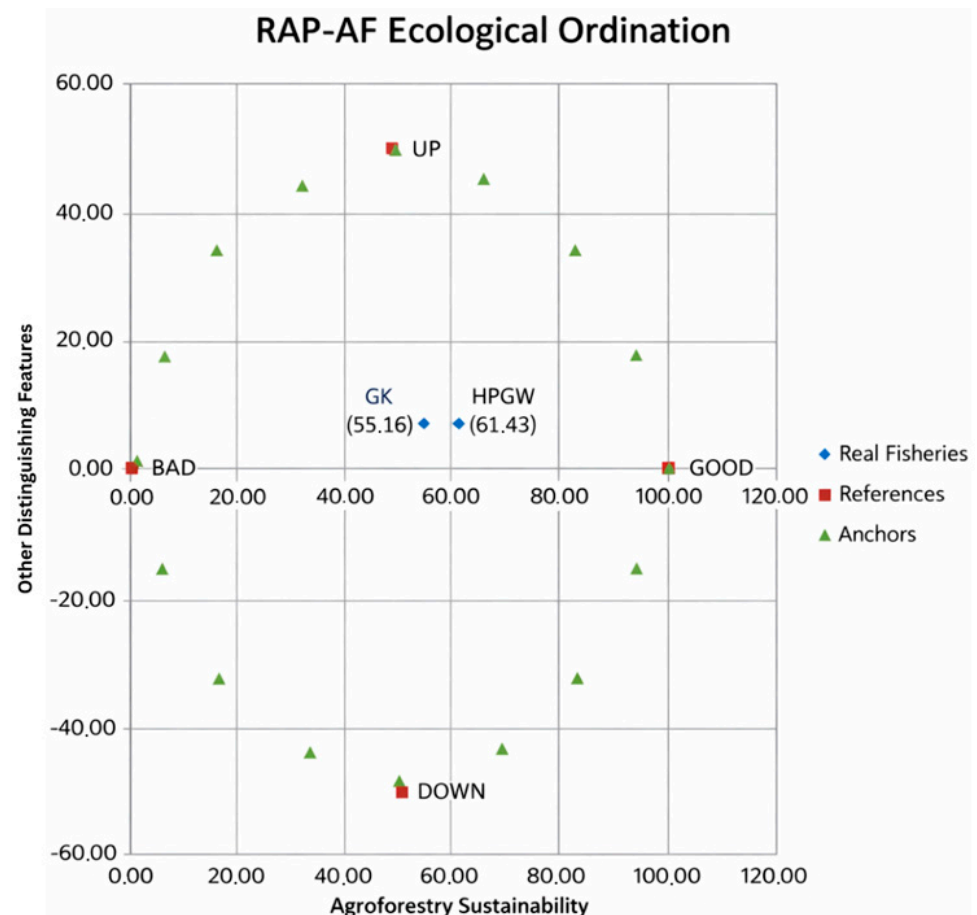


Figure 4. Agroforestry sustainability index: ecological dimension.

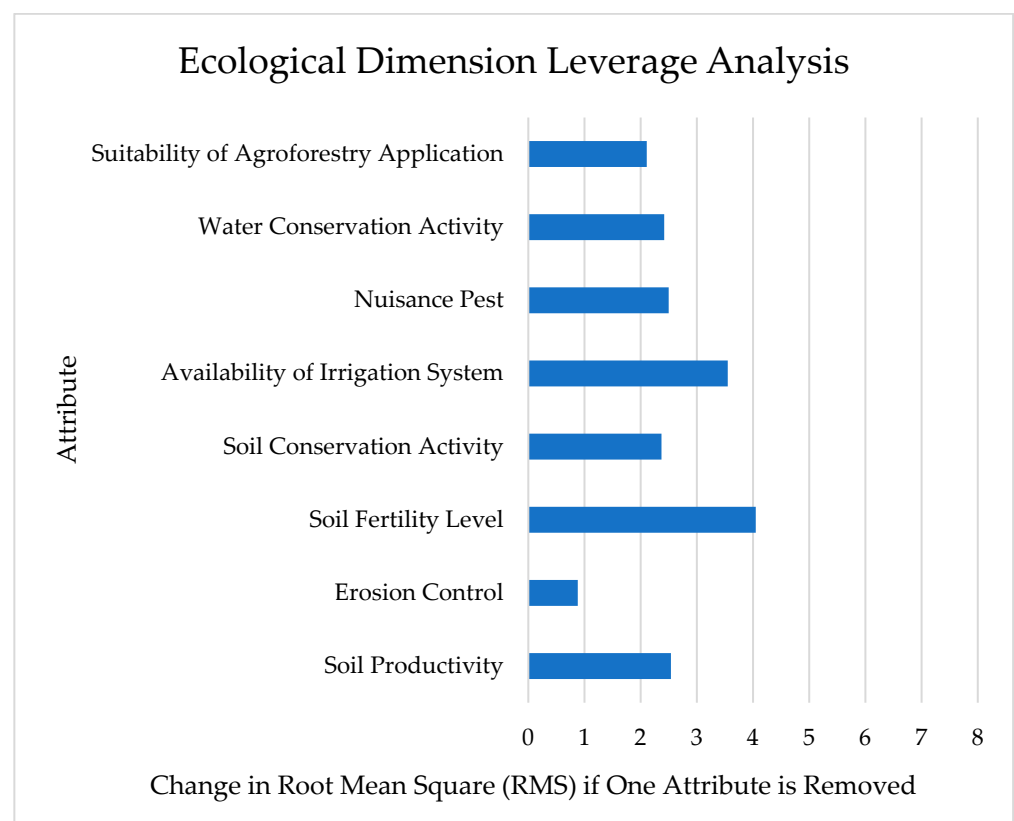


Figure 5. Leverage attributes that affect the sustainability of the ecological dimension.

In the economic dimension, high sensitivity of market-related attributes reflects the vulnerability of agroforestry-based livelihoods to price fluctuations and limited market access. Dependence on intermediaries and unstable selling prices have been widely identified as major constraints in smallholder agroforestry systems [24,25]. These results suggest that economic sustainability cannot be achieved solely through production enhancement but requires improved market structures and financial mechanisms. The economic dimension measures the impact of agroforestry on farmers' income and economic sustainability. In HPGW, the economic sustainability index reached 55.45, which is higher than the 39.14 recorded in GK (Figure 6). These results show that agroforestry positively contributes to the local economy in HPGW.

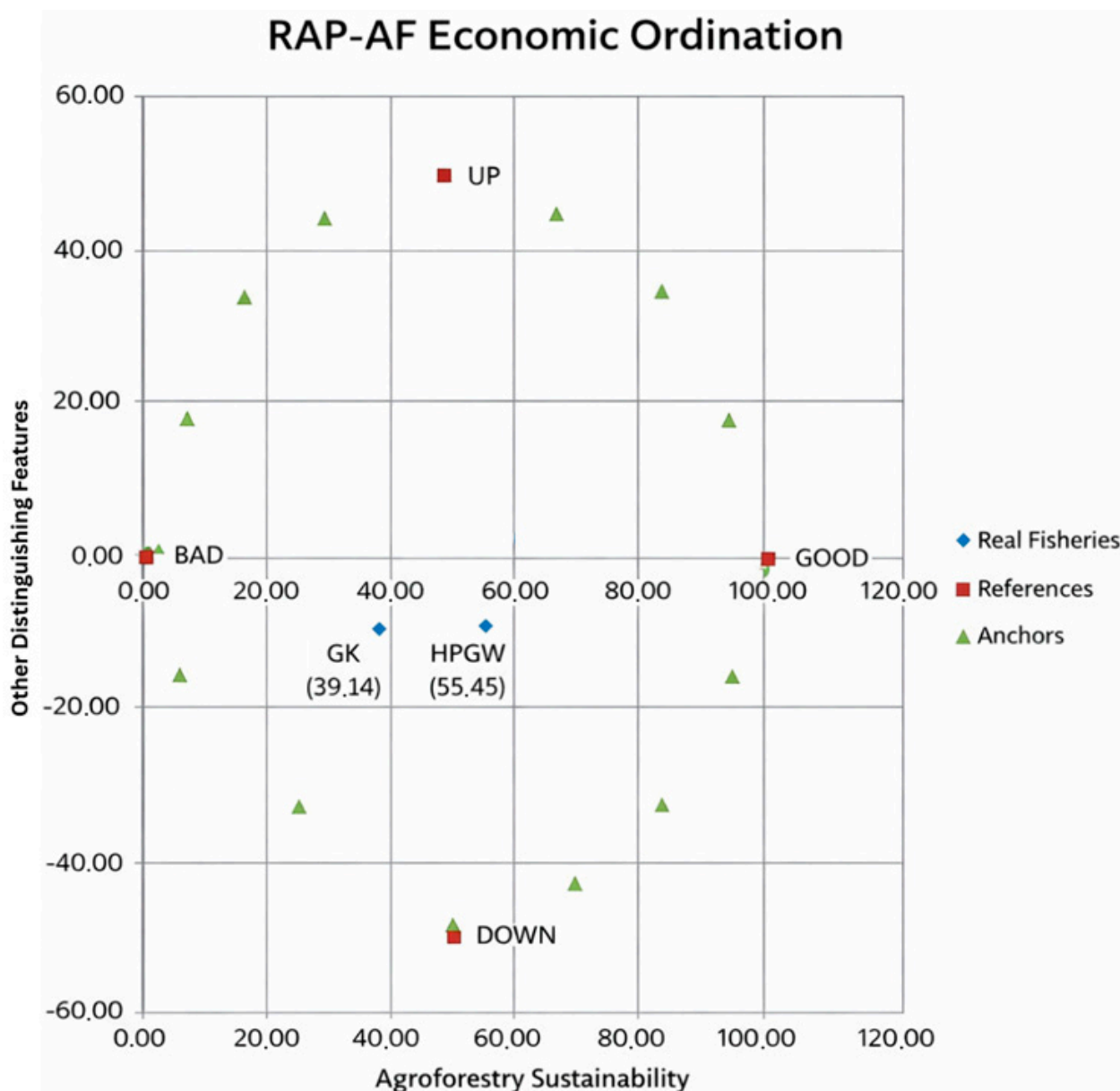


Figure 6. Agroforestry sustainability index economic dimension.

The existence of puspa and cardamom agroforestry in HPGW has increased the community's income. The integration of puspa trees and cardamom plants improves soil and environmental quality and provides valuable crops [26]. Agroforestry contributes to sustainable rural development as a proven natural resource management technology with a positive impact on the rural household economy [27]. However, the selling price of

cardamom in HPGW is unstable due to fluctuations in market demand, dependence on middlemen, and limited access to wider markets, which pose challenges to the development of agroforestry in HPGW.

According to the leverage analysis, the factors that greatly affect the economic sustainability of agroforestry in HPGW are the source of business capital [28], effectiveness of farming business value, and land ownership (Figure 7). Capital availability is crucial for agroforestry development [28]. Effective farming value supported by a proper business plan can help support farmers' transition from non-agroforestry to agroforestry activities [29]. Ownership poses an obstacle to the sustainable development of agroforestry. For example, in several African countries, land ownership, which is usually controlled by men, hinders the adoption of agroforestry technology by farmers, especially women [30].

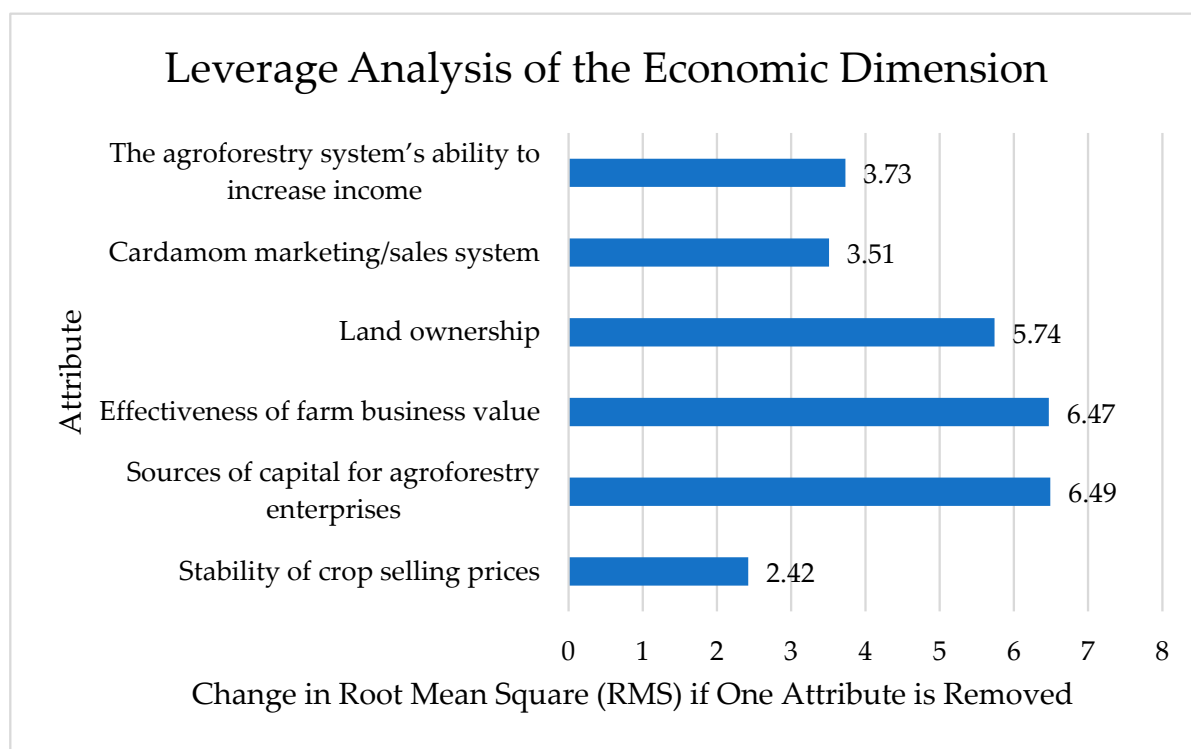


Figure 7. Leverage attributes that affect the sustainability of the economic dimension.

Social and institutional leverage attributes emphasize the importance of collective action, effective farmer organizations, and extension services. Strong social participation enhances knowledge exchange and adoption of sustainable practices, while institutional support provides the enabling environment necessary for coordination and long-term planning. The high sensitivity of these attributes aligns with studies highlighting that weak institutions often represent the main barrier to agroforestry sustainability in developing regions [7,8].

The social dimension in HPGW showed a relatively high sustainability value of 67.51, better compared to Mount Kendeng's value of 53.07 (Figure 8). This index reflects the Community's active participation in the agroforestry system and the agroforestry program's successful socialization in HPGW. The coordination of agroforestry activities between governments and non-state actors is primarily accomplished through collaboration and network strengthening. Through this approach, various parties can align their roles, resources, and goals of sustainable land management. Thus, agroforestry implementation becomes more effective because it is supported by the collaboration of agencies and community groups [31]. Socialization plays an important role in increasing farmers' understanding of

agroforestry programs. Through effective socialization activities, farmers become familiar with integrated land management practices, benefits, and goals. Additionally, socialization expands farmers' access to the information needed to appropriately implement agroforestry [32].

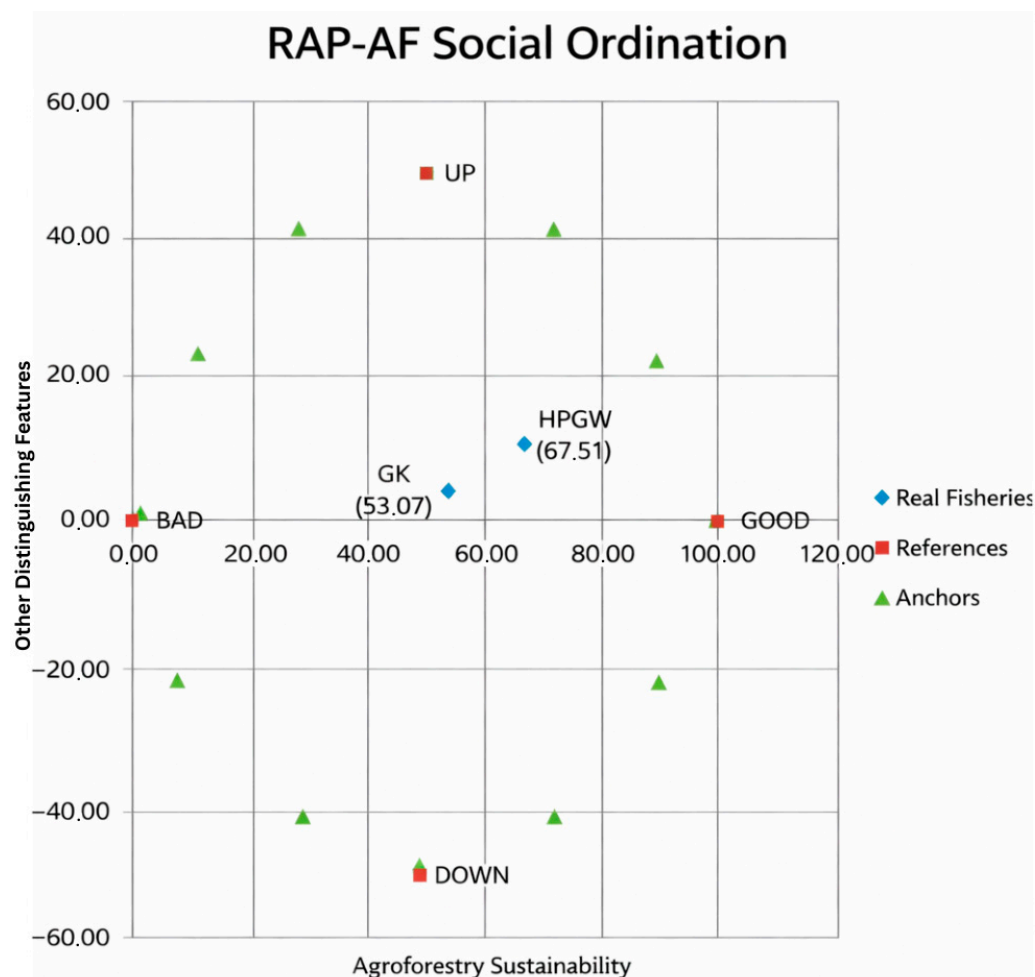


Figure 8. Agroforestry sustainability index of social dimension.

Increased community incomes from agroforestry have reduced reliance on illegal logging and encouraged more sustainable agricultural practices. This improvement in welfare also helps reduce conflicts that may arise between farmers and forest managers. Therefore, the success of agroforestry systems depends not only on economic and ecological factors but also on the active involvement of communities in the sustainable management of natural resources.

To achieve agroforestry sustainability, a management strategy that involves various socio-economic groups is needed. This approach ensures that everyone has an equal opportunity to participate in the decision-making and program implementation. Thus, forest conservation efforts can be carried out more effectively and sustainably [33].

According to the leverage analysis, the factors that greatly influence the sustainability of agroforestry in HPGW based on the social dimension are the participation of farmer group activities [28]. Community participation in the agroforestry system helps avoid conflict (Figure 9).

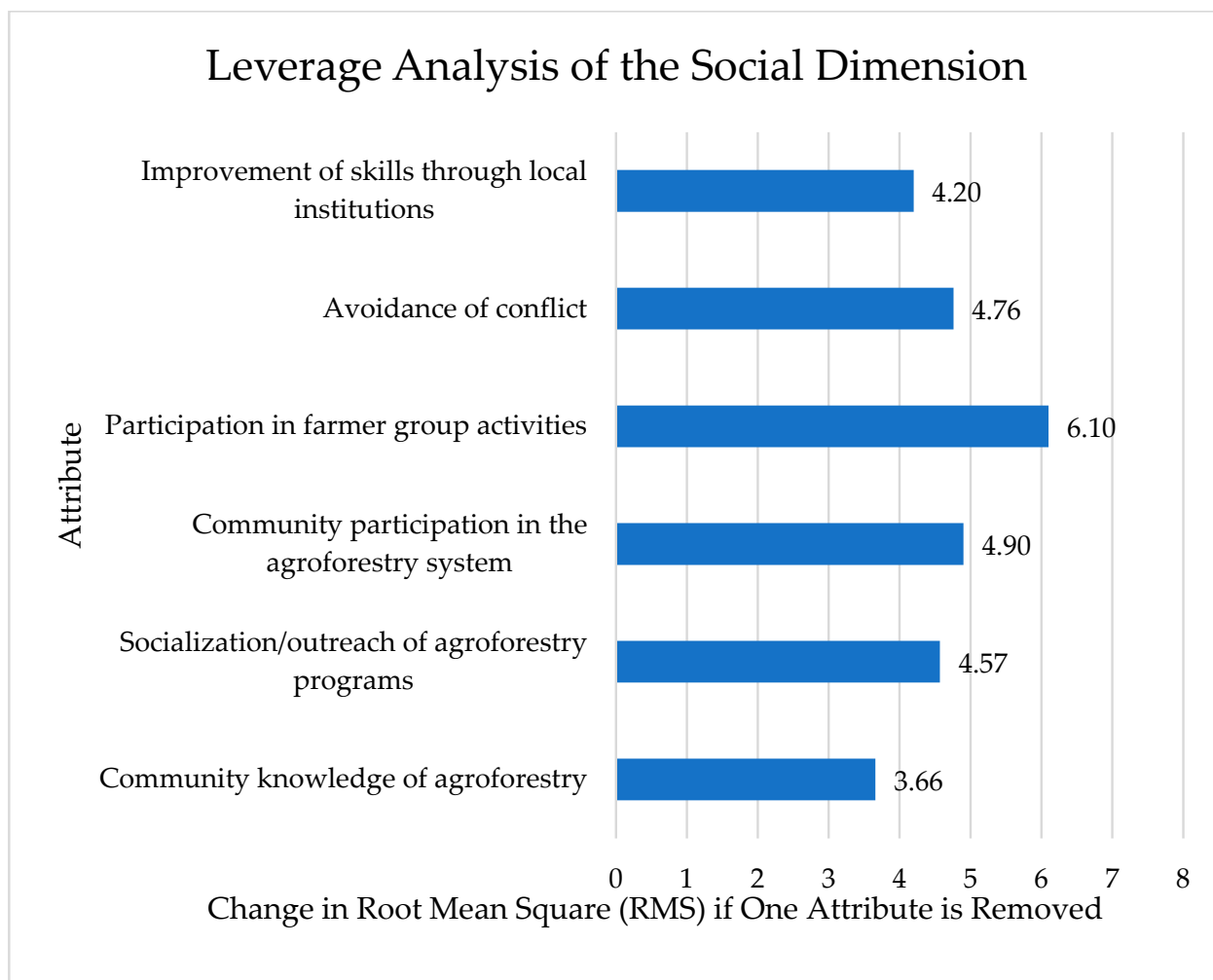


Figure 9. Leverage attributes that affect the sustainability of the social dimension.

The institutional dimension shows that agroforestry institutions in HPGW are still in the category of less sustainable, with an index value of 39.37. While this is still better compared to Mount Kendeng, which has a score of 16.88, the institutional status in HPGW shows that there is an urgent need to strengthen the institutional structures that support agroforestry.

The sustainability status of the institutional dimension in HPGW is included in the less sustainable category. As for the agroforestry pattern, Mount Kendeng is in the unsustainable category. HPGW's institutional sustainability status is higher than Mount Kendeng because HPGW's attribute scores are better. The sustainability status of the institutional dimension (Figure 10) is obtained from the assessment of six sustainability attributes: (1) the existence of farmer groups, (2) the institution/agency that oversees them, (3) the establishment of institutions to sell products, (4) the frequency of counseling, (5) the role of forestry extension workers, and (6) conformity with existing regulations.

According to the leverage analysis of the institutional dimension, improvements can be made by increasing access to training, enhancing the capacity of farmer groups, and providing regular counseling [34]. Additionally, strengthening cooperation between institutions such as Bumdes and other relevant parties is crucial for enhancing market access and supporting agroforestry sustainability.

According to the institutional dimension leverage analysis (Figure 11), improvements can be made by increasing farmers' access to various opportunities. Structured training helps farmers understand appropriate local agroforestry practices. With this increased

capacity, farmers are better prepared to adopt technologies and innovations that support sustainability [30].

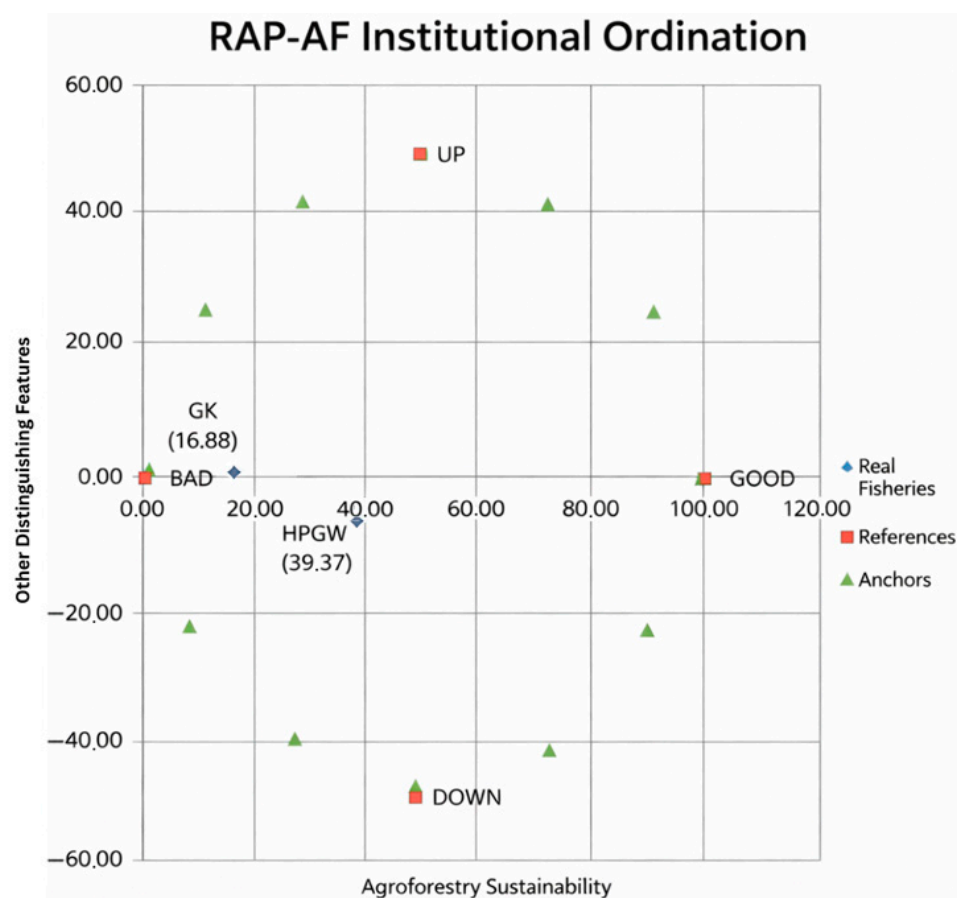


Figure 10. Agroforestry sustainability index: institutional dimension.

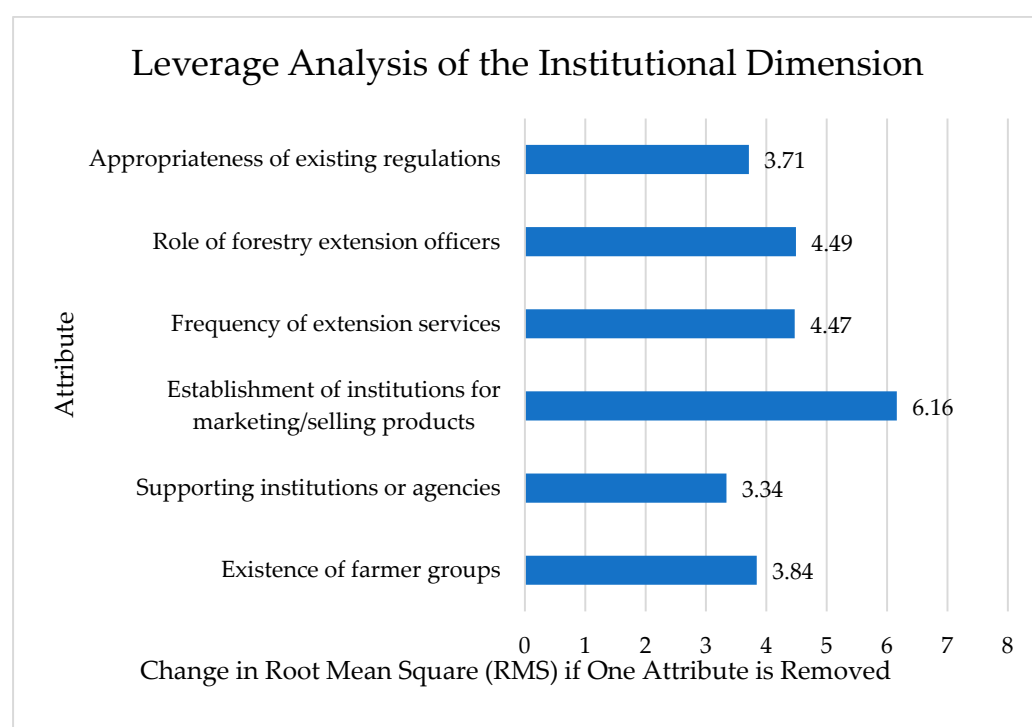


Figure 11. Leverage attributes that affect the sustainability of the institutional dimension.

Strengthening the capacity of farmer groups is also an important step in improving the institutional dimension. A strong farmer group can become a forum for learning, discussion, and coordination between members. With good institutional support, these groups can function as a driving center for agroforestry activities in the field.

It is also important to strengthen cooperation between institutions such as Bumdes and other related parties. This collaboration increases market access for agroforestry products, providing economic incentives for farmers. With the support of a solid institutional network, agroforestry programs can be made sustainable in the long term [35].

4.3. Dimensional Sustainability Patterns and Their Implications

The dimensional sustainability analysis reveals an uneven sustainability profile of the puspa–cardamom agroforestry system in the Gunung Walat Educational Forest. The ecological and social dimensions exhibit moderate sustainability, indicating that basic environmental functions and community engagement are relatively well established. However, the economic and institutional dimensions remain comparatively weak, limiting the overall sustainability performance.

This imbalance suggests that ecological suitability alone is insufficient to ensure sustainable agroforestry development. Without adequate institutional frameworks and market access, the benefits of agroforestry may not be fully realized by local communities. The comparison with the Mount Kendeng site further illustrates that stronger institutional arrangements and market integration can substantially improve sustainability outcomes, even under similar ecological conditions.

The institutional dimension emerges as a critical bottleneck in HPGW. Limited extension frequency, weak farmer organizations, and insufficient coordination between stakeholders constrain the effectiveness of agroforestry management. These findings reinforce the argument that institutional strengthening is a prerequisite for scaling up sustainable agroforestry practices [26,27].

4.4. Implications for Sustainable Agroforestry Management

The integration of puspa and cardamom offers significant ecological and economic potential, particularly in tropical forest landscapes where land-use pressure is increasing. However, the results of this study indicate that sustainability improvements should prioritize non-ecological dimensions, especially institutional and economic aspects. Strengthening farmer organizations, enhancing extension services, and improving market access are essential to translate ecological benefits into long-term livelihood gains.

From a management perspective, agroforestry development in educational forests such as HPGW should adopt a participatory and institution-centered approach. Collaborative governance involving forest managers, local communities, and supporting agencies can enhance coordination and accountability. Furthermore, linking agroforestry products to more stable and transparent markets may reduce economic vulnerability and incentivize sustainable land-use practices.

Overall, the findings highlight that agroforestry sustainability is a multidimensional challenge requiring integrated interventions. Addressing leverage attributes identified in this study can provide strategic entry points for improving sustainability performance while maintaining the ecological integrity of forest landscapes.

5. Conclusions

This study demonstrates that the RAP-AFS approach is an effective and reliable tool for evaluating the multidimensional sustainability of agroforestry systems. The low stress values, high coefficients of determination, and consistent Monte Carlo results confirm

the robustness of the model in capturing the complex interactions among the ecological, economic, social, and institutional dimensions of the puspa–cardamom agroforestry system.

The sustainability assessment indicates that the puspa–cardamom agroforestry system in the Gunung Walat Educational Forest (HPGW) has achieved a moderate level of sustainability. The ecological and social dimensions show relatively favorable performance, reflecting adequate environmental functions and community engagement. However, the economic and institutional dimensions remain less sustainable, constraining the overall sustainability of the system.

The sensitivity analysis reveals that sustainability outcomes are strongly influenced by leverage attributes related to soil management, market stability, community participation, and institutional support. These attributes represent critical entry points for improving agroforestry sustainability and highlight the interconnected nature of biophysical and socio-institutional factors.

The comparison with the Mount Kendeng agroforestry system underscores the importance of strong institutional arrangements and effective market access in enhancing sustainability performance. Even under comparable ecological conditions, differences in institutional support and economic structures can lead to substantially different sustainability outcomes.

Overall, the findings suggest that future agroforestry development in HPGW should prioritize strengthening institutional capacity, improving market mechanisms, and enhancing farmer organization effectiveness. By addressing these non-ecological constraints, the puspa–cardamom agroforestry system can be further developed as a sustainable land-use model that supports both forest conservation and local livelihoods.

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Abbreviations

The following abbreviations are used in this manuscript:

HPGW	Gunung Walat Educational Forest
RAP-AFS	Rapid Appraisal Technique for Evaluating Agroforestry Sustainability
FGDs	Focus Group Discussions
GK	Mount Kendeng
MDS	Multidimensional Scaling
RMS	Root Mean Square
CEC	Cation Exchange Capacity

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