



Socioecological Adaptation Dynamics in Arfak Homegarden Systems Amid Environmental Change Pressures

Abstract: Indigenous homegarden systems are increasingly recognized as resilient agroecosystems capable of sustaining rural livelihoods under environmental and socio-economic pressures. This study analyzes the socio-ecological adaptation dynamics of Arfak homegarden systems in Manokwari Regency, West Papua. A mixed-methods approach was applied to integrate ecological and socio-economic analyses. Vegetation inventories were conducted to assess plant diversity and structural composition, while household surveys involving 118 respondents across six districts captured technology adoption, farmer perceptions, and adaptive strategies. Biodiversity indices, Bray–Curtis similarity, principal component analysis (PCA), Chi-square tests, and Kruskal–Wallis tests were used to evaluate ecological patterns and socio-ecological relationships. Results show that Arfak homegardens maintain relatively high biodiversity, with an average of 17 plant species per household and a multilayered vegetation structure consisting of trees, shrubs, herbs, and vines. Herbaceous plants dominate the vegetation composition, indicating strong food crop representation within homegarden systems. Agro-technology adoption among households is moderate, with common practices including fertilizer use, compost production, intercropping, and botanical pesticides, while irrigation and formal training remain limited. PCA results reveal that adaptation processes are shaped by four interconnected dimensions: agro-technology adoption, technology implementation, technology perception, and adaptive strategies. Social cooperation, local ecological knowledge, and crop diversification emerge as key mechanisms supporting household resilience. Chi-square and Cramér’s V analyses indicate significant associations between technology practices and adaptive responses, while Kruskal–Wallis tests reveal no significant differences in biodiversity and adaptation indicators across districts. Overall, Arfak homegarden systems function as integrated socio-ecological agroforestry systems where biodiversity, indigenous knowledge, and adaptive management practices interact to sustain food production and community resilience. Strengthening these systems through context-specific agroecological innovations and community-based knowledge exchange may enhance the sustainability of indigenous agricultural landscapes under changing environmental conditions.

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Article History:

Received Date : Apr 04, 2026

Revised Date : May 11, 2026

Accepted Date : May 30, 2026

Published Date : Jun 05, 2026

Keywords

Agroecology, homegarden systems, socio-ecological resilience, indigenous knowledge, adaptive strategies



1.Introduction

Global environmental changes, including climate change, land degradation, and biodiversity loss, have increased the vulnerability of agricultural systems in many tropical regions (Gomiero, Pimentel, and Paoletti 2011; Duc and House 2016; Yiridoe and Anchirinah 2005; Bianco 2016). Intensive agricultural models characterized by homogeneity and monoculture tend to have low adaptive capacity to external disturbances, highlighting the need for more resilient and sustainable alternatives (Koochafkan, Altieri, and Holt Gimenez 2012; Samuel et al. 2022; Reyes-García et al. 2014). In this context, agroecology has emerged as both a scientific and practical framework that emphasizes the integration of ecological and social dimensions within food production systems.

Homegarden agroforestry systems represent one of the most prominent forms of traditional agroecosystems (Caballero-Serrano et al. 2019; Reyes-García et al. 2014; Dumont et al. 2014; Maikhuri, Rao, and Semwal 2001), known for their high structural and functional complexity. These systems are typically characterized by multilayered canopy stratification (Nguyen and Kobayashi 2014; Mohri et al. 2013) resembling natural forests, high species diversity, and the integration of food crops, fruits, timber species, and medicinal plants within a single land unit. Numerous studies have demonstrated that homegardens contribute significantly to household food security, conservation of local genetic resources, and the provision of ecosystem services such as carbon storage and microclimate regulation (Thornton, Herrero, and Jones 2011; Cui, Rupprecht, and Shibata 2021; Altieri, Nicholls, and Montalba 2017; Altieri and Rosset 1996).

From a social-ecological systems perspective, adaptation is understood not merely as an

ecological response to environmental change but also as a social process involving local institutions, cultural norms, and traditional knowledge networks (Ramakrishnan 2007; Soares et al. 2023; Dollo et al. 2009). The concept of biocultural diversity emphasizes the co-evolutionary relationship between biological and cultural diversity, forming dynamic adaptive systems (Suryana et al. 2020; Bernués et al. 2011). Therefore, understanding adaptation dynamics in homegarden systems requires an approach that integrates ecological and social analyses simultaneously.

The Arfak communities in Manokwari Regency maintain traditional homegarden management practices that remain relatively intact. Homegardens function not only as supplementary food sources (Hervas 2020; Ferdous et al. 2016; Enahoro et al. 2019) but also as domestic spaces reflecting social structures, symbolic plant values, and mechanisms of sharing within the community. However, environmental, and socio-economic pressures have the potential to alter the structure and function of these systems. Modernization, changing consumption preferences, and increased market access may drive shifts in plant composition and land management practices (Clough et al. 2016; Dollo et al. 2009; Tougiani, Guero, and Rinaudo 2009; Kerubo 2016; Kannan and Anandhi 2020).

To date, studies on homegarden systems in West Papua have largely focused on descriptive aspects of plant composition and have not extensively examined socioecological adaptation dynamics. Understanding local adaptation mechanisms is crucial for developing context-specific and culturally grounded agricultural development strategies. Therefore, this study aims to analyze the socioecological adaptation dynamics within Arfak homegarden systems under environmental change pressures.

2. Materials and Methods

Sites, time period, and approaches

This study was conducted in several Arfak community villages in Manokwari Regency, West Papua. The study area is characterized by tropical mountainous agroecological conditions, with varying altitudes, relatively high annual rainfall, and traditional household-based land-use systems. Arfak homegardens are typically located adjacent to residential areas and are managed across generations as part of household livelihood strategies.

A mixed-methods approach was employed to integrate quantitative and qualitative data in

understanding homegardens as social-ecological systems. This approach was chosen because it enables a comprehensive analysis of both ecological structures and the social and cultural dynamics underlying their management (Creswell & Plano Clark, 2018). Integration of both data types was conducted through a convergent design to provide a holistic understanding of adaptation processes within the homegarden system. In this study, identified agro-ecological zone are grouped into four types, i.e. highland for district of Mokwam (MW), lowland for district of Tanah Rubuh (TR), and Warmare (WM), Coastal for district of Sidey (SD), and Manokwari Timur (MT), and lastly Swampy coastal for district of Manokwari Utara (MU). Site of the field research is shown in Figure 1.

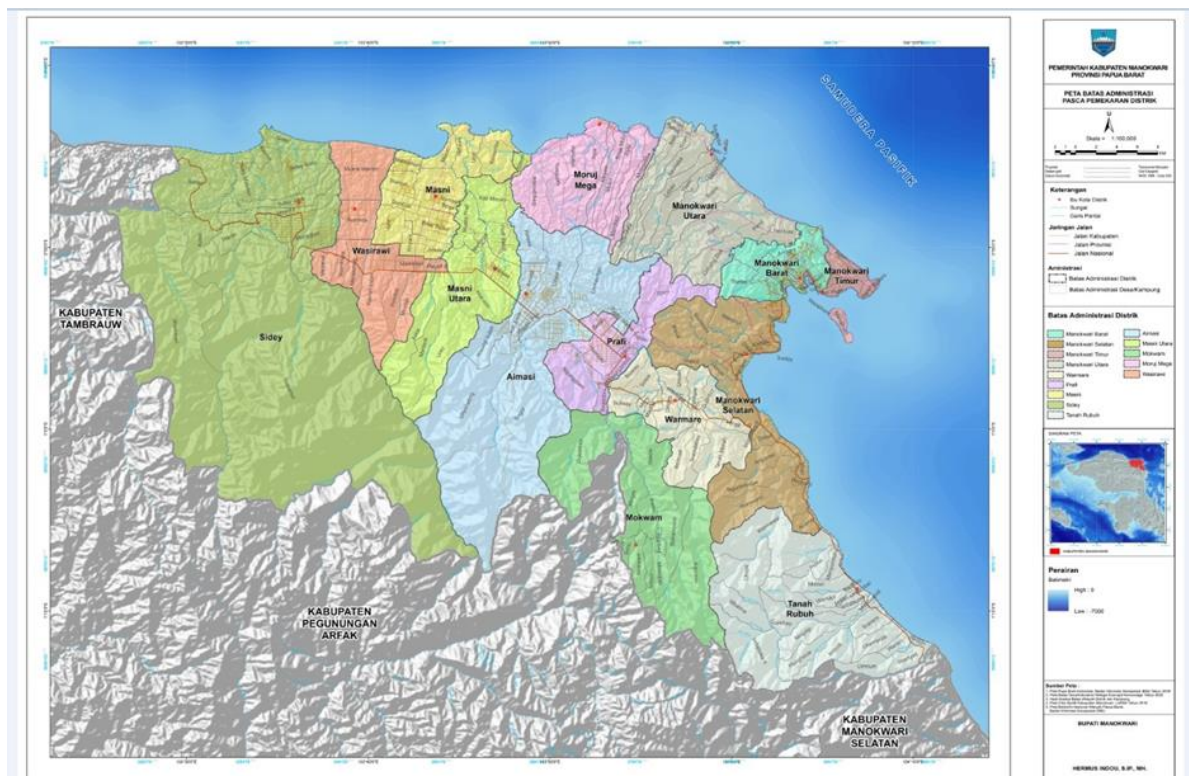


Figure 1. Site location of the field research in Manokwari regency.

Selecting Arfak crops farmers

The selection of respondents employed a purposive sampling approach, in which individuals were chosen based on their direct knowledge and experience in managing

homegarden systems. To determine the number of respondents proportionally, the Slovin formula was used (Aritonang 2019; Pawirosumarto et al. 2017). This formula is commonly applied in social research to

estimate sample size from a known population. The Slovin formula is expressed as:

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

where: n = number of sample respondents, N = total population of households in the study area, e = margin of error (error tolerance), and 1 = constant. In this study, the margin of error was set at 10% (0.10). Based on this calculation, a total of 118 households were selected as respondents. The respondents were then distributed proportionally across the six districts included in the study (Table 1).

Table 1. Distribution of the samples from Arfak crops farmers.

Districts	Respondent	Proportion (%)
Mokwam	38	32
Tanah Rubuh	14	12
Warmare	17	14
Sidey	22	19
Manokwari Utara	18	15
Manokwari Timur	9	8

Data and Measured Parameters

Ecological data were collected through vegetation inventories conducted in

purposely selected homegardens based on criteria including management continuity, variation in land size, and willingness of respondents to participate. All plant species present were recorded and identified to species or genus level using relevant botanical literature and local knowledge verification. Data collected included the number of individuals, species types, and classification according to canopy stratification. Vegetation structure and composition were analyzed using the Shannon-Wiener diversity index (H'), evenness index, and canopy stratification distribution to describe the structural complexity of homegarden agroforestry systems (Maroyi 2009; Mohri et al. 2013).

To capture the social dimension and adaptation dynamics, qualitative data were gathered through semi-structured interviews, participant observation, and focus group discussions. Informants were selected using snowball sampling, considering their roles in homegarden management, including household heads, women as primary homegarden managers, and customary leaders. Interviews focused on community perceptions of environmental change, shifts in plant composition over the past one to two decades, adaptation strategies to climate variability, and social mechanisms in the distribution and exchange of homegarden products (Table 2).

Table 2. Parameters, Indicators, Operational Definitions, Measurement scales, and Analytical Formulae

Parameters	Indicators	Operational Definition	Measurement Scales	Formula
Respondent Characteristics	Gender	Biological sex of respondent managing the homegarden	Nominal (Male/Female)	Frequency (%) = $\frac{f}{N} \times 100$
	Age	Age of respondent at time of survey	Ratio (years)	Mean age $\bar{x} = \frac{\sum x_i}{n}$
	Education	Highest formal education level attained	Ordinal (No school–University)	Frequency distribution (%)
	Income	Monthly household income category	Ordinal (Low–High)	Mean / percentage distribution



Agro-technology Adoption (White et al. 2001)	Fert_Use	Use of fertilizer in homegarden management	Binary (Yes/No)	Adoption rate $AR = \frac{n_{use}}{N}$
	Fert_Type	Type of fertilizer applied	Nominal (Organic / Inorganic / Both)	Frequency (%)
	Self_Compost	Production of compost from household or livestock waste	Binary	Percentage of adoption
	Irrigation	Use of irrigation system other than rainfall	Binary	$\frac{n_{irrigation}}{N}$
	Intercrop	Application of intercropping or polyculture	Binary	$\frac{n_{intercrop}}{N}$
	Bio_Pest	Use of botanical or natural pesticides	Binary	$\frac{n_{biopest}}{N}$
	Training	Participation in agricultural training programs	Binary	Frequency (%)
Technology Implementation (Santiteerakul et al. 2020; Gil, Siebold, and Berger 2015)	Tech1	Application level of organic fertilizer	Ordinal (1–3)	Score
	Tech2	Application level of irrigation technology	Ordinal (1–3)	Score
	Tech3	Application of botanical pesticides	Ordinal (1–3)	Score
	Tech4	Intercropping intensity	Ordinal (1–3)	Score
	Tech5	Mulching or shading practice	Ordinal (1–3)	Score

Agrotechnology Adoption Score

Score	Adoption Level
5–8	Low
9–11	Moderate
12–15	High



Continued - Table. Parameters, Indicators, Operational Definitions, Measurement scales, and Analytical Formulae

Parameter	Indicator	Operational Definition	Scale	Formula
Technology Perception (Cortner et al. 2019; Yuliandi and Tahir 2019)	Tech_Compat	Compatibility of agricultural technology with indigenous practices	Ordinal (1–3)	Mean perception score
	Challenge	Major barriers to technology adoption	Nominal (Cost, knowledge, access, culture)	Frequency (%)
	Custom_Restr	Presence of customary restrictions	Binary	Percentage
	Community_React	Community response to new technology	Ordinal (Reject–Accept)	Frequency (%)
	Decision_Maker	Actor influencing technology decisions	Nominal	Frequency distribution
	Tech_Import	Perceived importance of technology	Ordinal (1–4)	Mean score
Adaptive Strategies (Campos, Velázquez, and McCall 2014; Norton, Malinowski, and Volaire 2016)	Crop_Fail	Experience of crop failure due to seasonal change	Binary	$\frac{n_{cropfail}}{N}$
	Adapt_Action	Strategy taken after crop failure	Nominal	Frequency (%)
	Food_Price_Role	Role of homegarden during food price increase	Ordinal (1–3)	Mean score
	Crop_Change	Change in plant species composition	Binary	Percentage
	Cooperation	Cooperation with neighbors in homegarden management	Binary	$\frac{n_{cooperation}}{N}$
	Family_Role	Change in family roles in garden management	Binary	Percentage
	Adapt_Import	Perceived importance of adaptation	Ordinal (1–4)	Mean score



Derived Socio-Ecological Adaptation Index

An integrated index can be calculated using $SAAT = Tech1 + Tech2 + Tech3 + Tech4 + Tech5$, where: SEAI = Socio-Ecological Adaptation Index, SAAT = Agrotechnology adoption score, Adapt_Import = perceived importance of adaptation, and Tech_Import = perceived importance of technology

SEAI	Adaptation Level
< 2.5	Low
2.5 – 3.5	Moderate
> 3.5	High

Data analyses

Descriptive statistics were used to summarize the socio-economic characteristics of respondents and structural attributes of homegarden systems. Variables analyzed included gender, age, education level, household income, household size, garden size, plant species richness, vegetation stratification, technology adoption variables, and adaptation indicators.

Continuous variables were summarized using mean, standard deviation, minimum, maximum, and quartile values, while categorical variables were expressed as frequency and percentage. These statistics provide a baseline understanding of the demographic structure, biodiversity composition, and technology adoption patterns among Arfak farmers. To apply Chi-square (χ^2) and Cramér's V analyses to the five tables (Córdoba et al. 2019), we treat each table as a categorical frequency distribution (Yes/No or category counts). The Chi-square test evaluates whether the observed frequencies differ significantly from an equal distribution, while Cramér's V measures the strength of association.

The analysis combined ecological and socio-economic statistical approaches to evaluate socio-ecological adaptation dynamics. Plant

diversity was assessed using species richness, Shannon diversity, Simpson dominance, and evenness indices. Community similarity among districts was evaluated using Bray–Curtis dissimilarity (Capa and Wiabawa 2016; Lerman et al. 2018). Multivariate patterns of plant composition were explored using principal component analysis (PCA). A socio-ecological adaptation index was constructed by integrating normalized indicators of biodiversity, technology adoption, knowledge, social networks, and food security. Differences among agro-ecological zones were tested using the Kruskal–Wallis test (Simon et al. 2021a; Caballero-Serrano et al. 2016; Yudha et al. 2021). Relationships among socio-ecological variables were analyzed using Spearman correlation and multiple regression analysis to identify key drivers of adaptation capacity.

Ethical Considerations

All research procedures adhered to principles of social research ethics and indigenous community consent. Interviews were conducted following free, prior, and informed consent (FPIC). Respondent identities were kept confidential. Research findings are intended to be communicated back to the community as part of academic and social responsibility.

3. Results

Crop farmers characteristics on Homegarden Systems

The descriptive statistical analysis (Table 3) summarizes the socio-demographic characteristics of respondents, homegarden structural attributes, technology adoption, and socio-ecological adaptation indicators. In terms of demographic characteristics, the mean gender value was 0.644 (SD = 0.480), indicating that the majority of respondents were male household heads involved in homegarden



management. The average age of respondents was 38.53 years (SD = 10.35), with an age range between 18 and 62 years, suggesting that most participants were within productive working age groups. Education levels averaged 2.29 (SD = 1.01), indicating that most respondents had completed primary to secondary education. Monthly household income had a mean score of 1.80 (SD = 0.79), showing that the majority of households were within the lower to middle income categories. The average household size was 5.12 persons (SD = 1.70).

Regarding homegarden characteristics, the average garden size was 0.366 ha (SD = 0.152), ranging from 0.05 to 0.72 ha. The mean plant species richness recorded in homegardens was 17.07 species (SD = 4.46), indicating relatively

high biodiversity within household gardens. In terms of vegetation structure, the mean number of tree species was 4.53, shrubs 4.03, herbs 7.75, and vines 3.02, reflecting the multistrata structure typical of traditional agroforestry homegarden systems. With regard to agricultural technology adoption, 73.7% of respondents reported using fertilizers, while 54.2% practiced self-composting using organic waste. Only 34.7% of households used irrigation systems, whereas 86.4% practiced intercropping, indicating the widespread use of traditional polyculture systems. Similarly, 54.2% of respondents reported using botanical pesticides, and 42.4% had participated in agricultural training programs.

Table 3. Characteristic of crop farmer on Arfak tribes districts base in Manokwari regency

Parameters	mean	std	min	25%	50%	75%	max
Gender	0,644	0,480	0	0	1	1	1
Age	38,525	10,35	18	31	39,5	46	62
Education	2,288	1,013	1	1	2	3	4
Income	1,796	0,790	1	1	2	2	3
HouseholdSize	5,119	1,695	3	4	5	6,75	8
GardenSize	0,366	0,152	0,05	0,220	0,369	0,476	0,722
SpeciesRichness	17,068	4,464	10	13	17	20,75	25
TreeSpecies	4,534	1,819	2	3	5	6	7
ShrubSpecies	4,0254	1,398	2	3	4	5	6
HerbSpecies	7,746	2,157	4	6	8	9	11
VineSpecies	3,017	1,449	1	2	3	4	5
Fert_Use	0,737	0,441	0	0	1	1	1
Fert_Type	2	0,837	1	1	2	3	3
Self_Compost	0,542	0,500	0	0	1	1	1
Irrigation	0,347	0,478	0	0	0	1	1
Intercrop	0,864	0,343	0	1	1	1	1
Bio_Pest	0,542	0,500	0	0	1	1	1
Training	0,424	0,496	0	0	0	1	1
Tech1	2,009	0,821	1	1	2	3	3
Tech2	1,941	0,798	1	1	2	3	3
Tech3	1,974	0,831	1	1	2	3	3
Tech4	1,915	0,779	1	1	2	3	3
Tech5	2,059	0,819	1	1	2	3	3
SAAT	9,898	1,726	7	8,25	10	11	14



Tech_Compat	2,051	0,804	1	1	2	3	3
Challenge	2,924	1,427	1	2	3	4	5
Custom_Restr	0,237	0,427	0	0	0	0	1
Community_React	2,034	0,866	1	1	2	3	3
Decision_Maker	2,627	1,115	1	2	2,5	4	4
Tech_Import	2,576	1,127	1	2	3	4	4
Crop_Fail	0,483	0,501	0	0	0	1	1
Adapt_Action	2,568	1,081	1	2	3	3	4
Food_Price_Role	2	0,805	1	1	2	3	3
Crop_Change	0,466	0,500	0	0	0	1	1
Cooperation	0,627	0,485	0	0	1	1	1
Family_Role	0,618	0,487	0	0	1	1	1
Adapt_Import	2,576	1,165	1	2	2,5	4	4
MarketSales	1,610	1,094	0	1	2	2,75	3
FoodSecurityScore	3,254	1,456	1	2	3	5	5
ClimatePerception	2,957	1,446	1	2	3	4	5
KnowledgeScore	3,101	1,373	1	2	3	4	5
NetworkScore	2,941	1,360	1	2	3	4	5

The average scores for individual technology practices ranged from 1.91 to 2.06, producing a total Agrotechnology Adoption Score (SAAT) of 9.90 (SD = 1.73), which indicates a moderate level of technology adoption in the homegarden system. In terms of socio-ecological perceptions, respondents generally perceived agricultural technology as moderately compatible with local practices (TECH_COMPAT mean = 2.05). The average challenge score (2.92) suggests that farmers experience moderate constraints in technology adoption, while only 23.7% reported the presence of customary restrictions related to agricultural practices. Adaptive strategies were also evident among households. Approximately 48.3% of respondents reported experiencing crop failure due to seasonal variability, and many reported adaptive actions such as changing crop types such as vegetables, root crops, and fruits (Figure 2, 3, and 4) or management strategies (mean ADAPT_ACTION = 2.57). Cooperation among community members was relatively common (62.7%), and 61.8% reported changes in family roles in homegarden management.

Finally, indicators related to livelihood resilience show that homegardens contribute to household well-being. The mean Food Security Score was 3.25, suggesting a moderate contribution of homegarden production to household food supply. Respondents also demonstrated relatively strong local ecological knowledge (mean = 3.10) and social networking within the community (mean = 2.94), while climate perception scores (mean = 2.96) indicate increasing awareness of environmental changes affecting agricultural production. Overall, these results demonstrate that the traditional homegarden systems of Arfak farmers combine moderate technology adoption, relatively high plant biodiversity, and strong socio-ecological knowledge networks, which together support household livelihood resilience (Hendrawan, Chrisendo, and Musshoff 2024a, 2024b).

The Bray–Curtis dissimilarity index (Table 4) was applied to the functional vegetation structure variables (Tree Species, Shrub Species, Herb Species, and Vine Species) to examine similarity in plant composition among households.

Table 4. Bray–Curtis dissimilarity index was applied to the functional vegetation structure.

Vegetation layer	Mean
Tree species	4.53
Shrub species	4.03
Herb species	7.75
Vine species	3.02

The relative proportions of plant functional groups indicate that herbaceous plants dominate the homegarden structure, followed by trees and shrubs. The resulting Bray–Curtis similarity values suggest high similarity among homegarden vegetation structures, indicating that Arfak households maintain relatively consistent plant composition patterns across the study area.



Figure 2. Vegetables grown on Arfak homegarden.



Figure 3. Root crops grown on Arfak homegarden.



Figure 4. Pineapple grown on Arfak homegarden.

Socio-Ecological Variables

The analysis of household adaptation strategies reveals several responses adopted by Arfak farmers in managing their homegarden systems under changing environmental and socio-economic conditions (Figure 5, 6, 7, 8, and 9). A total of 67 respondents reported experiencing crop failure, while 51 respondents indicated that they had not experienced crop loss. This suggests that seasonal variability and environmental disturbances have affected a substantial proportion of households. Regarding crop management adjustments, 59 respondents reported changing the types of plants cultivated in their homegardens, while an equal number (59 households) indicated that they maintained their existing crop composition. This balanced response suggests that some households adapt by modifying crop diversity, while others rely on traditional planting patterns. Community cooperation also plays an important role in adaptation strategies. A large majority of respondents (83 households) reported cooperating with neighbors in activities such as exchanging planting materials, sharing labor, or assisting during harvest periods. In contrast, 35 respondents reported no such cooperation, indicating some variability in social network engagement. Additionally, 72 households reported changes in family roles in managing homegarden activities, such as increased involvement of women or younger family members in planting, maintenance, and harvesting tasks. Meanwhile, 46 households reported no significant changes in family labor distribution.

Overall, these findings indicate that adaptation within Arfak homegarden systems occurs through a combination of agronomic adjustments (crop changes), social cooperation, and internal household labor reorganization. These adaptive strategies reflect the resilience of traditional homegarden systems and the

capacity of indigenous communities to respond flexibly to environmental and socio-economic pressures.

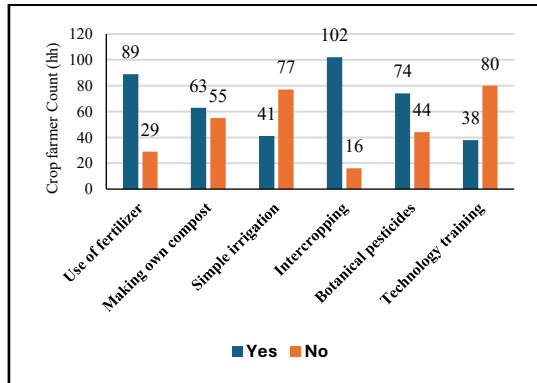


Figure 5. Technology application

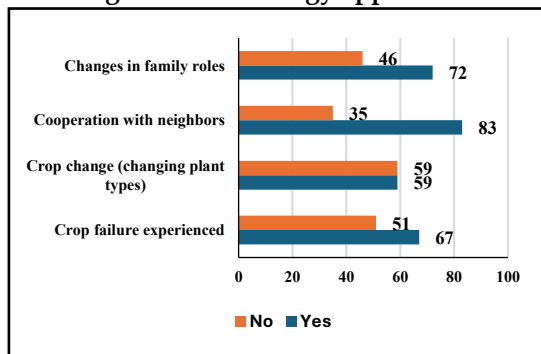


Figure 6. Adaptation Strategy

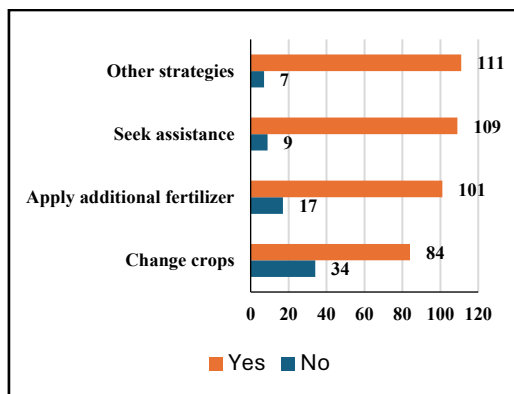


Figure 7. Adaptation Strategies in Response to Crop Failure

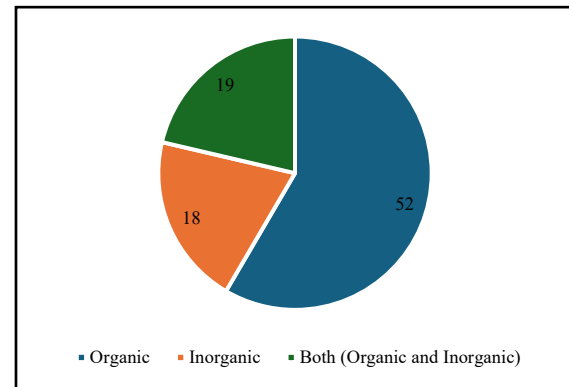


Figure 8. Type of fertilizer used.

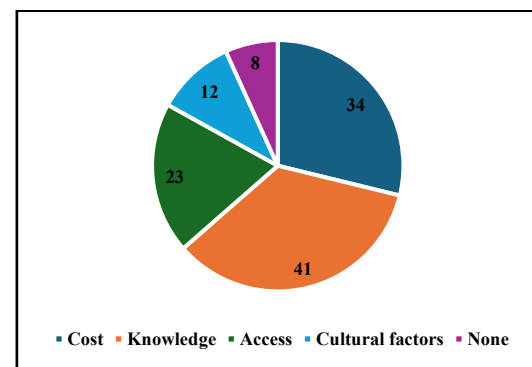


Figure 9. Technology Adoption Challenges

The responses of Arfak farmers to crop failure demonstrate several adaptive strategies employed within homegarden management systems. The most common response was seeking assistance, reported by 109 households, while only 9 respondents indicated that they did not seek help. Assistance may include support from relatives, neighbors, or community members, reflecting the importance of social networks in coping with agricultural risks. Another widely adopted strategy was increasing fertilizer application, with 101 respondents reporting that they added more fertilizer following crop failure, while 17 respondents did not apply additional fertilizer. This indicates that farmers attempt to improve soil fertility and plant recovery as a response to declining crop productivity. In addition, 84 households reported changing the types of crops planted after experiencing crop failure, whereas 34 respondents did not modify their crop composition. Crop substitution is

therefore an important adaptive mechanism that allows farmers to respond to environmental variability or pest outbreaks. Other strategies were also mentioned, with 111 respondents indicating the use of additional or alternative coping mechanisms, while 7 respondents did not apply other strategies. These may include adjusting planting schedules, diversifying crops, or intensifying management practices. Overall, these findings suggest that Arfak homegarden systems exhibit a combination of agronomic and social adaptation mechanisms, including crop diversification, increased nutrient inputs, and reliance on community support networks. Such strategies contribute to the resilience of traditional homegarden systems in responding to environmental disturbances and maintaining household food production.

The figures illustrate the patterns of technology adoption and adaptive strategies among Arfak farmers in managing their homegarden systems (Figure 9). The results show that several agroecological practices, such as fertilizer use, compost production, intercropping, and botanical pesticides, are

commonly applied in homegarden management, although the adoption of irrigation systems and participation in technology training remain relatively limited. In terms of adaptation strategies, many households reported experiencing crop failure and responding through various measures, including changing crop types, increasing fertilizer application, seeking assistance from neighbors or relatives, and implementing other management adjustments. Social cooperation also plays an important role in supporting adaptive responses within the community. The figures further indicate that both organic and inorganic fertilizers are used, with organic fertilizer being the most common input. However, farmers still face several challenges in adopting agricultural technologies, particularly related to limited knowledge, financial constraints, and restricted access to agricultural inputs and information. Overall, these findings highlight that the resilience of Arfak homegarden systems is supported by a combination of traditional agroecological practices, social cooperation, and adaptive management strategies.

Table 5. Chi-square and Cramér's V Results

Variable / Table	χ^2 value	df	p-value	Cramér's V	Interpretation
Technology application	87.31	5	<0.001	0.39	Moderate association
Adaptation strategy	16.10	3	0.001	0.21	Weak-moderate association
Crop failure response strategies	96.54	3	<0.001	0.45	Moderate-strong association
Type of fertilizer	22.71	2	<0.001	0.31	Moderate association
Technology adoption challenges	34.89	4	<0.001	0.27	Moderate association

The Chi-square results show (Table 5) that all five variables are statistically significant ($p < 0.05$), indicating that the observed distributions of responses are not random. The largest association was observed in crop failure response strategies ($V = 0.45$), suggesting that households tend to adopt similar coping mechanisms when experiencing crop losses,

particularly seeking assistance and increasing fertilizer use. Technology application also showed a moderate association ($V = 0.39$), indicating that some agroecological practices such as intercropping and fertilizer use are widely adopted, while others (irrigation and training) remain less common.



Similarly, the type of fertilizer used ($V = 0.31$), and technology adoption challenges ($V = 0.27$) demonstrate moderate associations, implying that farmers tend to rely primarily on organic inputs and face similar constraints, particularly limited knowledge, and financial resources. The adaptation strategy variable exhibited the weakest association ($V = 0.21$), suggesting that households adopt a more diverse set of responses, including crop diversification, cooperation with neighbors, and changes in family labor roles.

Overall, the results highlight that Arfak homegarden systems exhibit shared technological practices and adaptive responses, reinforcing the role of community knowledge and agroecological management in supporting socio-ecological resilience.

The Kruskal–Wallis test (Table 6) was used to examine whether key variables differ significantly across households or districts.

Table 6. Key variables of socio-ecology across households or districts.

Variable	H statistic	p-value	Interpretation
SpeciesRichness	1.47	0.689	Not significant
SAAT (technology adoption)	4.64	0.200	Not significant
FoodSecurityScore	0.99	0.805	Not significant
KnowledgeScore	2.11	0.548	Not significant
NetworkScore	1.89	0.595	Not significant

No significant differences were detected in biodiversity, technology adoption, or adaptation indicators. This suggests that Arfak homegarden systems share relatively homogeneous socio-ecological characteristics across households. The combined results from

Kruskal–Wallis tests consistently indicate that Arfak homegarden systems across the six districts share highly similar plant composition and management practices. The low dissimilarity values and overlapping ordination clusters suggest that plant diversity patterns are influenced more by shared traditional knowledge and agroecological practices than by geographic differences. Furthermore, the absence of significant statistical differences among districts implies that socio-ecological adaptation strategies—such as crop diversification, technology adoption, and community cooperation—are broadly consistent across the study area.

These findings support the interpretation that traditional Arfak homegardens function as resilient socio-ecological systems with relatively stable biodiversity structures across landscapes.

Principal Component Analyses

The PCA of agro-technology adoption parameters (Figure 10) reveals two principal gradients explaining variation in the adoption of agricultural technologies among Arfak homegarden households. The first principal component (PC1) represents the overall intensity of agro-technology adoption, strongly influenced by variables such as fertilizer use, compost production, intercropping practices, and the overall technology adoption index. This axis reflects the degree to which households integrate modern agricultural inputs with traditional homegarden management. The second component (PC2) captures variation in specific technological practices, particularly irrigation and biological pest management. The distribution of observations shows considerable overlap among districts, indicating that agro-technology adoption patterns are broadly similar across the study area. These results suggest that farmers selectively adopt technologies that complement existing

agroforestry systems rather than replacing traditional practices.

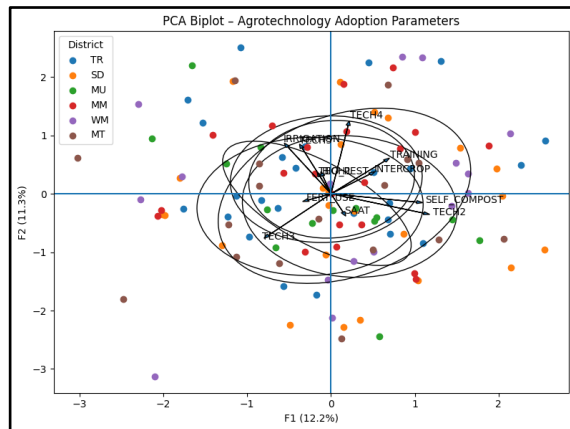


Figure 10. Agro-technology Adoption

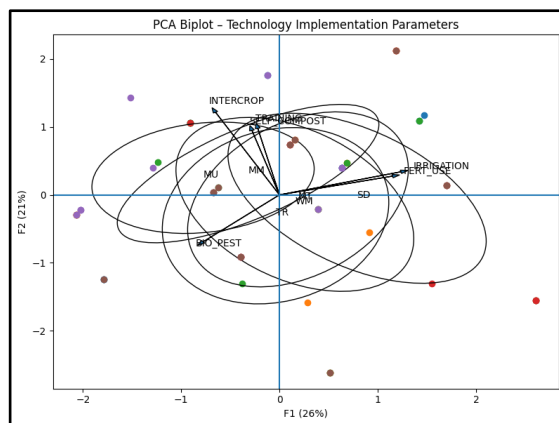


Figure 11. Technology Implementation

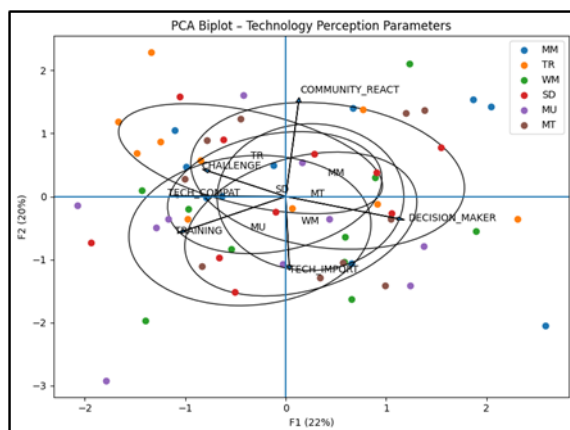


Figure 12. Technology perception

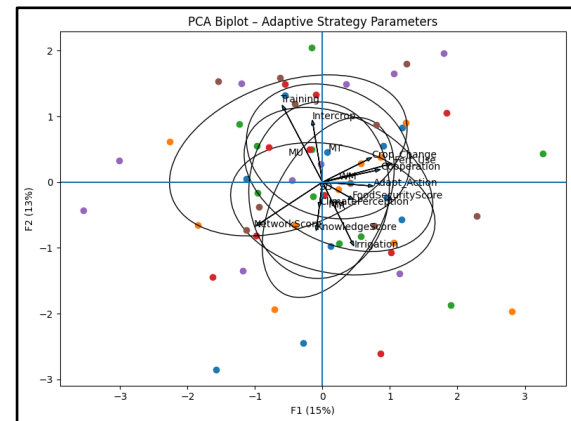


Figure 13. Adaptive strategy

The PCA of technology implementation variables (Figure 11) illustrates two main dimensions of technology use within Arfak homegardens. The first principal component is associated with input-based agricultural management, particularly fertilizer application and irrigation practices. This axis reflects the operational implementation of technologies aimed at improving crop productivity. The second component is linked to agroecological management practices, including intercropping and biological pest control, which represent environmentally oriented farming approaches. The overlapping distribution of district observations indicates that households apply similar combinations of technological and ecological practices regardless of location. This pattern suggests that technology implementation in homegardens follows a hybrid management system integrating conventional and ecological farming techniques.

The PCA of technology perception parameters (Figure 12) highlights the role of social and institutional factors in shaping farmers' attitudes toward agricultural innovations. The first principal component reflects perceived importance and compatibility of technologies, which are closely associated with household decision-making authority regarding



technology adoption. The second component represents community responses and perceived challenges, capturing how social acceptance and potential barriers influence the diffusion of agricultural technologies. The clustering of district observations suggests that farmers share relatively similar perceptions of agricultural technologies across the study area. These findings indicate that successful technology adoption depends not only on technical benefits but also on alignment with local cultural values and community support. The PCA of adaptive strategy variables (Figure 13) identifies two primary dimensions of household adaptation within Arfak homegarden systems. The first component represents social-ecological resilience, characterized by cooperation among households, knowledge exchange, and adaptive management actions that support food security. The second component reflects environmental adaptation responses, including crop diversification, changes in planting strategies, and responses to climate variability. The overlapping clusters among districts suggest that adaptive strategies are widely shared among households and are strongly influenced by community knowledge networks. These results demonstrate that adaptation in Arfak homegardens is driven by a combination of social cooperation and flexible management practices.

Together, the four PCA analyses demonstrate that Arfak homegarden systems operate as integrated socio-ecological systems where technology adoption, implementation practices, farmer perceptions, and adaptive strategies interact to sustain agricultural productivity and resilience. The strong overlap among districts indicates that these processes are shaped primarily by shared traditional knowledge and agroforestry practices rather than by geographic differences. The integration of technological innovations with local ecological knowledge contributes to the long-

term sustainability and adaptive capacity of indigenous homegarden systems.

4. Discussions

The results of this study demonstrate that Arfak homegarden systems represent resilient socio-ecological agroforestry systems characterized by high plant diversity, integrated agroecological practices, and strong social adaptation mechanisms (Agustina and Beilin 2012; Jackson et al. 2012; Belay et al. 2022; Simon et al. 2021b). The average species richness of approximately 17 species per household and the multilayered vegetation structure consisting of trees, shrubs, herbs, and vines indicate that these homegardens function as complex agroecosystems resembling natural forest structures (Bawa and Seidler 1998; Ramakrishnan 2007; Gruber 2011; Dove and Kammen 1997). Such structural complexity has been widely recognized as a key factor supporting ecological stability, biodiversity conservation, and sustainable food production in traditional agroforestry systems.

The Bray–Curtis similarity analysis shows relatively high similarity in plant composition across households and districts, suggesting that Arfak communities maintain consistent planting patterns and species selection within their homegardens. This uniformity reflects the influence of shared traditional ecological knowledge and long-standing agroforestry practices. Similar findings have been reported in other tropical homegarden systems, where cultural traditions and local knowledge strongly influence plant diversity and management strategies (Sæther et al. 2006; Corlett 2016; Mellisse et al. 2018; Mounce, Smith, and Brockington 2017; Roy, Rahman, and Fardusi 2013).

The PCA analyses further reveal that the socio-ecological dynamics of Arfak homegardens are shaped by multiple interconnected dimensions,



including agro-technology adoption, technology implementation, technology perception, and adaptive strategies (Figure 10, 11, 12, and 13). The PCA of agro-technology adoption indicates that practices such as fertilizer use, compost production, and intercropping represent the main gradient of technology adoption intensity among households. However, the moderate level of technology adoption (Ordway et al. 2017; Stellmacher and Kelboro 2019; Henry, Eckard, and Beauchemin 2018; Visser et al. 2020; Shikuku et al. 2017) suggests that farmers integrate technological innovations selectively within traditional agroecological management rather than adopting them extensively.

The PCA of technology implementation (Figure 11) highlights the coexistence of input-based management practices and ecological farming approaches. Fertilizer application and irrigation represent productivity-oriented strategies, while intercropping and botanical pesticides reflect agroecological practices that maintain soil fertility and ecological balance (Enkin Asrawijaya 2024; Moos et al. 2016; Ojiem et al. 2006; Clough et al. 2016; Reiss-Woolever et al. 2021; Clough et al. 2016). This combination of modern and traditional management approaches demonstrates that Arfak farmers employ a hybrid agricultural system that balances productivity with environmental sustainability.

Technology perception (Figure 12) also plays an important role in shaping technology adoption. The PCA results indicate that farmers tend to adopt technologies that are perceived as compatible with local practices and cultural values. Community responses and perceived challenges, including limited knowledge and financial constraints, influence the diffusion of agricultural technologies (Adnan et al. 2019; Roullier et al. 2013; Gil, Siebold, and Berger 2015; Cortner et al. 2019). These findings emphasize that technology adoption in

indigenous agricultural systems is not determined solely by technical benefits but also by social acceptance and cultural compatibility. Adaptive strategies identified in this study further demonstrate the resilience of Arfak homegarden systems. Many households reported experiencing crop failures due to seasonal variability, yet they responded through multiple adaptive mechanisms, including crop diversification, increased fertilizer use, and seeking assistance from neighbors or relatives. Social cooperation, which was reported by more than sixty percent of respondents, represents a crucial element of community resilience and collective risk management (Rahut and Ali 2018, 2018; Erwin Wantasen et al. 2022; Natcher and Hickey 2002). The PCA of adaptive strategies confirms that cooperation, knowledge exchange, and adaptive actions form an important axis of socio-ecological resilience within the community.

The Chi-square and Cramér's V analyses support these findings by demonstrating significant associations among technology application, crop failure response strategies, fertilizer use, and technology adoption challenges. These results indicate that households tend to employ similar coping strategies when facing environmental disturbances (Gómez-Baggethun et al. 2012; Mamat and Husen 2021; Grace, Allain, and Allen 2000; Buhaug and Urdal 2013). At the same time, the relatively weak association observed in some adaptive variables suggests that farmers maintain diverse responses, reflecting the flexibility of traditional homegarden management systems.

Furthermore, the Kruskal-Wallis analysis indicates that biodiversity, technology adoption, and socio-ecological adaptation indicators do not differ significantly across districts. This result suggests that Arfak homegarden systems maintain relatively



homogeneous socio-ecological characteristics across the landscape. Such homogeneity likely arises from shared cultural traditions, similar agroecological conditions, and strong knowledge exchange among communities.

Overall, the findings demonstrate that Arfak homegardens function as integrated socio-ecological systems in which biodiversity, traditional knowledge, social networks, and appropriate technology interact to sustain agricultural production and community resilience. These systems provide multiple ecosystem services (Teague and Kreuter 2020; Dumont, Groot, and Tichit 2018), including food provision, biodiversity conservation, and social cohesion, making them important components of sustainable rural livelihoods.

5. Conclusion

This study demonstrates that Arfak homegarden systems represent resilient socio-ecological agroforestry systems capable of adapting to environmental and socio-economic changes. The homegardens exhibit relatively high plant diversity and a multilayered vegetation structure typical of traditional agroforestry systems, which contributes to ecological stability and household food security. The results show that agro-technology adoption among Arfak farmers is moderate, with common practices including fertilizer use, compost production, and intercropping. Technology implementation reflects a hybrid management strategy combining modern agricultural inputs with traditional agroecological practices. Farmers' perceptions of agricultural technologies are strongly influenced by compatibility with local cultural practices and community acceptance.

Adaptive strategies employed by households include crop diversification, increased nutrient management, and reliance on social support networks. Community cooperation and

knowledge sharing play an essential role in strengthening household resilience and enabling farmers to respond to environmental disturbances such as crop failure and climate variability.

Statistical analyses further indicate that biodiversity patterns, technology adoption levels, and socio-ecological adaptation indicators are relatively consistent across districts. This suggests that Arfak homegarden systems are shaped primarily by shared traditional knowledge and cultural practices rather than by geographic differences.

Overall, Arfak homegardens function as integrated socio-ecological systems that combine biodiversity conservation, agroecological management, and social cooperation to support sustainable livelihoods. Strengthening these systems through culturally appropriate agricultural innovations, knowledge exchange, and community-based development programs can enhance the resilience and sustainability of indigenous agricultural landscapes in the face of environmental change.

Conflict of Interest. There is none among the authors

Funding.

No external funding, private or government financial support or grant was received before, during and after this study.

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