Hue University Journal of Science: Agriculture and Rural Development
Vol. 135, Số 3D, 31–43, 2026

pISSN 2588-1191
eISSN 2615-9708

Applying indigenous knowledge to enhance climate adaptation and promote green agriculture in Quang Tri Province and Hue City, Vietnam

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(Received: 23 October 2025; Accepted: 22 May 2026)

Abstract. This study examines the role of indigenous knowledge in enhancing climate adaptation capacity and promoting green agricultural development among ethnic minority communities in the mountainous areas of Quang Tri Province and Hue City, using a mixed-methods approach that combines quantitative and qualitative analyses. The findings indicate that indigenous knowledge has evolved into an integrated system of adaptive practices that effectively supports informed agricultural decision-making under climate variability, particularly in resource conservation, soil fertility maintenance, and disaster risk reduction. However, its contribution to income growth and scalability remains limited, reflecting constraints on market access, technical capacity, and policy support. The study emphasizes that the effectiveness of indigenous knowledge lies not only in individual practices but also in the flexible integration of different strategies, while highlighting the need to combine indigenous knowledge with scientific innovations and policy mechanisms to enhance its practical application in climate adaptation and sustainable agricultural development.

Keywords: Indigenous knowledge; climate change adaptation; sustainable livelihoods; green agriculture; ethnic minority communities

1 Introduction

Climate change represents one of the most critical challenges to global sustainable development, particularly within the agricultural sector, which depends directly on natural conditions. In Vietnam, the frequency and intensity of extreme weather events, including storms, floods, droughts, landslides, and saltwater intrusion, are increasing, causing severe damage to agricultural production and rural livelihoods. According to the Ministry of Natural Resources and Environment (2021), over the past five decades, the average temperature in the Central region has increased by 0.5-1.3 °C. Rainfall has decreased during the dry season but intensified in the rainy season, leading to prolonged droughts alternating with severe floods [1]. This situation highlights an urgent need to strengthen climate

adaptation capacity and promote green growth in agriculture [2].

Indigenous knowledge (IK), developed through long-term observation and adaptation by local communities to natural conditions, is an essential resource for responding to climate change. For ethnic minority communities, particularly those living in mountainous areas, IK is not only the foundation of agricultural production but also a cultural heritage that reflects the harmonious relationship between humans and nature [3, 4]. Traditional practices such as terraced cultivation, seasonal calendar adjustment, drought-resistant seed selection, the use of organic fertilizers, and the development of agroforestry systems have proven effective in maintaining soil fertility, protecting the environment, and mitigating the impacts of natural disasters [5]. When integrated with advances in science and technology, IK can significantly contribute to transforming agriculture toward sustainable, climate-adaptive systems [6].

A growing body of international research further confirms the important role of IK in enhancing agricultural sustainability and climate resilience. Empirical evidence from countries such as India, the Philippines, and several African regions demonstrates that traditional practices—including crop rotation, cover cropping, and community-based water management—can effectively mitigate the impacts of extreme weather events and improve adaptive capacity [7]. In Vietnam, although the application of IK in agricultural production has been explored in various local contexts, existing studies have primarily focused on descriptive documentation of practices rather than systematically evaluating their effectiveness or linking them to broader climate adaptation and green growth frameworks. This gap is particularly evident in Central Vietnam, one of the regions most vulnerable to climate change impacts, where integrated assessments of IK in relation to adaptive capacity and sustainable agricultural transformation remain limited [8].

Addressing this gap, the present study aims to provide a systematic and quantitative assessment of the effectiveness of IK in climate-adaptive agricultural production across mountainous communes in Quang Tri Province and Hue City. By linking local knowledge practices with measurable dimensions of economic, environmental, and adaptive performance, this study offers new empirical insights into how IK contributes to both climate resilience and the promotion of green agriculture, thereby extending beyond the predominantly descriptive approaches of previous research.

Quang Tri Province and Hue City are characterized by predominantly hilly and mountainous terrain. They are home to several ethnic minority communities, including the Bru-Van Kieu, Pa Ko, Co Tu, and Ta Oi. Local communities have developed farming systems well adapted to natural conditions, such as wet-rice and upland-rice cultivation, integrating afforestation with medicinal plant cultivation, conserving indigenous crop varieties, and utilizing forest land in accordance with traditional customs [9]. However, under the combined pressures of climate change and urbanization, much of this IK is at risk of being lost unless it is systematically documented, revitalized, and reapplied in contemporary contexts.

In this context, and in response to the identified research gap, the present study aims to systematically identify and quantitatively assess forms of IK for preventing and mitigating climate- and disease-induced risks in agricultural production, and to evaluate their effectiveness and adaptability under current climate change conditions. The findings aim to provide a scientific basis for conserving, leveraging, and integrating IK

pISSN 2588-1191
eISSN 2615-9708

into sustainable agricultural development strategies aligned with green growth objectives in Central Vietnam.

2 Methodology

The study employed a mixed-method approach that combined qualitative and quantitative techniques within a community-participatory framework, aiming to comprehensively reflect the knowledge and production experiences of ethnic minorities under climate change conditions. The methodological framework was adapted from the Climate Vulnerability and Capacity Analysis (CVCA) proposed by CARE International (2010), and integrated with Participatory Rural Appraisal (PRA) and Rapid Rural Appraisal (RRA) techniques [8, 10, 11, 12]. Quantitative data were collected through household surveys using structured questionnaires, while qualitative data were obtained from focus group discussions, in-depth interviews, and field observations. All data were processed and analyzed using descriptive statistics combined with qualitative synthesis [13].

The research process comprised four main stages: (1) collecting secondary documents and climate-socioeconomic data; (2) conducting field surveys and community interviews; (3) analyzing data; and (4) synthesizing results.

The questionnaire was developed based on an analytical framework of IK and climate change adaptation, comprising the following main components: household characteristics; forms of IK in agricultural production; levels of application; and the effectiveness of these practices in adapting to natural disasters and climate change. To quantify respondents' evaluations, the study employed a five-point Likert scale, ranging from 1 (very low) to 5 (very high). This scale was selected for its suitability to the cognitive capacity of mountainous communities, enabling respondents to distinguish between assessment levels clearly. It has also been widely applied in studies on IK and climate change adaptation [4, 10].

The study used stratified random sampling to ensure the sample was representative across spatial and social characteristics. The study population was stratified based on administrative units, ethnic groups, and livelihood conditions. Households were then randomly selected within each stratum using lists provided by local authorities. The sample size was determined using Cochran's formula (1977) for large populations, with a 95% confidence level and a margin of error of 5%, resulting in a minimum required sample size of approximately 384 observations [14]. To enhance data reliability and minimize potential biases in field surveys, 392 households were selected. This sample size is considered sufficient for descriptive statistical analysis and basic quantitative assessment.

The sample was distributed across 56 communes in Quang Tri Province and Hue City, with an average of approximately 7 households per commune. It was adjusted flexibly according to the population size of each locality. For analytical presentation, the 56 surveyed communes were grouped into five former district-level areas: Minh Hoa District, Huong Hoa District, Dakrong District, A Luoi District, and Nam Dong District. All surveyed households belonged to ethnic minority groups and were primarily engaged in agricultural livelihoods, ensuring alignment with the study's objective of examining IK in climate change adaptation.

After collection, the data were coded, entered, and analyzed using descriptive statistical methods and qualitative analysis. The score for each question was calculated as a weighted mean of responses based on the five-point Likert scale, using the following formula:

$$\bar{X} = \frac{(X_1 \times 1) + (X_2 \times 2) + (X_3 \times 3) + (X_4 \times 4) + (X_5 \times 5)}{X_1 + X_2 + X_3 + X_4 + X_5} \quad (1)$$

In Equation (1), X1 to X5 represent the numbers of respondents selecting the corresponding score levels. This approach allows for a comprehensive assessment of respondents' evaluations for each survey item and is widely used in multi-criteria evaluation studies [15]. Quantitative results were combined with qualitative data obtained from interviews and field observations to enhance the reliability and interpretability of the findings.

To clearly interpret the results, mean values are divided into five evaluation levels, ranging from very low to very high. The interval width is calculated using the formula:

$$\Delta D = \frac{D_{max} - D_{min}}{M} \quad (2)$$

Where Dmin = 1, Dmax = 5, and M = 5, the interval width (ΔD) is 0.8. Accordingly, the classification levels are as follows: 1.00–1.80: Very low; 1.81–2.60: Low; 2.61–3.40: Moderate; 3.41–4.20: High; 4.21–5.00: Very high.

3 Results and discussion

3.1 General background of the study area

The study area comprises 56 communes located in the ethnic minority and mountainous regions of Quang Tri Province and Hue City, in the western part of Central Vietnam, bordering the Lao People's Democratic Republic. These include 34 communes in Quang Tri and 22 in Hue, home to the Bru-Van Kieu, Pa Ko, Co Tu, and Ta Oi ethnic communities, which are classified as socioeconomically disadvantaged groups with particularly difficult socio-economic conditions [16]. The terrain is characterized by low hills and mountains with elevations ranging from 300 to 1,700 meters, dissected by narrow valleys and mountain ranges, providing favorable conditions for the development of slope-based agroforestry and livestock farming systems.

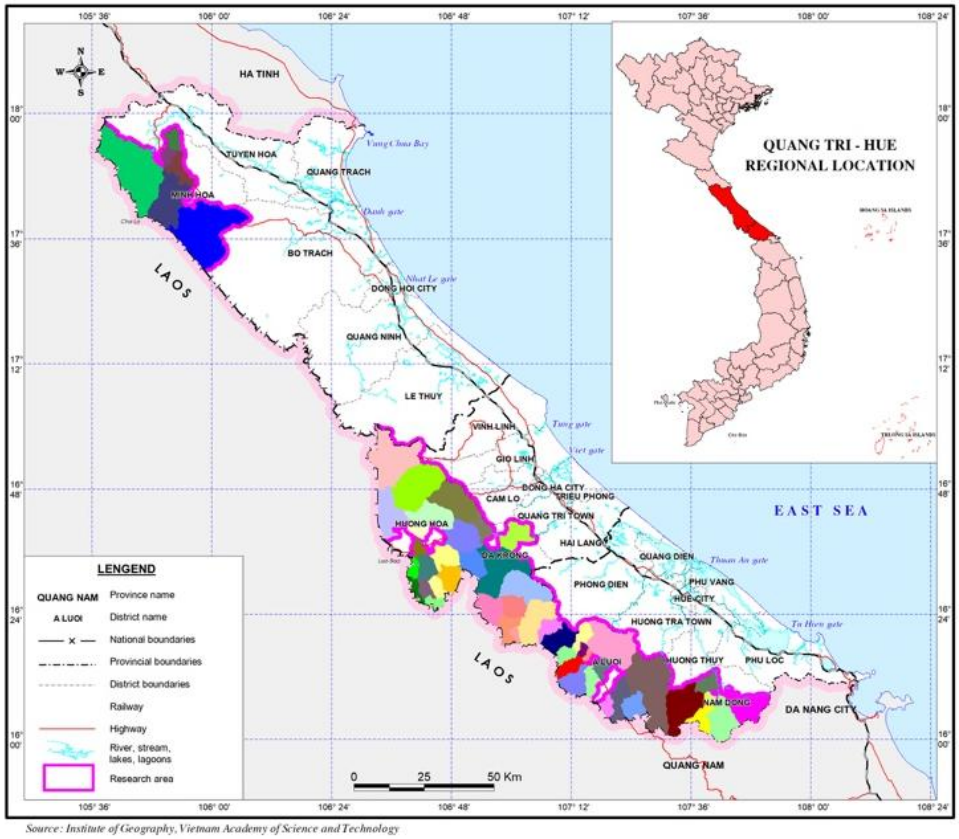

Figure 1. Location of the study area

pISSN 2588-1191
eISSN 2615-9708

The study area has a tropical monsoon climate with two distinct seasons: a hot, dry summer influenced by the southwest monsoon and a rainy winter influenced by the northeast monsoon. The mean annual temperature ranges from 21°C to 25°C, and annual rainfall varies between 2,100 and 3,700 mm [8]. This climatic seasonality strongly affects cropping calendars and agricultural livelihoods. The dominant soil types are red-yellow ferralitic and ancient alluvial soils, which are prone to degradation if not properly managed. Natural forests play an essential role in regulating the microclimate, retaining water, and supporting local livelihoods. The total population of the region was approximately 180,179 (as of 2024), with an average density of 40 persons per square kilometer [17, 18, 19]. More than 80% of the labor force is engaged in agriculture and forestry, and most lack formal technical training. Limited infrastructure and the heavy dependence of production on natural conditions make the region particularly vulnerable to climate change. Therefore, conserving and promoting IK in agricultural production is essential to enhancing adaptive capacity and advancing green growth among ethnic minority communities in Quang Tri Province and Hue City, Central Vietnam.

3.2 Characteristics of the survey sample

Table 1 shows that the characteristics of surveyed households vary across localities. The proportion of male respondents is notably high (ranging from 81.6% to 95.2%), reflecting the leading role of men in agricultural production. The average age of household heads ranges from 38 to 46 years, indicating that the main labor force falls within the working-age group.

Table 1. Characteristics of surveyed households

No.	Household characteristics	Unit	Districts				
			Minh Hoa	Huong Hoa	Dakrong	A Luoi	Nam Dong
	Total surveyed households	Household	49	105	84	112	42
1	Male	%	81.6	93.3	90.5	89.3	95.2
	Female	%	18.4	6.7	9.5	10.7	4.8
2	Average age	Years	42	38	43	46	44
3	Educational attainment	%					
	No formal education		22.4	20.0	26.2	26.8	21.4
	Primary school		40.8	38.1	47.6	44.6	47.6
	Lower secondary school		18.4	9.5	10.7	7.1	9.5
	Upper secondary school		10.2	5.7	9.5	8.1	14.3
	Above upper secondary		8.2	26.7	6.0	13.4	7.2

Source: Survey data

Overall, the level of educational attainment remains relatively low, with a high proportion of respondents having no formal education or only primary education (over 60% in most localities). In contrast, the proportion of respondents with upper secondary education or higher is limited, except in Huong Hoa, where the rate of education above upper secondary level is relatively higher (26.7%). This suggests disparities in educational access across different areas and represents an important factor influencing local people's ability to adopt new technologies and adapt to climate change.

Limited education and vocational skills constrain residents' ability to adapt to or shift to alternative livelihoods. At the same time, a high dependence on agriculture further reduces their resilience to climate change. Consequently, strengthening education, promoting vocational training, and diversifying income sources are essential measures to enhance climate adaptation capacity, increase household income, and foster sustainable development among ethnic minority communities in Quang Tri Province and Hue City.

3.3 Analysis of the indigenous knowledge resources of local people

Indigenous knowledge in disaster prediction

The IK of the mountainous communities in Quang Tri Province and Hue City represents the outcome of a long process of intergenerational accumulation and transmission through observation and production experience. Among these knowledge domains, weather and disaster forecasting constitutes a particularly practical field, enabling communities to proactively cope with extreme climatic conditions and minimize agricultural risks and losses.

Residents predict weather changes by interpreting natural signs such as the behavior of animals (frogs, bees, birds, dogs), the phenology of plants (banana flowers, bamboo shoots, longan trees, forest orchids), and environmental cues (dark clouds, rainbows, grass humidity, or cricket sounds). For example, low-flying dragonflies indicate impending rain, and bees building hives close to the ground signal impending severe storms. At the same time, the absence of earthworms emerging from the soil suggests a prolonged drought. These experiences, refined through generations, have formed a system of "ecological indicators" that guide decisions on planting, harvesting, and disaster prevention.

Amid the increasing complexity of climate change, this body of knowledge serves as an important complementary information source for community-based early warning and disaster risk management systems. Integrating IK with modern forecasting technologies enhances the effectiveness of response efforts while simultaneously preserving cultural heritage and strengthening climate adaptation capacity among the mountainous communities of Quang Tri Province and Hue City.

The findings indicate that IK in disaster prediction has evolved beyond experiential understanding into a structured knowledge system that directly supports agricultural decision-making. Compared to earlier periods, before climate change became more complex, local communities have shifted from a “passive response” to a “proactive adaptation” approach, as reflected in their use of ecological indicators to adjust cropping calendars and reduce risks. This finding is consistent with previous studies [4, 7]. This highlights the transformation of IK from experiential understanding into a dynamic adaptive system.

However, it should be noted that the effectiveness of this knowledge is largely based on local perceptions. At the same time, empirical evidence suggests that the accuracy of some natural indicators may decline as climatic

pISSN 2588-1191
eISSN 2615-9708

conditions become increasingly unpredictable. This highlights a discrepancy between perceived and actual effectiveness. Therefore, IK should be regarded as a complementary resource and integrated with modern meteorological forecasting systems to enhance reliability. These findings clarify the role of IK as a key component of community-based adaptation systems, while emphasizing the need to integrate multiple knowledge sources amid intensifying climate change.

Indigenous knowledge in agricultural production for climate disaster adaptation

The survey identified five major domains of IK that mountainous communities in Quang Tri Province and Hue City apply in agricultural production to adapt to climatic conditions: (1) soil preparation; (2) cultivation, crop care, and fertilization; (3) seasonal calendar adjustment; (4) crop and livestock selection; and (5) harvesting and product preservation. These practices demonstrate a profound understanding of local environmental conditions and accumulated community experience (Table 2).

Among the adaptation measures, early adjustment of the cropping calendar had the highest application rate (96.4%), followed by clearing alluvial soils after floods (89.3%), early harvesting to avoid disasters (77.8%), and fertilizing based on weather conditions (76.0%). Traditional practices such as wet-rice cultivation on terraced fields (72.7%), covering crops with bamboo, rattan, and plastic sheets during the cold season (47.4%), and applying flexible cropping calendars for vegetables, maize, and peanuts (68.4%) continue to contribute to maintaining stable production. In livestock management, constructing stables to shield animals from the Northeast monsoon (69.9%) and planting fodder grasses for feed storage (43.1%) are among the most common adaptive measures.

Table 2. IK-based agricultural practices for climate change adaptation

No.	Stage of application	Adaptive agricultural practice	Number of households applied	
			Number (Households)	Ratio (%)
1	Soil preparation	- Clearing alluvial soils after floods	350	89.3
		- Practicing wet rice cultivation on terraced fields	285	72.7
2	Cultivation, crop care, and fertilization	- Using bamboo/rattan frames and plastic sheets to protect plants from cold	186	47.4
		- Applying fertilizers according to weather conditions	298	76.0
		- Building stables to protect livestock from the Northeast monsoon	274	69.9
		- Planting grass in low-yield areas for buffalo/cattle feed during winter	169	43.1
3	Seasonal calendar adjustment	- Adjusting cropping schedules early to avoid storms and floods	378	96.4
		- Applying flexible seasonal calendars for vegetables, maize, and peanuts	268	68.4

No.	Stage of application	Adaptive agricultural practice	Number of households applied	
			Number (Households)	Ratio (%)
4	Crop and livestock selection	- Using indigenous trees for afforestation and medicinal purposes (e.g., *Talauma sp.*, *Erythrophleum sp.*, *Dalbergia sp.*, *Aquilaria sp.*, *Lasianthus sp.*, *Canarium sp.*)	148	37.8
		- Beekeeping in areas with *Tetrameles sp.* and *Acanthopanax sp.* trees	169	43.1
		- Raising indigenous pig breeds	159	40.6
5	Harvesting and product preservation	- Harvesting early to avoid storms and floods	305	77.8

Source: Survey data

Regarding seed resources and livelihood conservation, residents plant indigenous tree species for forest restoration and medicinal purposes (37.8%), raise bees under the forest canopy (43.1%), and maintain native pig breeds (40.6%). In the post-harvest stage, additional survey results show that sun-drying is widely practiced (88.7-94.6%), drying during prolonged rainfall is adopted by 28.7-42.8% of households, and elevating or constructing storage facilities to prevent flooding is adopted by more than 75%. Overall, these adaptive practices illustrate the communities' ability to apply and mobilize IK to reduce climate risks, stabilize yields, and enhance production efficiency.

The above findings indicate that IK in agricultural production is not merely a collection of fragmented experiences, but has evolved into an integrated system of adaptive practices closely linked to local ecological conditions. Adjustments in cropping calendars, the selection of crop varieties and livestock, and post-flood soil rehabilitation not only reflect flexible adaptive capacity but also demonstrate a shift in local production strategies—from passive responses to proactive climate risk management. However, the effectiveness of these practices is not uniform, as it remains highly dependent on natural conditions and the small-scale nature of production systems. This suggests that, while IK holds significant adaptive value in specific contexts, it also faces certain limitations when confronted with increasingly unpredictable extreme climate events.

In addition, IK plays an important role in maintaining ecological balance and guiding sustainable agricultural development by conserving local varieties, using natural materials, and reducing chemical inputs. Nevertheless, its practical effectiveness remains constrained by limited linkages to markets, scientific advancements, and supportive policy frameworks. Therefore, IK should be viewed not only as a traditional resource but as a component of an integrated knowledge system, in which its combination with scientific innovation and policy support is essential. Such an approach would not only enhance adaptive effectiveness but also promote the development of ecological agriculture aligned with green growth and sustainable livelihoods for ethnic minority communities in mountainous areas.

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eISSN 2615-9708

Evaluation of the effectiveness of indigenous knowledge in agricultural production for adaptation to climate change and disasters

Table 3. Household assessment of the effectiveness of IK-based agricultural practices

Criterion	Indicator	Types of IK practices						Average score	Classification
		Weather forecasting for production	Soil preparation	Cultivation, care, and fertilization	Seasonal calendar adjustment	Crop variety selection	Harvesting and agricultural product preservation		
Economic	Increasing crop and livestock productivity	4.6	4.5	4.5	4.2	4.7	4.1	**4.4**	Very high
	Improving household income	2.5	4.0	4.1	4.6	4.2	4.2	**3.9**	High
Institutional-policy	Alignment with local socioeconomic development policies	4.4	4.5	2.8	2.9	4.4	4.1	**3.9**	High
Cultural-social	Alignment with the customs and practices of local people	4.4	4.4	4.4	4.5	4.4	4.1	**4.4**	Very high
	Potential for scaling up adaptive measures in the community	2.4	4.5	4.4	4.2	4.4	2.8	**3.8**	High
Adaptation to Disasters and Climate Change	Suitability during storms and tropical depressions	4.8	4.4	4.4	4.5	4.4	4.1	**4.4**	Very high
	Suitability during heavy rain and post-flood recovery	4.7	2.5	4.1	4.9	4.2	4.4	**4.1**	High
	Suitability during prolonged drought conditions	4.8	4.4	4.6	4.2	4.5	4.4	**4.5**	Very high
	Reducing landslides and soil erosion	4.9	4.4	4.4	4.2	4.7	4.4	**4.5**	Very high
Environmental effectiveness	Promoting crop diversification	2.8	4.5	4.4	4.7	4.9	4.1	**4.2**	Very high
	Increasing vegetation cover	4.4	4.6	4.5	4.4	4.4	4.0	**4.4**	Very high
	Improving soil fertility	4.6	5.0	5.0	4.4	4.6	4.4	**4.7**	Very high

Source: Survey data

The results in Table 3 indicate clear differences in IK effectiveness across different criteria. Overall, environmental and climate adaptation indicators were rated at high to very high levels (4.2–4.7), whereas economic performance and scalability were rated only at moderate to high levels (3.8–3.9). This suggests that IK plays a strong role in resource conservation and climate risk reduction but has not been translated into proportionate economic benefits. For instance, the indicator "improving soil fertility" scored 4.7 (very high), while "increasing household income" reached only 3.9 (high), highlighting a gap between ecological effectiveness and economic value.

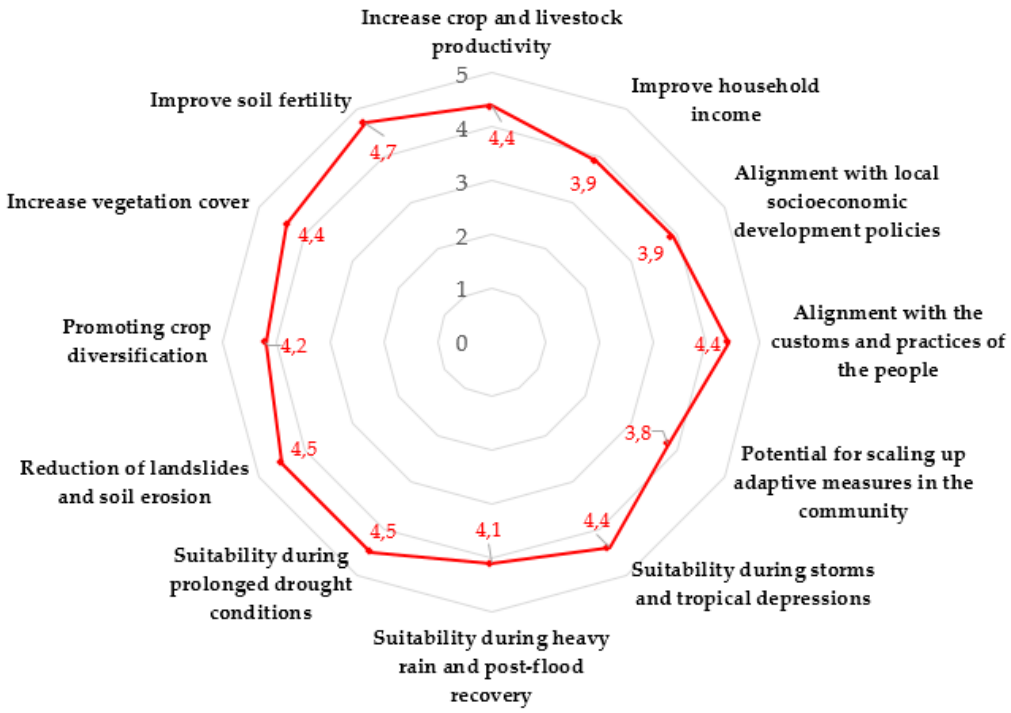

Figure 2. Distribution of household ratings by IK domains.

Source: Survey data

Within the economic dimension, although practices such as adjusting cropping calendars and selecting appropriate crop varieties contributed to increased productivity (4.4 – high), income improvement remained limited due to market dependency and small-scale production. Evidence from Pa Ko and Bru–Van Kieu households in Huong Hoa shows that while rice and maize yields have improved, unstable market prices have resulted in inconsistent income. This indicates that IK contributes more to "stabilizing production" than to "income growth" in the absence of market integration and value chain linkages.

From an institutional and socio-cultural perspective, a notable discrepancy exists between cultural appropriateness and scalability. While "compatibility with local practices" was rated very high (4.4–4.5), "scalability" was rated lower at 3.8 (high). This reflects the context-specific nature of IK, which is closely tied to local ecological and cultural conditions. For example, free-range indigenous pig farming among the Chut people or under-forest medicinal plant cultivation by the Ta Oi demonstrates high ecological effectiveness. Still, it is difficult to replicate without access to forest land or supportive policies. Therefore, scaling up IK requires contextual adaptation rather than simple replication.

Regarding climate adaptation, all indicators were rated high to very high, with "suitability during prolonged drought conditions" and "reducing landslides and soil erosion" receiving the highest average scores (4.5). This confirms the effectiveness of practices such as slope-based cultivation, contour farming, and the use of native plant species. In A Luoi, Ta Oi households apply intercropping systems on sloping land to reduce

pISSN 2588-1191
eISSN 2615-9708

soil erosion during heavy rainfall. However, some practices—such as land preparation during heavy rainfall—received low scores (2.5), indicating IK's limitations in the face of increasingly extreme and unpredictable climate events.

In terms of environmental performance, all indicators were rated very high (4.4–4.7), highlighting the important role of IK in maintaining agro-ecosystem sustainability. Practices such as organic fertilization, maintaining vegetation cover, and using native species not only improve soil fertility but also enhance carbon sequestration. In Minh Hoa and Nam Dong, households combining traditional farming with native species have demonstrated faster soil recovery following extreme weather events.

Importantly, the effectiveness of IK depends not only on individual practices but also on the integration of multiple strategies. Households that simultaneously applied cropping calendar adjustments, native crop selection, and soil restoration achieved higher scores in both environmental and climate adaptation criteria. This suggests that IK operates as an integrated system in which the interactions among practices determine overall effectiveness. In contrast, isolated application of single practices may reduce adaptive capacity under changing climate conditions.

From a development perspective, the findings reveal key constraints in transforming IK into economic value and scaling up its application. Although these practices are highly rated for ecological and adaptive effectiveness, limitations in market access, technical support, and policy frameworks constrain their economic potential. Therefore, IK should be integrated with scientific innovations, value chain development, and supportive institutional mechanisms. Such an approach would not only enhance adaptive effectiveness but also enable broader application, contributing to green agricultural development and sustainable livelihoods for ethnic minority communities in mountainous areas.

Overall, the results confirm that IK serves as a foundational component for enhancing ecological resilience and stabilizing agricultural production. However, its economic impact and scalability remain limited. Moreover, the relatively high scores (4.0–4.7) largely reflect perceived effectiveness, which may not fully correspond to actual long-term outcomes. Therefore, IK should be considered as part of a broader integrated adaptation system, where its combination with scientific knowledge, market mechanisms, and policy support is essential for achieving comprehensive effectiveness and promoting sustainable, climate-resilient agriculture in mountainous regions.

4 Conclusion

This study confirms that IK plays a significant and context-dependent role in enhancing climate adaptation capacity and sustaining agricultural production among ethnic minority communities in the mountainous areas of Quang Tri and Hue. The results show that indigenous practices are widely applied, with cropping calendar adjustment having the highest adoption rate (96.4%), followed by post-flood soil restoration (89.3%) and early harvesting to avoid disasters (77.8%). Evaluation results also indicate that environmental and climate adaptation criteria were rated at high to very high levels, particularly "reducing landslides and soil erosion" (4.5) and "improving soil fertility" (4.7). These findings demonstrate that IK has evolved from isolated experiences into a structured system of adaptive practices, playing a significant role in resource conservation and enhancing resilience to climate-related hazards.

However, the study also reveals a clear gap between ecological and economic effectiveness. While productivity-related indicators were rated at

a high level (approximately 4.4), "income improvement" scored only 3.9 and "scalability" 3.8. This reflects limitations in translating production efficiency into economic value, due to small-scale production, unstable market conditions, and insufficient institutional support. In addition, some practices showed low effectiveness under extreme climate conditions, such as land preparation during heavy rainfall (2.5), indicating that IK has certain limitations in the face of increasingly unpredictable climate variability.

From a practical perspective, the findings suggest that IK should be integrated into a comprehensive adaptation framework, in which the combination of scientific innovation, value chain development, and policy support plays a critical role. Promoting locally appropriate production models, strengthening market linkages, and enhancing farmers' technical capacity are essential to transforming ecological benefits into sustainable economic outcomes. At the same time, flexible mechanisms are needed to support the scaling up of effective practices in ways that are adapted to each community's specific ecological and cultural contexts.

Overall, the study provides both scientific and practical foundations for the conservation, promotion, and integration of IK into climate-adaptive and green agricultural development strategies. This represents an important pathway for enhancing resilience, ensuring sustainable livelihoods, and advancing sustainable agricultural development in mountainous ethnic minority regions under increasing climate change pressures.

Acknowledgments

This work was supported by Hue University under the Core Research Program, Grant No. NCTB.DHH.2026.02; This research would like to thank the support of Hue University under the grant name DHH2026-19-08.

Funding

This work was supported by the Ministry of Education and Training under project code B2026-DHH-12.

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