Contents lists available at Science-Gate

International Journal of Advanced and Applied Sciences

Journal homepage: https://www.science-gate.com/IJAAS.html

Enhancing sustainable food security through agricultural skills training and access to green technology: The mediating role of agricultural human resource empowerment in Indonesia's 3T regions

Sahat Simbolon [1,*], Agus Susanto [1], Tennisya Febriyanti Suardi [2], Adrian Babtissay Simbolon [3], Nasib Nasib [1]

[1]*Management Study Programs, Institut Bisnis Informasi Teknologi dan Bisnis, Medan, Indonesia*
[2]*Agribusiness Study Program, Universitas Medan Area, Medan, Indonesia*
[3]*Management Study Programs, Universitas Wirahusada Medan, Medan, Indonesia*

ARTICLE INFO

Article history:
Received 18 May 2026
Received in revised form
20 September 2026
Accepted 8 October 2026

Keywords:
Agricultural training
Green technology
Farmer empowerment
Food security
Sustainable agriculture

ABSTRACT

This study examines the influence of agricultural skills training and access to environmentally friendly agricultural technologies on sustainable food security through the empowerment of agricultural human resources in the 3T regions of Nias Regency. It aims to investigate the structural relationships among these variables and assess the mediating role of agricultural human resource empowerment. A quantitative survey design was adopted, involving 48 respondents purposively selected based on predefined criteria. The respondents included active farmers, agricultural extension officers, village authorities, representatives of the Agricultural Office, and community leaders. A pre-test of the research instrument was conducted before the main survey to ensure clarity and reliability. Data were collected through face-to-face questionnaires using a five-point Likert scale and analyzed using structural equation modelling–partial least squares (SEM-PLS). The results show that agricultural skills training and access to environmentally friendly agricultural technologies have positive and significant effects on agricultural human resource empowerment and sustainable food security. Agricultural human resource empowerment also plays a significant mediating role in the relationships between agricultural skills training and technology access and sustainable food security. These findings highlight the need to strengthen food security in 3T regions not only through physical support and increased agricultural production but also by enhancing farmers' capacities, independence, and sustainable resource management.

© 2026 The Authors. Published by IASE. This is an open access article under the CC BY-NC-ND license (https://creativecommons.org/licenses/by-nc-nd/4.0/).

1. Introduction

Food security is one of the strategic pillars in national development, especially in under-developed, frontier, and outermost (3T) regions, which still confront numerous structural issues in the agricultural system (Prayitno et al., 2025). Availability of land, natural resources, or production capacity alone does not determine food security; the quality of agricultural human resources (HR), as the major actors of the food production system (Bulkis et al., 2026), is also a significant determinant. The building of farmers' capacity through skills, knowledge, and adaptive capacity enhancement is an important element in achieving sustainable agricultural productivity and improving long-term food security, particularly given the backdrop of climate change, limited access to technology, and food system vulnerabilities (Yusriadi et al., 2026). Agricultural difficulties in undeveloped, border, and outermost (3T) regions in Indonesia are often more complex than those in developed regions, including poor infrastructure, weak institutional support, restricted access to technology, and minimal agricultural technical training. These conditions imply that communities still rely on traditional agricultural systems with poor productivity, which are less resilient to climate change, market conditions, and new innovations in modern agricultural technology (Ben Hassen and El Bilali, 2022). Consequently, food security in these areas is still somewhat vulnerable, particularly to disruptions in food distribution, major weather changes, or global economic pressures that influence the stability of local food systems (Song et al., 2024).

* Corresponding Author.
Email Address: sahatsimbolonitnb@gmail.com (S. Simbolon)
https://doi.org/10.21833/ijaas.2026.09.025
Corresponding author's ORCID profile:
https://orcid.org/0000-0002-2927-5361
2313-626X/© 2026 The Authors. Published by IASE.
This is an open access article under the CC BY-NC-ND license (https://creativecommons.org/licenses/by-nc-nd/4.0/)

One of the areas that is confronting this food security problem is the Nias Islands. Nias is an archipelago with considerable potential of agricultural resources, strategic opportunities to promote regional and local food security. This potential, however, has not been completely harnessed because of the low agricultural human resource (HR) capacity and weak institutional support for the food production system. Food security in Nias is rather low, mainly because of restricted food availability, limited access to modern farming technologies, and high levels of rural poverty. This condition leads most farmers to adopt conventional agriculture characterized by low productivity and limited capacity to respond to climate change, market dynamics, and agricultural innovation development (Fragomeli et al., 2026). Recent studies have indicated that low farmer technological literacy, limited agricultural extension services and inefficient farmer institutions are important hurdles to advancing sustainable agricultural transformation, particularly in rural and remote locations (Amolegbe et al., 2026). Thus, the food security problem in Nias is not only about production aspects, but also about the low quality of agricultural HR, limited access to technology, and the less-than-optimal role of institutions in encouraging a more adaptive, productive, and sustainable agricultural transformation.

The low productivity of farmers in Nias is mainly caused by the reliance on conventional agricultural systems, poor technical training, and limited access to agricultural innovation. These factors lead to less-than-ideal production efficiencies, low adaptation to environmental change, and restricted sustainability of the agricultural system. Recent studies reveal that limited access to technical training and agricultural innovation severely constrains productivity growth, technology adoption, and farmers' capacity to face the hazards of climate change and market volatility (Meng et al., 2024). Furthermore, local institutions such as farmer groups and village cooperatives have not yet functioned ideally to transfer knowledge, distribute information, and increase market access (Abdelaziz and Abay, 2026). However, empirical studies indicate the critical importance of farmer institution building in enhancing the coordination of output, boosting market access, and speeding the diffusion of sustainable agricultural technologies (Shi et al., 2026).

Studies in the past have indicated that agricultural training boosts farmer competence and production, and technology adoption enhances the efficiency and sustainability of agricultural systems (Caffaro et al., 2025). Other studies have also stressed the strategic importance of building local institutions for agricultural resilience and market access (John and Hungu, 2026; Markow et al., 2023; Vandenberg and Krellenberg, 2026). However, most research still looks at these three components in isolation and has not merged training, technology, and institutional improvement into a coherent empowerment paradigm, particularly when considering 3T regions.

Furthermore, the emergence of modern agricultural technologies such as smart farming, the Internet of Things (IoT), and green technology creates new prospects to enhance food security (Zhou et al., 2026). However, the application of these technologies in the 3T regions still faces several hurdles such as low technology literacy, insufficient institutional capacity, and limited policy backing. Thus, technology intervention alone is not enough without simultaneous enhancement of human resource capacity and local agricultural governance.

This study aims to fill the gap in previous research by developing an integrated model to empower agricultural human resources through agricultural skills training, access to green technology, and strengthening local institutions as an interconnected system that supports food security sustainability in the 3T (Underdeveloped and Remote Areas), especially the Nias Islands. This study contributes to the literature by combining these three elements into a more holistic empowerment framework, unlike earlier studies that merely looked at each factor in part. Thus, this study specifically aims to analyze the effect of agricultural skills training and access to green technology on agricultural human resource empowerment and sustainable food security and to examine the mediating role of agricultural human resource empowerment in this relationship based on this gap. Theoretically, this study is expected to contribute to the literature on agricultural human resource empowerment and food security. Practically, the results of this study are expected to be the basis for recommendations for local governments, agricultural extension workers, farmer groups, and other stakeholders in formulating more adaptive, productive, and sustainable agricultural development policies in the 3T (Underdeveloped and Remote Areas).

2. Literature review

Sustainable food security is a state in which the food system can supply sufficient, safe, nutritious, affordable, and stable food for the community while ensuring environmental, social, and economic sustainability (Tyczewska et al., 2023). The World Food Summit defines food security in four fundamental dimensions: availability, access, use, and stability (Byaruhanga and Isgren, 2023). From the sustainability perspective, food security is not only a function of the volume of production but also of the capacity of the agricultural system to sustain long-term productivity without impairing natural resources and socio-economic balance (Frimawaty et al., 2013). Under the Human Capital Theory framework, farmers' knowledge, skills, and flexibility, expressed as a capacity, constitute a strategic asset for the establishment of a sustainable agricultural system.

Farmer capacity, access to technology, and level of empowerment are closely related to sustainable food security (Aworh, 2023). Farmers with proper skills and access to agricultural technologies are generally more productive, efficient, and able to react to changes in the environment and market dynamics. However, other research has indicated that the relationship between farmer empowerment and food security is still inconclusive, particularly in distant locations with inadequate technical and institutional capacities (Siaw et al., 2024).

Agricultural skills training is the process of improving farmers' capacity via the development of knowledge, technical skills, work attitudes, and managerial abilities in agricultural operations (Sun, 2026). Training is considered a strategic tool to improve the quality of human resources so that they may perform more effectively, adaptively, and with a continuous improvement attitude from a human resource development point of view. Agricultural training involves more than just methods of cultivation, including land management, optimal utilization of production inputs, integrated pest management, post-harvest handling, and the capacity of farmers to make knowledge-based decisions (Ruf, 2026).

Agricultural skills training is very critical since many farmers still have challenges in acquiring information, understanding new technologies, and changing agricultural methods for climate change and market demands (Albertz and Pilz, 2025). Previous studies have documented that training and agricultural human resource development greatly boost technical knowledge, farm management skills, access to updated agricultural information, and the effectiveness of farmer groups, as shown by higher crop production and income. In fact, this is the empowerment of agricultural human resources through training that makes farmers capable of identifying problems, choosing suitable solutions, and independently adopting innovations. Farmers with better capabilities tend to be more confident in managing farm activities, employing local resources, and making decisions together (Yang et al., 2025). Hence, agricultural skills training should be seen not only as a knowledge transmission process but also as an empowering process that allows farmers to participate as proactive agents in agricultural development (Cheng et al., 2024).

Training in agricultural skills results in sustainable food security and empowerment (Hernandez et al., 2024). Farmers with good training are better able to raise output, maintain quality of product, reduce the risk of crop failure, and use more effective and ecologically friendly agricultural methods (Ma et al., 2023). As farmers' capacities increase, agricultural production systems become more secure, versatile, and sustainable, and contribute to long-term food security.

Access to environmentally friendly agricultural technology refers to the ability of farmers to acquire, comprehend, and use agricultural technologies that improve productivity while maintaining environmental sustainability (Brenya and Zhu, 2023). Technologies include water-saving irrigation systems, organic fertilizers, integrated pest control, climate-adaptive seeds, basic mechanization, digital agricultural technology, and climate-smart agricultural practices (Musani et al., 2025). Access is an important notion since technology itself is not sufficient; farmers also need to have the opportunity, knowledge, information, and institutional support to properly embrace and use these technologies (Bhagat et al., 2024). In sustainable agriculture, access to environmentally friendly technology is vital to improve production efficiency, reduce environmental degradation, and improve resilience to climate change (Ma and Rahut, 2024).

Empirical research has frequently emphasized the positive impact of environmentally friendly agricultural technology on productivity development, resource efficiency, and agricultural sustainability. For example, climate-smart agriculture has been demonstrated to increase farmers' output and revenue, while increasing adaptive ability to climate change and lowering environmental risks. Furthermore, the use of technology is highly related to agricultural human resource empowerment, as farmers with higher access to technology are likely to have better possibilities to develop knowledge, improve decision-making capacity, and increase their options for output (Ishtiaque et al., 2024). However, past research also shows that the use of environmentally friendly technology is still hindered by the lack of financial capacity, technological literacy, weak institutional support, and infrastructure, especially in rural and impoverished regions (Ma et al., 2024). These findings indicate that access to technology alone is not adequate to achieve sustained food security unless it is coupled with agricultural skills training and empowerment of human resources.

Agricultural human resource empowerment refers to the process of strengthening farmers' capacity, independence, participation, and ability to manage agricultural resources productively and sustainably (Pandey et al., 2025). Empowerment is not merely limited to the provision of assistance, but involves a broader process that enables farmers to acquire knowledge, technical skills, self-confidence, access to resources, and decision-making capabilities in agricultural activities (Murtiningrum et al., 2023). Within the agricultural development framework, empowerment is regarded as a strategic approach because farmers are positioned not as passive recipients of development programs, but as active agents in strengthening agricultural systems and food security.

Empirical evidence shows that agricultural human resource empowerment is substantially associated with the improvement of farmers' production, creative ability, access to knowledge, and institutional engagement (Duan et al., 2024). Empowered farmers are in a better position to optimize local resources, respond to environmental and market changes, and sustain agricultural

productivity. But earlier research also reveals that the empowerment benefits are typically hampered by a lack of strong institutional support, restricted access to technology, and inadequate training continuity, particularly in rural and disadvantaged areas (Otari et al., 2024). The results suggest that empowerment is a key channel via which development inputs such as training and access to technology can contribute to the overarching objective of sustainable food security. Hence, this study considers agricultural human resource empowerment as an intervening variable that enhances the relationship between agricultural skills training, access to environmentally friendly agricultural technology, and sustainable food security.

2.1. Research hypotheses

Based on the theoretical foundations and empirical findings from previous studies, this study develops a set of hypotheses, which are systematically formulated and presented in Table 1.

Table 1: Research hypotheses

No	Hypothesis statement
H1	Agricultural skills training positively and significantly affects agricultural human resource empowerment.
H2	Agricultural skills training positively and significantly affects sustainable food security.
H3	Access to environmentally friendly agricultural technology positively and significantly affects agricultural human resource empowerment.
H4	Access to environmentally friendly agricultural technology positively and significantly affects sustainable food security.
H5	Agricultural human resource empowerment positively and significantly affects sustainable food security.
H6	Agricultural skills training positively and significantly affects sustainable food security through agricultural human resource empowerment.
H7	Access to environmentally friendly agricultural technology positively and significantly affects sustainable food security through agricultural human resource empowerment.

3. Methods

This study used a quantitative survey approach to evaluate the structural links between agricultural skills training, access to environmentally friendly agricultural technology, agricultural human resource empowerment, and sustainable food security in Nias Regency. The quantitative technique was chosen as the most suitable for the empirical assessment of causal links between variables and validation of the suggested conceptual model.

The research was conducted in Nias Regency, North Sumatra Province, in Gido, Hiliduho, and Idanogawo districts. They were picked on purpose as they are agricultural regions with significant production potential, but are nevertheless characterized by structural problems, such as restricted access to agricultural technology, insufficient farmer training, and weak institutional support. This backdrop makes Nias an interesting place to study concerns of sustainable food security in disadvantaged, frontier, and outermost (3T) regions of Indonesia.

The target group was active farmers and major agricultural stakeholders with direct involvement in farming activities, agricultural empowerment, and local food security programs. Sampling was done purposively with 48 respondents based on the criteria. The sample consisted of 30 active farmers, 7 agricultural extension officers, 4 village administrators, 4 officials of the Nias Regency Agricultural Office, and 3 community leaders. The respondents were selected based on the following criteria: (1) active in agricultural activities for at least three years; (2) directly involved in the production of food crops; (3) participated in agricultural training programs; and (4) have knowledge on environment-friendly agricultural practices or technologies. As recommended by Hair et al. (2016), the sample size is considered adequate for Partial Least Squares Structural Equation Modeling (PLS-SEM), where the minimum sample size should be greater than ten times the largest number of structural paths directed at a latent construct.

The research instrument was constructed based on the established indicators from prior studies for each concept and measured on a five-point Likert scale from 1 (strongly disagree) to 5 (strongly agree). The instrument measured four major constructs, namely agricultural skills training, access to eco-friendly agricultural technology, agricultural human resource empowerment, and sustainable food security.

To confirm the appropriateness and context fit of the indicators, the questionnaire was content validated by three experts in agricultural and rural development before the main survey. A pilot test was then conducted with 10 respondents to test the clarity, consistency, and reliability. The pilot test findings indicated acceptable reliability, as the Cronbach's Alpha values were above the recommended cut-off point of 0.70.

Interviewer-administered structured questionnaires were used to collect data to decrease misunderstanding among the respondents and to increase the data accuracy. Direct field-based data collection was particularly critical given that some rural parts of Nias had low literacy rates and poor technological access. To minimize sampling bias, the eligibility of the respondents was checked with the cooperation of local authorities and the Agricultural Office of Nias Regency.

The data were analyzed using SmartPLS version 4.0 with Structural Equation Modeling-Partial Least Squares (SEM-PLS). SEM-PLS was selected due to its appropriateness for prediction models, mediation analysis, and very modest sample sizes. The analysis was performed in two steps. The first stage was the assessment of the measurement model (outer model), which includes convergent validity, discriminant validity, and construct reliability. The

convergent validity was examined by outer loadings and Average Variance Extracted (AVE). The reliability was measured by Cronbach's Alpha and Composite Reliability. The second stage was to evaluate the structural model (inner model) such as R-squared, F-squared, path coefficient, t-statistics and p-value to determine the significance and strength of the hypothesized link.

The study was performed according to research ethics norms. Prior to data collection, all respondents were informed of the aims of the study, and their freely given informed consent was obtained. The privacy and anonymity of the participants were assured, and all data collected were utilized strictly for academic and research purposes.

The study was conducted according to ethical principles recognized in social science research. Prior to data collection, all respondents were informed about the objectives of the study, and their voluntary informed consent was obtained before participation. Participants were assured that their responses would remain anonymous and confidential, and that all collected data would be used solely for academic purposes.

4. Research results

4.1. Outer model testing

The measurement model (outer model) was evaluated to assess the validity and reliability of the constructs. The results of convergent validity, discriminant validity, and construct reliability are summarized in Table 2.

Table 2: Outer loading values

Variable	Code	Outer loading	Description
Agricultural skills training	PKP1	0.812	Valid
	PKP2	0.846	Valid
	PKP3	0.791	Valid
	PKP4	0.828	Valid
	PKP5	0.807	Valid
	PKP6	0.835	Valid
Access to environmentally friendly agricultural technology	ATP1	0.801	Valid
	ATP2	0.824	Valid
	ATP3	0.786	Valid
	ATP4	0.854	Valid
	ATP5	0.831	Valid
	ATP6	0.819	Valid
Agricultural human resource empowerment	PSDM1	0.833	Valid
	PSDM2	0.861	Valid
	PSDM3	0.847	Valid
	PSDM4	0.809	Valid
	PSDM5	0.826	Valid
	PSDM6	0.858	Valid
Sustainable food security	KPB1	0.815	Valid
	KPB2	0.842	Valid
	KPB3	0.829	Valid
	KPB4	0.806	Valid
	KPB5	0.850	Valid
	KPB6	0.837	Valid

As shown in Table 2, all indicators have outer loading values above the threshold of 0.70, which indicates that the measuring items have fulfilled the convergent validity requirements and sufficiently represent their respective constructs. The results of construct reliability and validity are shown in Table 3.

Table 3: Construct reliability and validity

Variable	Cronbach's alpha	Composite reliability	AVE	Description
Agricultural skills training	0.895	0.919	0.654	Reliable
Access to environmentally friendly agricultural technology	0.887	0.914	0.640	Reliable
Agricultural human resource empowerment	0.912	0.932	0.697	Reliable
Sustainable food security	0.903	0.925	0.673	Reliable

The Cronbach's Alpha and Composite Reliability values of all constructs are above the acceptable level of 0.70, as presented in Table 3. Furthermore, all constructs have Average Variance Extracted (AVE) values larger than 0.50. These results show that all constructs in this study have the properties of construct reliability and convergent validity. The results of the discriminant validity based on the Fornell-Larcker criterion are reported in Table 4.

Table 4: Discriminant validity — Fornell-Larcker criterion

Variable	PKP	ATP	PSDM	KPB
Agricultural skills training	0.809			
Access to environmentally friendly agricultural technology	0.612	0.800		
Agricultural human resource empowerment	0.674	0.692	0.835	
Sustainable food security	0.641	0.663	0.728	0.820

As shown in Table 4, the square root of the AVE for each construct is greater than the inter-construct correlation values. This indicates that each construct has satisfied the discriminant validity criterion.

4.2. Inner model testing

The structural model (inner model) was evaluated to check the predictive relevance and the explanatory power of the proposed model. At this stage, the R-squared values were checked to find out to what extent the exogenous variables explain the variation of the endogenous constructs. The higher R-squared values indicate the stronger predictive power of the model. The results of R-squared analysis are shown in Table 5.

Table 5: R-squared results

Endogenous variable	R-squared	Adjusted R-squared	Description
Agricultural human resource empowerment	0.612	0.595	Moderate
Sustainable food security	0.728	0.710	Strong

Based on Table 5, the R-squared value for the agricultural human resource empowerment variable is 0.612. This means that agricultural skills training and access to environmentally friendly agricultural technology are able to explain 61.2% of the variance in agricultural human resource empowerment, while the remaining 38.8% is explained by other factors

outside the research model. The R-squared value for the sustainable food security variable is 0.728. This means that agricultural skills training, access to environmentally friendly agricultural technology, and agricultural human resource empowerment are able to explain 72.8% of the variance in sustainable food security, while the remaining 27.2% is influenced by other variables outside the research model. Furthermore, the F-squared results can be shown in Table 6.

Table 6: F-squared results

Variable relationship	F-squared	Description
Agricultural skills training → agricultural human resource empowerment	0.214	Medium
Access to environmentally friendly agricultural technology → agricultural human resource empowerment	0.286	Medium
Agricultural skills training → sustainable food security	0.091	Small
Access to environmentally friendly agricultural technology → sustainable food security	0.124	Small
Agricultural human resource empowerment → sustainable food security	0.362	Large

Based on Table 6, the strongest effect is shown by the relationship between agricultural human resource empowerment and sustainable food security, with an F-squared value of 0.362. This indicates that agricultural human resource empowerment has a strong substantive contribution to improving sustainable food security. Meanwhile, agricultural skills training and access to environmentally friendly agricultural technology show small to medium effects on the endogenous variables in the model. Then the results of the hypothesis testing are shown in Table 7. The results of the hypothesis testing are reported in Table 7. The findings show that agricultural skills training has a positive and significant effect on agricultural human resource empowerment ($\beta = 0.381$; $t = 3.742$; $p < 0.001$), which therefore supports H1. Agricultural skills training has also a substantial and positive association with sustainable food security ($\beta = 0.214$; $t = 2.184$; $p = 0.030$), supporting H2. Furthermore, the presence of eco-friendly agricultural technology has a significant impact on agricultural human resource empowerment ($\beta = 0.456$; $t = 4.315$; $p < 0.001$), supporting H3, and on sustainable food security ($\beta = 0.246$; $t = 2.527$; $p = 0.012$), supporting H4. The results also reveal that agricultural human resource empowerment has the most favorable effect on sustainable food security ($\beta = 0.487$; $t = 5.628$; $p < 0.001$), which supports H5. The mediation test also indicates that agricultural human resource empowerment significantly mediates the relationship between agricultural skills training and sustainable food security ($\beta = 0.185$; $t = 3.116$; $p = 0.002$), confirming H6. Agricultural human resource empowerment also significantly mediates the relationship between access to environmentally friendly agricultural technology and sustainable food security ($\beta = 0.222$; $t = 3.684$; $p < 0.001$), hence supporting H7. Overall, these findings imply that agricultural skills training and access to eco-friendly agricultural technology are both important in enhancing sustainable food security directly and indirectly through agricultural human resource empowerment.

Table 7: Path coefficients and hypothesis testing

Hypothesis	Variable relationship	Original sample	T-statistics	P-value	Decision
H1	Agricultural skills training → agricultural human resource empowerment	0.381	3.742	0.000	Accepted
H2	Agricultural skills training → sustainable food security	0.214	2.184	0.030	Accepted
H3	Access to environmentally friendly agricultural technology → agricultural human resource empowerment	0.456	4.315	0.000	Accepted
H4	Access to environmentally friendly agricultural technology → sustainable food security	0.246	2.527	0.012	Accepted
H5	Agricultural human resource empowerment → sustainable food security	0.487	5.628	0.000	Accepted
H6	Agricultural skills training → agricultural human resource empowerment → sustainable food security	0.185	3.116	0.002	Accepted
H7	Access to environmentally friendly agricultural technology → agricultural human resource empowerment → sustainable food security	0.222	3.684	0.000	Accepted

5. Discussion

The findings indicate that agricultural skills training has a positive and significant effect on agricultural human resource empowerment. This result confirms that training functions not only as a mechanism for knowledge transfer but also as a strategic instrument for strengthening farmers' capacity, decision-making ability, and independence in managing agricultural activities. This finding is consistent with previous studies by Plana-Farran et al. (2023) and Zhang and Yang (2025), which reported that agricultural training significantly improves farmers' technical competencies, adaptive skills, and managerial capabilities. From the perspective of Human Resource Development, training plays an important role in enhancing farmers' human capital and adaptive readiness. In the context of Nias, where agricultural activities are still dominated by traditional family-based farming systems and intergenerational knowledge transfer, training becomes highly relevant in reducing knowledge gaps and increasing farmers' capacity to respond to climate and market uncertainties. However, previous studies by Setiawan et al. (2024) found that training alone often produces limited long-term effects when not supported by institutional strengthening and post-training assistance.

The findings further suggest that the teaching of agricultural skills has a favorable and considerable impact on sustainable food security. The result

indicates that the higher the skills of farmers, the more stable the production, the lower the risks of crop failure, and the higher the efficiency in the use of resources. Raji et al. (2024) and Shafieisabet and Mirvahedi (2025) came to similar conclusions, demonstrating that farmer training greatly improves local food production systems and household food security. Agricultural training is a strategic intervention to improve resilience in Nias, where food production is very vulnerable to erratic rainfall patterns, low mechanization, and insufficient irrigation infrastructure. However, Hakim et al. (2025) found opposite results, indicating that training does not necessarily immediately increase food security when farmers are faced with significant financial and technological restrictions. This implies that the success of Nias' training is contingent on the integration of supporting resources.

Access to eco-friendly agricultural technology was found to have a favorable impact on the empowerment of agricultural human resources and sustainable food security. These results are in line with the research of Liu (2024) that highlighted the role of climate-smart and green agricultural technologies in increasing productivity, building resilience, and improving resource efficiency. In Nias, access to technology is hindered by geographical isolation, insufficient transport infrastructure, and limited coverage of agricultural extension. Technologies such as climate-adaptive seeds, organic fertilizers, and water-efficient irrigation have high potential to increase production outcomes, but their uptake depends on local acceptance and farmers' capacity to adapt them to the agroecological circumstances of Nias. However, Ma et al. (2024) pointed out that the acceptance of technology in distant areas is often met with opposition due to cultural attachment to conventional farming practices and limited technological literacy.

Empowerment is the most dominant factor in building local food systems and has the largest direct influence on sustainable food security, i.e., agricultural human resource empowerment. This finding is in line with previous studies by Zhou et al. (2025), which showed that farmers who are empowered are better able to manage production resources, access to markets, and adjust to agricultural risks. In Nias, empowerment is of considerable socio-cultural relevance as farming operations are often incorporated in communal structures and collective ideals such as gotong royong. These social institutions provide chances for communal learning and sharing of resources. But counter findings by Sahoo et al. (2024) implied that empowerment alone may not be sufficient to increase food security when farmers still face structural constraints such as poor market access, limited financial capital, and inadequate policy support. The situation is still applicable in Nias, where institutional capacity and market integration are still relatively weak, further emphasizing the necessity of combining empowerment with larger systemic assistance.

The mediation results further demonstrate that agricultural human resource empowerment strongly moderates the relationship between agricultural skills training, access to environmentally friendly agricultural technology, and sustainable food security. These findings are consistent with the ideas of Ospina and Collazos (2025) and Sahoo et al. (2025), who argued that sustainable food systems not only require access to information and technology, but also empowered individuals who can translate these inputs into productive outcomes. In Nias, structural hurdles such as poor infrastructure, fragmented institutional support, and a strong cultural dependence on conventional farming make empowerment a vital bridging tool. However, Wereta et al. (2026) have indicated that the mediating effect of empowerment may be weakened if the training programs are sporadic and the technology diffusion lacks strong institutional coordination. Nevertheless, a critical view of empowerment in Nias has shown that it should not be seen as a stand-alone strategy but needs to be combined with ongoing training, affordable green technologies, and improved farmer institutions. This study also adds to the literature by indicating that sustainable food security in underprivileged agricultural areas is best attained through a holistic and integrated empowerment strategy instead of piecemeal interventions.

6. Conclusion

The study indicated that agricultural skills training and access to environmentally friendly agricultural technologies are crucial to improving agricultural human resource empowerment and sustainable food security in the 3T region of Nias Regency. Agricultural human resource empowerment was the most influential element of all the factors evaluated. It implies that farmers with greater technical capacity, decision-making capacity, and independence are better equipped to sustain agricultural productivity and long-term food sustainability. Findings underline the limited potential of training and technological therapies without integration within empowerment-based approaches.

In the specific case of Nias, where the agricultural systems are still based on traditional farming techniques, lack of infrastructure, poor farmer institutions, and limited market access, practical interventions should be more context-sensitive. Local governments should focus on decentralized farmer training programs in villages, strengthen agricultural extension services in remote areas, increase access to climate-adaptive seeds and low-cost, environmentally friendly technologies, and strengthen farmer groups as community-based institutional support systems. Such solutions are particularly significant in Nias, where geographical remoteness and socio-cultural dependence on

conventional farming still represent considerable obstacles. Therefore, a holistic empowerment approach of training, technology access, and institutional development is important to increase sustained food security in marginalized agricultural communities.

Several limitations of the present investigation should be noted. First, the sample size is small; hence, the generalizability of the findings beyond the setting of Nias Regency is limited. The second drawback is that the study was conducted in selected districts in a 3T region, which may not be representative of the broader agricultural context in other rural areas. Thirdly, the cross-sectional approach has limits in capturing long-term changes in farmers' empowerment and food security. Future research can use larger sample sizes, longitudinal approaches and wider regional coverage to better the empirical understanding of sustainable food security in poor agricultural areas.

List of abbreviations

3T	Disadvantaged, frontier, and outermost regions
ATP	Access to environmentally friendly agricultural technology
AVE	Average variance extracted
HR	Human resources
IoT	Internet of Things
KPB	Not defined in the manuscript
PKP	Agricultural human resource empowerment
PLS-SEM	Partial least squares structural equation modelling
PSDM	Not defined in the manuscript
SEM-PLS	Structural equation modelling–partial least squares

Acknowledgment

The authors would like to thank the Ministry of Education, Culture, Research, and Technology of the Republic of Indonesia (Kemendikbudristek) for the financial support through the Regular Fundamental Research Program. With this funding, the researchers have been able to carry out a study that contributes to the development of knowledge, the strengthening of innovation, and the solving of issues relevant to the requirements of the community. The results of this study are intended to be useful for the promotion of research, education, and sustainable development in Indonesia.

Compliance with ethical standards

Ethical considerations

Ethical approval was obtained from the Research and Community Service Institute (LPPM), Institut Bisnis Informasi Teknologi dan Bisnis, Indonesia (Approval No. 035/LPPM-ITNB/SPD/II/2026). Informed consent was obtained from all participants before data collection. Participation was voluntary, and responses were collected and analyzed anonymously to ensure confidentiality.

Conflict of interest

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

References

Abdelaziz F and Abay KA (2026). Digital literacy training to promote diffusion of digital agricultural tools to smallholder farmers: Evidence from a randomized intervention in Egypt. Food Policy, 141: 103108. https://doi.org/10.1016/j.foodpol.2026.103108

Albertz A and Pilz M (2025). Green skills at Industrial Training Institutes in India: An exploratory study of VET teachers' subjective theories. International Journal of Educational Development, 118: 103406. https://doi.org/10.1016/j.ijedudev.2025.103406

Amolegbe KB, Dedehouanou SFA, Muhammad-Lawal A, and Daudu AK (2026). Digital technology knowledge and farmer's e-commerce valuation in Nigeria. Journal of Integrative Agriculture, 25(6): 2229-2241. https://doi.org/10.1016/j.jia.2025.12.056

Aworh OC (2023). African traditional foods and sustainable food security. Food Control, 145: 109393. https://doi.org/10.1016/j.foodcont.2022.109393

Ben Hassen T and El Bilali H (2022). Impacts of the Russia-Ukraine war on global food security: Towards more sustainable and resilient food systems? Foods, 11(15): 2301. https://doi.org/10.3390/foods11152301 **PMid:35954068 PMCid:PMC9368568**

Bhagat R, Walia SS, Sharma K, Singh R, Singh G, and Hossain A (2024). The integrated farming system is an environmentally friendly and cost-effective approach to the sustainability of agri-food systems in the modern era of the changing climate: A comprehensive review. Food and Energy Security, 13(1): e534. https://doi.org/10.1002/fes3.534

Brenya R and Zhu J (2023). Agricultural extension and food security – The case of Uganda. Global Food Security, 36: 100678. https://doi.org/10.1016/j.gfs.2023.100678

Bulkis S, Nugroho A, Summase AP, Mudatsir R, and Summase I (2026). Institutional framework for improving food security in crisis-prone areas in Indonesia. Journal of Agriculture and Food Research, 27: 102774. https://doi.org/10.1016/j.jafr.2026.102774

Byaruhanga R and Isgren E (2023). Rethinking the alternatives: Food sovereignty as a prerequisite for sustainable food security. Food Ethics, 8: 16. https://doi.org/10.1007/s41055-023-00126-6

Caffaro F, Roccato M, Bagagiolo G, Cavallo E, and Pampuro N (2025). Training and social-psychological drivers of farmers' intention to adopt renewable energy for agricultural machinery: An Italian study. Energy Conversion and Management: X, 28: 101360. https://doi.org/10.1016/j.ecmx.2025.101360

Cheng C, Gao Q, Ju K, and Ma Y (2024). How digital skills affect farmers' agricultural entrepreneurship? An explanation from factor availability. Journal of Innovation & Knowledge, 9(2): 100477. https://doi.org/10.1016/j.jik.2024.100477

Duan M, Hou Y, Zhang B, Chen C, Sun Y, Luo Y, and Tan T (2024). Skill sets and wage premium: A network analysis based on Chinese agriculture online job offers. Technological Forecasting and Social Change, 201: 123260. https://doi.org/10.1016/j.techfore.2024.123260

Fragomeli R, Punzo G, and Annunziata A (2026). Agriculture 4.0 technologies among Italian farmers: A C-TAM-TPB approach with sustainability and economic factors. Journal of Cleaner Production, 559: 148316. https://doi.org/10.1016/j.jclepro.2026.148316

Frimawaty E, Basukriadi A, Syamsu JA, and Soesilo TB (2013). Sustainability of rice farming based on eco-farming to face food security and climate change: Case study in Jambi Province, Indonesia. Procedia Environmental Sciences, 17: 53-59. https://doi.org/10.1016/j.proenv.2013.02.011

Hair JF Jr, Hult GTM, Ringle CM, and Sarstedt M (2016). A primer on partial least squares structural equation modeling (PLS-SEM). 2nd Edition, SAGE Publications, Thousand Oaks, USA.

Hakim TR, Gunawan GG, and Sagita NI (2025). Strategy of the agriculture and food security office of Sumedang District in optimizing the productivity of food crops and horticultural (study of farmer empowerment in Pamulihan Sub-District Sumedang Regency in 2022–2023). International Journal of Business, Economics, and Social Development, 6(3): 413-421. https://doi.org/10.46336/ijbesd.v6i3.1009

Hernandez D, Pasha L, Yusuf DA, Nurfaizi R, and Julianingsih D (2024). The role of artificial intelligence in sustainable agriculture and waste management: Towards a green future. International Transactions on Artificial Intelligence, 2(2): 150-157. https://doi.org/10.33050/italic.v2i2.552

Ishtiaque A, Krupnik TJ, Krishna V et al. (2024). Overcoming barriers to climate-smart agriculture in South Asia. Nature Climate Change, 14: 111-113. https://doi.org/10.1038/s41558-023-01905-z

John Y and Hungu OA (2026). Strengthening food security in developing countries; does climate smart agriculture perspective matters among smallholder farmers? Strategic Business Research, 2(1): 100105. https://doi.org/10.1016/j.sbr.2026.100105

Liu Z (2024). Green technology based agricultural product quality and market prices in China. Journal of King Saud University-Science, 36(10): 103451. https://doi.org/10.1016/j.jksus.2024.103451

Ma H, Mi X, Zheng Y, Lv N, Zhang S, Hu C, Wu X, and Cao Y (2024). How to promote cooperative innovation in environmentally friendly technology: A case of agricultural biotechnology in China. Chinese Journal of Population, Resources and Environment, 22(2): 127-135. https://doi.org/10.1016/j.cjpre.2024.06.003

Ma W and Rahut DB (2024). Climate-smart agriculture: Adoption, impacts, and implications for sustainable development. Mitigation and Adaptation Strategies for Global Change, 29: 44. https://doi.org/10.1007/s11027-024-10139-z

Ma W, McKay A, Rahut DB, and Sonobe T (2023). An introduction to rural and agricultural development in the digital age. Review of Development Economics, 27(3): 1273-1286. https://doi.org/10.1111/rode.13025

Markow J, Fieldsend AF, von Münchhausen S, and Häring AM (2023). Building agricultural innovation capacity from the bottom up: Using spillover effects from projects to strengthen agricultural innovation systems. Agricultural Systems, 209: 103670. https://doi.org/10.1016/j.agsy.2023.103670

Meng X, Yang S, and Pan G (2024). Innovation practices in agricultural transformation in East China: Exploring the impact and implications of the new professional farmer training model. Heliyon, 10(14): e34671. https://doi.org/10.1016/j.heliyon.2024.e34671 **PMid:39130451 PMCid:PMC11315191**

Murtiningrum F, Noer M, Wahyuni I, and Wahyuni S (2023). Empowerment in the development of agricultural areas. IOP Conference Series: Earth and Environmental Science, 1160: 012059. https://doi.org/10.1088/1755-1315/1160/1/012059

Musani I, Ansar M, and Suprapto A (2025). Contribution of environmentally friendly technology in sustainable agricultural practices to overcome climate change. The Journal of Academic Science, 2(1): 407-416.

Ospina AR and Collazos AZ (2025). Model for assessing environmental sustainability performance in the agricultural sector: A case study on plantain cultivation. Global Transitions, 7: 175-188. https://doi.org/10.1016/j.glt.2025.04.001

Otari S, Bapat VA, Lakkakula J, Kadam US, and Suprasanna P (2024). Advancements in bionanotechnological applications for climate-smart agriculture and food production. Biocatalysis and Agricultural Biotechnology, 57: 103117. https://doi.org/10.1016/j.bcab.2024.103117

Pandey SC, Modi P, Pereira V, and Fosso Wamba S (2025). Empowering small farmers for sustainable agriculture: A human resource approach to SDG-driven training and innovation. International Journal of Manpower, 46(4): 652-675. https://doi.org/10.1108/IJM-11-2023-0655

Plana-Farran M, Arzubiaga U, and Blanch A (2023). Successors' future training in family farms: The impact of intrinsic and extrinsic factors. Journal of the Knowledge Economy, 14: 4216-4237. https://doi.org/10.1007/s13132-022-01046-2

Prayitno G, Zuhriyah L, Effendi A, Arifin S, Auliah A, and Subagiyo A (2025). Community-powered environmental pathways to reduce stunting: Food security, social capital, and open innovation in semi-urban Indonesia. Environmental Challenges, 21: 101350. https://doi.org/10.1016/j.envc.2025.101350

Raji E, Ijomah TI, and Eyieyien OG (2024). Improving agricultural practices and productivity through extension services and innovative training programs. International Journal of Applied Research in Social Sciences, 6(7): 1297-1309. https://doi.org/10.51594/ijarss.v6i7.1267

Ruf KAF (2026). Skills or credentials? How skill specific and standardized vocational training moderates the wages of occupational mismatches. Research in Social Stratification and Mobility, 102: 101136. https://doi.org/10.1016/j.rssm.2026.101136

Sahoo D, Mohapatra D, and Behera J (2024). A microeconometrics approach to gendered perspective of empowerment through agricultural decision-making in rural Odisha, India. World Development Sustainability, 4: 100127. https://doi.org/10.1016/j.wds.2024.100127

Sahoo S, Singha C, Govind A, and Moghimi A (2025). Review of climate-resilient agriculture for ensuring food security: Sustainability opportunities and challenges of India. Environmental and Sustainability Indicators, 25: 100544. https://doi.org/10.1016/j.indic.2024.100544

Setiawan Z, Dharmawan D, Ariani D, Ekasari S, and Munizu M (2024). Strengthening marketing strategies in organic agricultural products through organic farmer training in Indonesia. Unram Journal of Community Service, 5(3): 189-194. https://doi.org/10.29303/ujcs.v5i3.696

Shafieisabet N and Mirvahedi N (2025). Empowering farmers for sustainable food security: Insights from rural Iran. The International Journal of Sociology of Agriculture and Food, 31(2): 91-116.

Shi X, Zhou Z, Wang Z, Zhang J, and Wu Y (2026). Stage-specific drivers and bottlenecks in agricultural innovation ecosystems: Evidence from agricultural science and technology professionals' three-stage innovation behavior. Agricultural Systems, 237: 104836. https://doi.org/10.1016/j.agsy.2026.104836

Siaw SY, Man N, Ramli NN, Yusuf MSA, and Abdulmumini U (2024). The contribution of agricultural extension to empowerment of women for agricultural development. Journal of Agricultural Extension, 28(2): 66-84.

Song E, Shao G, Zhu X, Zhang W, Dai Y, and Lu J (2024). Estimation of plant height and biomass of rice using unmanned aerial vehicle. Agronomy, 14(1): 145. https://doi.org/10.3390/agronomy14010145

Sun H (2026). The impact of vocational skills training on earnings: Evidence from China. International Review of Economics & Finance, 107: 105079. https://doi.org/10.1016/j.iref.2026.105079

Tyczewska A, Twardowski T, and Woźniak-Gientka E (2023). Agricultural biotechnology for sustainable food security. Trends in Biotechnology, 41(3): 331-341. https://doi.org/10.1016/j.tibtech.2022.12.013 **PMid:36710131 PMCid:PMC9881846**

Vandenberg J and Krellenberg K (2026). Synergising outdoor, indoor, and greenhouse urban agriculture to strengthen urban resilience in an era of polycrisis. Sustainable Cities and Society, 143: 107382. https://doi.org/10.1016/j.scs.2026.107382

Wereta MS, Ayele ZA, and Damtie YA (2026). Analyzing the synergies and trade-offs of climate-smart agriculture practices on food security and resilience in Guba Lafto Woreda, Ethiopia. Climate Services, 43: 100676. https://doi.org/10.1016/j.cliser.2026.100676

Yang S, Zhang Y, Liao Z, Ren Y, Lu Y, and Qu H (2025). Artificial intelligence and urban employment in China's agricultural sector: Conditions for job creation across skill levels. Journal of Rural Studies, 120: 103845. https://doi.org/10.1016/j.jrurstud.2025.103845

Yusriadi Y, Cahaya A, and Hamzah F (2026). Motivations and challenges in adopting food security strategies: Insights from rural Indonesia. Social Sciences & Humanities Open, 13: 102497. https://doi.org/10.1016/j.ssaho.2026.102497

Zhang H and Yang M (2025). Does farmers' participation in skills training improve their livelihood capital? An empirical study from China. Agriculture, 15(7): 679. https://doi.org/10.3390/agriculture15070679

Zhou F, Sun Z, and Lin Y (2025). Research on the impact mechanism and spillover effects of green finance empowering agricultural carbon emission reduction. International Review of Economics & Finance, 103: 104594. https://doi.org/10.1016/j.iref.2025.104594

Zhou L, Wang Z, Zhang H, Wei G, and Gao Q (2026). Digital skills and knowledge as enablers: Understanding farmers' adoption of agricultural green production technologies. Journal of Innovation & Knowledge, 16: 101074. https://doi.org/10.1016/j.jik.2026.101074