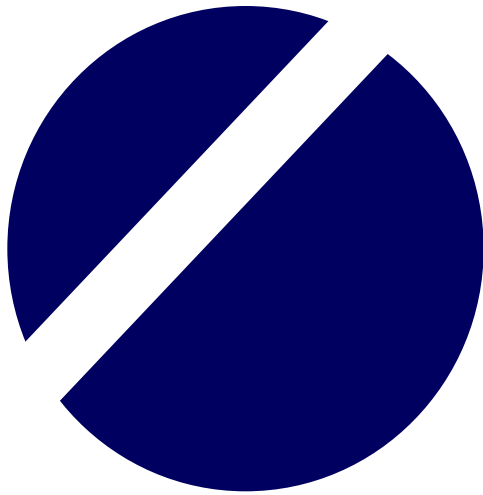


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CLIMATE-SMART AGROFORESTRY IN VIETNAM: A REVIEW OF CURRENT PRACTICES, CHALLENGES, AND OPPORTUNITIES

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ABSTRACT

This paper reviewed the current practices, challenges, and opportunities of Vietnam's climate-smart agroforestry (CSAF). The study aimed to conduct climate-smart agroforestry in Vietnam during 2024 - 2025 through evaluating the resilience to climate change, socio-economic and environmental impacts, identifying the obstacles to its scaling, and providing recommendations for sustainable development. Through a systematic analysis of policy documents, case studies, and stakeholder consultations, the study found that CSAF enhances land-use efficiency, promotes biodiversity conservation, and supports climate change mitigation by increasing carbon sequestration. However, the adoption of CSAF faces significant barriers, including policy fragmentation, limited technical knowledge, and insufficient financial resources. Agroforestry models remained small-scale and subsistence-oriented, with few transitioning to commercial production. The study recommends improving policy alignment between the agriculture and forestry sectors, providing targeted financial support, and enhancing farmer capacity through training and technology transfer. Strengthening market access for agroforestry products and fostering public-private partnerships are also crucial for scaling CSAF in Vietnam. These efforts are essential for achieving Vietnam's climate adaptation and mitigation goals while supporting rural livelihoods and sustainable agricultural development.

Key words: agriculture, forestry, sustainability, policy

INTRODUCTION

Climate change poses profound challenges to agriculture worldwide, affecting food security, rural livelihoods, and ecosystem health (FAO 2021). In Vietnam, where agriculture remains a crucial sector, the impacts of climate change are increasingly evident, including rising temperatures, shifting rainfall patterns, and more frequent extreme weather events (World Bank Group 2019). These challenges threaten both productivity and the sustainability of rural landscapes across the country's diverse agroecological zones.

In response to these challenges, Climate-Smart Agroforestry (CSAF) has emerged as a promising solution. Agroforestry integrates trees, crops, and livestock within agricultural landscapes to increase resilience, enhance carbon sequestration, and support biodiversity (FAO 2013), making agroforestry climate-smart. Globally, agroforestry practices span nearly 1 billion hectares of land and engage millions of farmers, especially in tropical regions (Baral 2022). CSAF is mentioned as a part of Climate-Smart Agriculture (CSA) as “a transformative approach which is built on three interlinked pillars, including (i) increasing agricultural productivity and incomes; (ii) enhancing resilience; and (iii) reducing or removing greenhouse gas emissions” (Palombi and Sessa 2013; Tesema and Mekoya 2025).

Vietnam's long-standing tradition of agroforestry offers a rich foundation for scaling CSAF. With an estimated 77.8% of agricultural land featuring more than 10% tree cover, agroforestry practices have been widely adopted across the country (Baral 2022). These systems range from traditional home gardens and integrated farming systems to more specialized models tailored to specific regions, such as coffee agroforestry in the Central Highlands or mangrove-based systems in coastal areas.

Despite Vietnam's commitment to sustainable development and climate adaptation, as evidenced by its inclusion of agroforestry in its Nationally Determined Contributions (NDCs), the widespread adoption of CSAF remains limited. Barriers include policy fragmentation and being hidden in the Forestry Policy, limited access to technical knowledge, and resource constraints for smallholder farmers (Nguyen et al. 2022). Additionally, the diverse agroecological zones of Vietnam, from the Northern Mountains to the Mekong Delta, present unique challenges and opportunities for CSAF implementation. It is likely that a gap in a comprehensive review of the existing climate-smart agroforestry systems in Vietnam.

This paper aimed to provide a comprehensive review of climate-smart agroforestry (CSAF) in Vietnam, focusing on several critical areas. First, it examined the current status of agroforestry and CSAF practices across Vietnam's key agroecological zones, highlighting both traditional and modern approaches. Second, it reviewed the institutional and policy frameworks that support CSAF development, identifying strengths and gaps in governance. Third, the paper evaluated the socio-economic and environmental impacts of CSAF systems, including their role in improving food security, increasing farmer incomes, enhancing biodiversity, and mitigating climate change. Fourth, it discussed the challenges and opportunities for scaling up CSAF in Vietnam, considering factors such as market access, land-use rights, and climate-related risks. Finally, the paper offered recommendations for enhancing CSAF adoption and effectiveness, focusing on policy reforms, capacity-building, and financial mechanisms to promote sustainable and scalable agroforestry models.

By synthesizing current knowledge, identifying gaps, and proposing targeted recommendations, this review seeks to inform policymakers, researchers, and practitioners on strategies to promote CSAF as a key approach for sustainable agriculture and climate resilience in Vietnam. The findings of this study will contribute to ongoing efforts to align agricultural development with Vietnam's climate commitments and sustainable development goals.

MATERIALS AND METHODS

This study employed a systematic review approach to examine CSAFs in Vietnam, drawing from a combination of peer-reviewed literature, policy documents, and case studies across diverse agroecological zones. The methodology was designed to address the key objectives outlined in the introduction. The study was conducted in Vietnam during 2024 – 2025.

Literature search and selection. A comprehensive literature search was conducted using academic databases including Web of Science, Scopus, and Google Scholar. Key search terms included “climate-smart agriculture”, “agroforestry”, “Vietnam”, “climate change adaptation”, and “sustainable agriculture”. The search was limited to publications from 2014 to 2024 to ensure up-to-date information. Additional grey literature, including government reports and policy documents, was sourced from relevant Vietnamese government websites and international organizations working in Vietnam.

Policy analysis. National and regional policies related to climate-smart agriculture and forestry, were reviewed including Vietnam’s Nationally Determined Contributions (NDCs), the National Strategy on Climate Change, and the Agricultural Development Plan 2021-2030. Emphasis was placed on

understanding how these policies support or limit CSAF models and their scaling potential, particularly for sustainable land use and carbon sequestration.

Case study compilation. To contextualize the application of CSAF, detailed case studies were compiled across different agroecological zones (Mulia and Nguyen 2021). The case studies covered traditional agroforestry practices and their climate-smart adaptations. For example, in the Northern Mountains, focus was on the integration of leguminous trees into maize and cassava systems, and on shade-grown coffee production supported by CSAF initiatives in the Central Highlands.

RESULTS AND DISCUSSION

Current status of agroforestry and climate-smart agroforestry practices in Vietnam. CSAF is recently defined as “an integrated approach to land use that combines trees, crops, and sometimes animals within managed farmlands, offering a sustainable farming system that helps mitigate and adapt to climate change” (Kabato et al. 2025). Therefore, the differences between Climate-Smart Agroforestry (CSAF) and Business-as-usual (BAU) Agroforestry are likely paired by categories involving: purpose and goals; management practices; climate impact; economic & social context; and technology & data use.

In summary, CSAF = Agroforestry redesigned for climate mitigation + adaptation + sustainable productivity, using planned, measurable, climate-smart strategies, while Business-as-usual agroforestry = Traditional agroforestry without explicit climate objectives or systematic planning (Table 1).

Table 1. Differences between Climate-Smart Agroforestry (CSAF) and Business-as-usual (BAU) Agroforestry

Category	Climate-Smart Agroforestry (CSAF)	Business-as-usual (BAU) Agroforestry
Purpose and goals	<ul style="list-style-type: none"> • Designed explicitly to address climate change. • Has three core goals: <ul style="list-style-type: none"> ○ Increase productivity (sustainably) ○ Enhance climate resilience/adaptation ○ Reduce or remove greenhouse gas emissions • Focused on long-term sustainability and climate outcomes 	<ul style="list-style-type: none"> • Traditional or conventional agroforestry practised without a climate-focused strategy. • Main goals are usually livelihood, shade, soil protection, or production, not climate mitigation. <p>Often follows existing local customs or market-driven decisions</p>
Management practices	<p>Uses deliberate, evidence-based design:</p> <ul style="list-style-type: none"> • Improved tree–crop species selection for climate tolerance • Soil carbon management • Water-efficient layouts • Diversification to spread climate risks • Monitoring of carbon, yields, and resilience metrics 	<p>Practices may be inherited, informal, or simplified:</p> <ul style="list-style-type: none"> • Limited species diversity • Minimal climate risk planning • Little or no monitoring of carbon or climate impacts <p>Management may be reactive rather than strategic</p>

Climate impact	Explicitly aims to: <ul style="list-style-type: none"> • Sequester carbon • Reduce emissions (e.g., through nitrogen-fixing trees, reduced fertilizer use) • Improve climate resilience for farmers 	<ul style="list-style-type: none"> • May still sequester carbon and provide ecosystem benefits, but not intentionally or optimally. • Climate impacts are usually not measured or maximized.
Economic and social context	Often part of: <ul style="list-style-type: none"> • Climate finance programs • Certification schemes • Government or NGO climate-adaptation projects • Corporate sustainability supply-chain commitments 	<ul style="list-style-type: none"> • Typically low-investment, small-scale, or traditional. • Less likely to be integrated with climate finance or monitoring systems.
Technology and data use	Frequently uses: <ul style="list-style-type: none"> • Mapping/GIS for planning • Climate models or risk assessments • Digital tools for monitoring trees, soil, and carbon • Traceability systems in supply chains 	<ul style="list-style-type: none"> • Usually low-tech, relying on farmer knowledge and local practice.

Agroforestry is an integral part of Vietnam’s agricultural heritage, practised widely across the country’s diverse agroecological zones. This integration of trees, crops, and livestock has provided Vietnamese farmers with sustainable livelihoods for centuries. Today, agroforestry remains a crucial component of rural development, especially in regions vulnerable to climate change, such as the Northern Mountains, Central Highlands, and the Mekong Delta. In Vietnam, a project named Reduce Emissions through Climate Smart Agroforestry (RECAF) was conducted under the REDD+ framework to guide practical measures to reduce deforestation, promote forest regeneration and agroforestry aimed at increasing forest carbon capture, which is likely a key to Viet Nam’s Climate Change Strategy (FAO 2023).

Northern Mountains: Traditional and modified agroforestry systems. In the Northern Mountains, agroforestry is primarily practised by ethnic minority communities who rely on traditional models like shifting cultivation and mixed tree-crop systems. These systems incorporate native tree species such as *Acacia*, *Eucalyptus*, and fruit-bearing trees like longan and litchi, alongside staple crops like maize and cassava (Mulia and Phuong 2021). These practices not only provide food security but also play a key role in reducing soil erosion and improving water retention in the region’s steep terrains (Mulia and Nguyen 2021).

Recently, CSAF models have been introduced to increase the resilience of these traditional systems. For example, ICRAF and other development partners have piloted projects that integrate leguminous trees with maize and cassava, enhancing soil fertility and sequestering carbon (Simelton et al. 2019). In addition, the planting of fast-growing species like *Acacia* helps generate quick economic returns while also providing biomass for energy. These modified systems, which apply diverse potential forest trees, demonstrate how CSAF can enhance productivity and environmental resilience in the Northern Mountains while diversifying income sources for farmers (Baral 2022).

Central Highlands: Agroforestry for coffee and pepper production. The Central Highlands, known for its coffee and black pepper production, is a region where agroforestry plays a vital role in both economic development and environmental protection. Traditional agroforestry systems here typically integrate shade trees with coffee plantations, offering both ecological and economic benefits (Ntawuruhunga et al. 2023). Trees like *Canarium* and *Albizia* provide shade, improve microclimates, and enhance soil health, reducing the need for chemical inputs.

In recent years, CSAF models have been promoted to further improve the sustainability of coffee and black pepper production. These models include the integration of nitrogen-fixing trees, which enhance soil fertility and reduce the reliance on synthetic fertilizers. In some areas, farmers are also adopting multi-strata agroforestry systems with multiple vertical layers of vegetation, similar to a natural forest, where trees of different heights are intercropped with coffee, providing various ecosystem services such as carbon sequestration and new habitats for biodiversity (Nguyen et al. 2022). These practices are gaining attention due to their potential to mitigate the effects of climate change, particularly in regions prone to droughts and irregular rainfall (Mulia and Nguyen 2021).

Mekong Delta: Agroforestry for climate resilience in flood-prone areas. In the Mekong Delta, agroforestry systems have long been adapted to the region's unique hydrological conditions. Farmers here traditionally practice integrated farming systems that combine fish farming, rice cultivation, and tree planting, known as '*Vuon-Ao-Chuong*' (VAC) or garden-pond-livestock systems. This model allows for the sustainable management of floodplains by diversifying production and reducing risks associated with climate variability (Tran and Tran 2024b).

With rising sea levels and increased flooding due to climate change, CSAF models are being piloted to enhance the resilience of these integrated systems. For example, flood-tolerant trees such as *Melaleuca* are being introduced in combination with rice and aquaculture to create buffer zones that protect farmlands from flooding while providing additional income sources through timber and honey production (Nguyen et al. 2022). These CSAF approaches are proving valuable in flood-prone areas, where the risks from climate change are especially acute.

Central Coast: Agroforestry for coastal protection and livelihood diversification. In Vietnam's central coastal regions, where sandy soils and saltwater intrusion present significant challenges, agroforestry has been adopted as a strategy for coastal protection and livelihood diversification. Farmers in these areas traditionally integrate cashew, coconut, and fruit trees with crops like peanuts and sweet potatoes. These systems help stabilize sandy soils and prevent desertification (Mulia and Phuong 2021).

CSAF models in the region focus on planting salt-tolerant tree species, such as *Casuarina* and *Rhizophora*, which serve both economic and ecological purposes. These trees not only provide timber and non-timber forest products but also protect coastal areas from storm surges and soil degradation (Octavia et al. 2022). Additionally, farmers are experimenting with silvofishery systems, where trees are planted along the edges of shrimp or fish ponds to provide shade, improve water quality, and enhance biodiversity (Baral 2022).

Red River Delta: Urban and peri-urban agroforestry. In the Red River Delta, where urbanization is rapidly expanding, agroforestry is being promoted as part of peri-urban farming systems. Traditional home garden systems, or *vuòn nhà*, have long been practised in this densely populated region, integrating fruit trees, vegetables, and small livestock in compact spaces (Nguyen et al. 2022).

CSAF initiatives here focus on enhancing the ecological functions of these systems by introducing more diverse tree species and promoting organic farming practices. These urban agroforestry systems contribute to food security, improve air and water quality, and provide green

spaces that mitigate the urban heat island effect (Simelton et al. 2019). Additionally, they offer an opportunity for cities like Hanoi to develop sustainable urban agriculture models that can be replicated in other densely populated areas.

Institutions and policies supporting agroforestry development

Policy document system related to climate-smart agroforestry. Several national policies and legal frameworks have been established to support agroforestry, although there are no specific standalone policies exclusively dedicated to it (Hoang et al. 2018). Instead, agroforestry is often embedded within broader agricultural, forestry, and environmental policies. Resolution No. 26 (Vietnam Gov. 2008) was one of the foundational documents that provided strategic directions for rural development, emphasizing the integration of sustainable practices like agroforestry. This resolution promoted innovations in CSAF, improved land use, and increased investments in rural infrastructure and farmer training. Decision No. 1895 (Vietnam Gov. 2012) focused on developing high-tech agriculture, including the application of advanced technologies to improve productivity and promote CSAF.

In 2016, two key decrees were issued: Decree No. 119 (Vietnam Gov. 2016a), which provided specific policies for managing coastal forests in response to climate change, supporting agroforestry in these sensitive areas; and Decree No. 168 (Vietnam Gov. 2016b), which regulated the assignment of forest and water surface areas to ensure sustainable resource management in state-owned agricultural and forestry companies, which directly benefits CSAF.

The Forestry Law (Vietnam Assembly 2017) is a cornerstone for agroforestry development, as it outlines clear regulations on forest management, encouraging the integration of crops and trees in CSAF models. Additionally, Decision No. 419 (Vietnam Gov. 2017) approved the national program to reduce greenhouse gas emissions through sustainable forest management, reinforcing CSAF's role in carbon sequestration and forest conservation efforts.

Policies regarding payment for forest environmental services (PFES), established under Decree No. 156 (Vietnam Gov. 2018b), created financial mechanisms that incentivize CSAF models by providing funds for forest protection and development. The 2020 Environmental Protection Law also ensures that agroforestry models align with sustainable environmental standards, requiring efficient resource use and minimal environmental harm.

Circular No. 02/2020 (MARD 2020) sets criteria for recognizing agroforestry farms based on production scale and product value, facilitating state support for qualifying CSAF models. Moreover, the Sustainable Agricultural Development Strategy outlined in Decision No. 150/2022 (Vietnam Gov. 2022a) emphasizes sustainable agricultural practices, including CSAF, as key to optimizing resource use and protecting the environment.

Overall, these legal frameworks provide essential support for developing CSAF models in Vietnam by encouraging sustainable practices, offering financial incentives, and ensuring alignment with environmental and rural development policies. The impacts of related policies on climate-smart agroforestry in Vietnam are summarized in Table 2.

Table 2 shows that the policy landscape supporting climate-smart agroforestry (CSAF) in Vietnam has evolved significantly over the past two decades. Key policy documents have laid the groundwork for CSAF development, beginning with Resolution No. 26/2008/NQ-TW (Vietnam Gov. 2008), which emphasized agricultural innovation and rural infrastructure investment. Subsequent policies, such as Decree No. 119/2016/ND-CP (Vietnam Gov. 2016a) and the 2017 Forestry Law (Vietnam Assembly 2017), established frameworks for sustainable forest management and integrated land use practices. The national program for reducing greenhouse gas emissions (Vietnam Gov. 2017)

aligned closely with CSAF objectives, providing financial support for such models. The 2020 Environmental Protection Law (Ministry of Natural Resources and Environment 2020) ensured that agricultural practices, including CSAF, prioritize resource efficiency and environmental protection. Recent policies, including the new Land Law (Vietnam Assembly 2024), further promote sustainable agricultural production and provide flexible land-use regulations conducive to CSAF implementation. These policies collectively create a supportive environment for CSAF, addressing various aspects from land use and forest management to climate change mitigation and sustainable agricultural development. However, while this policy framework is comprehensive, the effectiveness of implementation and the need for more specific CSAF-focused policies remain areas for further consideration in Vietnam's pursuit of sustainable and climate-resilient agriculture. The gap is likely an issue that needs to be dealt with in the future (e.g. improving tree–crop species selection for climate tolerance; soil carbon management; water-efficient layouts; diversification to spread climate risks; monitoring of carbon, yields, and resilience metrics; and using digital tools for monitoring trees, soil, and carbon).

Table 2. Direct and indirect impacts of policies on the development of CSAF

Document Title	Direct and Indirect Impacts on Climate-smart Agroforestry
Resolution No. 26/2008/NQ-TW dated August 5, 2008, on Agriculture, Farmers, and Rural Areas by the Central Executive Committee of the Communist Party (Vietnam Gov. 2008)	<ul style="list-style-type: none"> • Supports the innovation and development of climate-smart agroforestry models. • Improves the efficiency of land and resource use. • Invests in rural infrastructure, supporting agroforestry models. • Provides training and support for farmers to adopt new models.
Decree No. 119/2016/ND-CP dated August 23, 2016, by the Government on Regulations for Policies on the Management, Protection, and Sustainable Development of Coastal Forests in Response to Climate Change (Vietnam Gov. 2016a)	<ul style="list-style-type: none"> • Provides policies for the protection and sustainable development of coastal forests, supporting the integration of forests and agriculture in climate-smart models. • Encourages the use of agroforestry models to enhance resilience and adaptation to climate change, such as soil protection and erosion reduction. • Issues regulations on the management of coastal forest resources, helping maintain and improve soil and water quality in agroforestry models. • Provides support mechanisms and encourages research and the application of new technologies in coastal forest management and the development of climate-smart agroforestry models.
Decree No. 168/2016/ND-CP dated December 27, 2016, by the Government on Regulations for the Assignment of Forests, Gardens, and Water Surface Areas in Special-use and Protective Forest Management Boards, and State-owned Agricultural and Forestry Companies (Vietnam Gov. 2016b)	<ul style="list-style-type: none"> • Assignment of forests and water surface areas helps ensure sustainable resource management. • Facilitates investment in new technologies and techniques. • Clarifies management responsibilities, enhancing the efficiency of models. • Provides financial and technical support mechanisms. • Supports the testing and optimization of climate-smart agroforestry models.

Document Title	Direct and Indirect Impacts on Climate-smart Agroforestry
Law No. 16/2017/QH14 Forestry Law issued by the National Assembly on November 15, 2017 (Vietnam Assembly 2017)	<ul style="list-style-type: none">• Clearly regulates forest protection and development, enabling the integration of forest trees into climate-smart agroforestry models.• Supports models combining crops and forest trees, improving the efficiency of land and resource use.• Promotes sustainable forest resource management, helping agroforestry models maintain sustainability and enhance environmental protection.• Provides legal and policy frameworks to support research, application, and scaling up of climate-smart agroforestry models.
Decision No. 419/2017/QĐ-TTg by the Prime Minister on the Approving the national program on reduction of greenhouse gas emissions through the mitigation of deforestation and forest degradation; conservation and enhancement of forest carbon stocks and sustainable management of forest resources through 2030 (Vietnam Gov. 2017)	<ul style="list-style-type: none">• Strengthens forest conservation and sustainable management, improving soil quality and increasing carbon stock.• Agroforestry models contribute to enhancing carbon stock in soil and vegetation.• Implements pilot models to assess the effectiveness of agroforestry models.• Provides training and raises awareness on sustainable forest resource management.• Offers policies and financial support for the application of agroforestry models.• Encourages cross-sector cooperation to achieve conservation and sustainable development goals.
Decree No. 83/2018/ND-CP by the Government on Agricultural Extension (Vietnam Gov. 2018a)	<ul style="list-style-type: none">• Encourages the application of new technology and innovation in agriculture, supporting the development of climate-smart agroforestry models.• Provides training and technical guidance on climate-smart agroforestry for farmers.• Provides financial support and materials for agroforestry models, including equipment and necessary resources.• Encourages the testing and research of climate-smart agroforestry models through pilot projects.• Promotes cooperation between government agencies, NGOs, and businesses to develop climate-smart agroforestry models.
Decree No. 156/2018/ND-CP by the Government dated November 16, 2018, on the Mechanism for Payment for Forest Environmental Services (Vietnam Gov. 2018b)	<ul style="list-style-type: none">• Payments for forest environmental services provide financial resources for forest protection and development activities. Climate-smart agroforestry models can utilize these financial resources to invest in sustainable forest and agricultural management methods, promoting sustainable development and improving production efficiency.
Law No. 72/2020/QH14 dated November 17, 2020, Environmental Protection Law 2020 issued by the National Assembly (Vietnam Assembly 2020)	<ul style="list-style-type: none">• Ensures that models use resources efficiently and do not harm the environment.• Encourages the application of advanced technology to optimize resource use and reduce pollution.• Requires effective waste management, including recycling in agroforestry.

Document Title	Direct and Indirect Impacts on Climate-smart Agroforestry
Decision No. 150/QĐ-TTg dated January 28, 2022, by the Prime Minister on the Approval of the Sustainable Agricultural and Rural Development Strategy for the Period 2021-2030, Vision to 2050 (Vietnam Gov. 2022a)	<ul style="list-style-type: none">• Conducts environmental impact assessments for major projects to ensure compliance with environmental protection standards.• Designs models to withstand climate change and promote sustainable development.• Promotes education and awareness on environmental protection.• Emphasizes the development of sustainable agriculture, including the application of agroforestry models to optimize resource use and protect the environment.• Provides policies and support mechanisms to encourage investment in sustainable agricultural models, including agroforestry. This may include financial, technical, and training policies to help farmers and businesses implement these models.• Outlines climate change adaptation measures, in which agroforestry models can play a key role. The models help improve the resilience of agricultural systems to harsh climatic conditions and enhance carbon sequestration.
Resolution No. 19-NQ/TW dated June 16, 2022, of the Central Executive Committee on Agriculture, Farmers, and Rural Areas until 2030, Vision to 2045 (Vietnam Gov. 2022b)	<ul style="list-style-type: none">• Sets goals to promote the transition to sustainable agricultural production models, with agroforestry being a key solution to improve production efficiency and protect the environment.• Emphasizes the application of advanced technology and innovation in agricultural production. Climate-smart agroforestry models often incorporate new technology to optimize production and enhance resilience to climate change.• Aims to improve the lives and incomes of farmers, including supporting agroforestry models to create stable and sustainable income sources for rural communities.• Sets policies and mechanisms to support agricultural development, including agroforestry models, to promote sustainable development and address current challenges.
Circular No. 12/2022/TT-BNNPTNT dated September 20, 2022, by the Ministry of Agriculture and Rural Development providing guidance on certain forestry activities under the Sustainable Forestry Development Program and the National Target Program for Socio-economic Development in Ethnic Minority and Mountainous Areas for the Period 2021-2030, Phase I from 2021 to 2025 (MARD 2022)	<ul style="list-style-type: none">• Provides detailed guidance on forestry activities under the Sustainable Forestry Development Program, including policies and measures to support forestry development in ethnic minority and mountainous areas. These activities may include the application of agroforestry models to improve livelihoods and protect the environment.• Links forestry activities with sustainable development goals, where agroforestry models are encouraged as they help maintain ecological balance, protect forest resources, and enhance rural livelihoods.• Supports the implementation of the National Target Program for socio-economic development in ethnic minority and mountainous areas, where agroforestry models can contribute to raising incomes and improving living conditions in these areas.

Document Title	Direct and Indirect Impacts on Climate-smart Agroforestry
Law No. 31/2024/QH15 dated January 18, 2024, Land Law issued by the National Assembly (Vietnam Assembly 2024)	<ul style="list-style-type: none">• Helps coordinate policies and resources from forestry and socio-economic development programs, creating conditions for the implementation of agroforestry.• Facilitates the application of climate-smart agroforestry models by providing flexible land-use regulations, allowing the integration of multiple types of crops and livestock on the same piece of land. This supports the implementation of agroforestry models, optimizing land resource use.• Can include areas designated for agroforestry models into land use planning, making it easier to implement these models, particularly by combining agricultural and forestry cultivation.• Provides incentives and support mechanisms for developing sustainable production models, including climate-smart agroforestry models. Supportive policies, such as tax incentives, financial assistance, and training, can help farmers adopt and sustain these models.• Regulates the management and protection of land resources, ensuring that agroforestry models are implemented within the legal framework while also contributing to environmental protection and maintaining ecosystem sustainability.

Institutions and stakeholders promoting the development of CSAF. Numerous public sector institutions and stakeholders play important roles in promoting climate-smart agroforestry models in Vietnam, notably: (1) The Government of Vietnam: The highest authority in managing and directing policies and programs related to agroforestry; and The Ministry of Agriculture and Rural Development (MARD) is the primary agency responsible for managing agriculture, forestry, and rural development, including agroforestry activities; (2) The General Department of Forestry: Under MARD, it manages forest-related activities, including programs and policies on agroforestry; (3) The General Department of Irrigation: Also under MARD, it supports agricultural activities related to irrigation and water resource management, affecting agroforestry models; (4) The Vietnam Academy of Forest Science and related units: Plays a role in researching and developing agroforestry models, and providing policy recommendations and technical solutions; (5) The National Agricultural Extension Center and Provincial Agricultural Extension Centers: They transfer technology and guide farmers and cooperatives in applying agroforestry models; (6) The Vietnam Academy of Agricultural Sciences (VAAS): Participates in researching and developing agricultural solutions, including agroforestry; and (7) Universities offering agricultural education: These institutions contribute to the conduct scientific research and training and extension to promote high-quality human resources for the development of climate-smart agroforestry models.

In addition to the public agencies mentioned above, private domestic and international organizations support the development of climate-smart agroforestry in Vietnam. Notably, agroforestry systems have been implemented through projects from ICRAF Vietnam, including the Agroforestry for Smallholder Livelihoods in Northwest Vietnam (AFLi) Project (2011–2021) funded by the Australian Centre for International Agricultural Research; Research on Fruit-based Agroforestry Practices in Northwest Vietnam (2020) self-funded by ICRAF; Research on the Contribution of Agroforestry to Vietnam’s Nationally Determined Contributions (NDC) (2017-2020) co-funded by the CGIAR Research Program on Climate Change, Agriculture, and Food Security (CCAFS) and ICRAF; and the Climate-Smart Agriculture Practices in North Central Vietnam Project (2015–2018) funded by CCAFS.

The AFLi project introduced several agroforestry models in the Northwest region, including simple models with 2-3 crops and more integrated models with more than three components.

The research on fruit-based agroforestry in the Northwest identified nine agroforestry practices, providing information on annual income and estimated carbon sequestration to demonstrate the potential for climate change mitigation. The study on the role of agroforestry in Vietnam's NDCs compiled information on agroforestry practices in several provinces based on data from local partners. The Climate-Smart Agriculture Practices Project disseminated information about three agroforestry practices with scalability in suitable regions.

Additionally, cooperatives, businesses, farms, and individual farmers are the actual implementers of agroforestry models, under the guidance and support of management and research agencies. These groups need to be made aware of the roles of climate-smart agroforestry models to leverage individual and local potential and promote the development of these models.

Institutions and policies on the development of CSAF. Vietnam is increasingly aware of the benefits of agroforestry. The country's institutions and policies play an important role in promoting the development of climate-smart agroforestry models. Agroforestry has been included in Vietnam's 2020 Nationally Determined Contributions (NDC) as a key measure for soil conservation, maintaining food production, and carbon sequestration in response to climate change. The online database on agroforestry (SCAF) reported that Vietnam's total agroforestry cultivation area reached about 900,000 hectares during the 2013-2014 period (Nguyen et al. 2022).

Agroforestry models in Vietnam have developed rapidly and are highly diverse (Pham 2015). Statistics show 13 main agroforestry models, namely: (1) traditional home gardens, (2) the garden-pond-livestock (VAC) system, (3) the garden-pond-forest-livestock (VACR) system, (4) mangrove forest and aquaculture systems, (5) *Melaleuca* forest systems integrated with agriculture and aquaculture, (6) forest systems combined with upland fields and gardens, with or without livestock, (7) intercropping agricultural crops in regenerating forests, (8) intercropping perennial crops with planted forests, (9) intercropping annual crops with planted forests, (10) livestock grazing under forest canopies or in regenerating forests, (11) growing fodder crops within forests, (12) intercropping annual crops in fruit orchards or perennial plantations, and (13) mixed cropping systems with support trees, shade trees, or multipurpose trees.

Additionally, the International Centre for Research in Agroforestry (ICRAF) notes that Vietnam's agroforestry models have evolved into smart farming models through strategies that combine livelihood diversification and environmental protection. According to this organization, Vietnam's agroforestry models can be grouped into: (1) wood-based agroforestry systems, (2) perennial crop-based agroforestry systems, (3) fruit tree-based agroforestry systems, and (4) agroforestry systems in mangrove forests (Nguyen et al. 2022).

Regardless of how they are classified, previous studies (Muchane et al. 2020; Nguyen et al. 2022; Pham 2015) have emphasized the roles of climate-smart agroforestry systems in terms of economic, social, and environmental aspects.

Economic impacts: Agroforestry improves livelihoods, diversifies products, reduces production costs by lowering input material use, and facilitates quicker capital turnover, thereby increasing and stabilizing farmers' income (Muchane et al. 2020; Nguyen et al. 2022).

Social impacts: A recent study highlighted the importance of improving food security and nutrition for the population, as well as empowering women in economic and family development

activities. According to the research restoring degraded land through agroforestry could enhance food security for 1.3 billion people (Muchane et al. 2020).

Ecological and environmental impacts: Agroforestry contributes to reducing water and chemical inputs through the efficient use of resources. It has a high potential to sequester significant amounts of carbon in soil and vegetation, helping mitigate emissions and absorb greenhouse gases while playing an important role in forest landscapes. Agroforestry also effectively reduces soil erosion and sedimentation when trees are planted along contour lines and strips (Nguyen et al. 2022). It can reduce soil erosion by up to 50% and increase soil carbon content by 21%. Furthermore, agroforestry helps increase biodiversity, conserve forests, and enhance ecosystem services.

The role of agroforestry in addressing climate change is clear (e.g. Agroforestry plays a crucial role in mitigating and adapting to climate change through carbon storage, increasing adaptive capacity, reducing vulnerability, and reducing climate risk (Quandt et al. 2023)). As it is included in national climate change strategies and commitments. Among the Nationally Determined Contributions (NDCs) of 147 countries, about 40% propose agroforestry as a solution, with the highest mention in Africa, where 71% of the countries include it.

Globally, CSAF is likely considered an approach of the REDD⁺ framework (e.g. Reduce Emissions through Climate Smart Agroforestry (RECAF) project addressed in Vietnam (FAO 2023). Of the 73 countries with National REDD⁺ Strategies, about 50% identify agroforestry as a measure to reduce forest degradation (Muchane et al. 2020; Nguyen et al. 2022; Pham 2015; Pham et al. 2020). In conclusion, agroforestry models can contribute to multiple Sustainable Development Goals (SDGs), including (i) No Poverty, (ii) Zero Hunger, (iii) Good Health and Well-being, (iv) Gender Equality, (v) Clean Water and Sanitation, (vi) Affordable and Clean Energy, (vii) Climate Action, and (viii) Life on Land (Octavia et al. 2022).

Despite the clear benefits of agroforestry and CSAF, their adoption at scale in Vietnam faces several challenges. Policy gaps, limited access to financial and technical support, and the high initial investment costs required for transitioning to agroforestry systems are significant barriers. Many farmers lack the resources or knowledge to implement CSAF practices, and there is often a preference for monoculture systems that promise quicker economic returns (Simelton et al. 2019).

However, the potential for scaling up CSAF in Vietnam is immense. With growing government support, international collaboration, and a clear recognition of the need for sustainable agriculture, there are opportunities to expand agroforestry practices across the country. The integration of agroforestry into national policies on climate change adaptation and rural development, along with incentives for ecosystem services, can help overcome these barriers (Ministry of Natural Resources and Environment 2020).

Strengths and opportunities. CSAF is redesigned much better than the traditional ones because of its larger scale, which is appropriate for climate mitigation, adaptation, and sustainable productivity, using planned, measurable, climate-smart strategies. The very nature of agroforestry systems in different ecological systems, plus the Government's appointment of 'Net Zero Carbon by 2045' is an opportunity to apply CSAF in Vietnam. CSAF offer numerous advantages over traditional agricultural models, providing mitigation and adaptation to climate change, economic, ecological, and social benefits. These systems enhance crop yields, diversify agricultural products, and contribute to poverty reduction in rural areas by increasing the production of valuable goods such as wood, fruits, and agricultural products for consumption and trade (Nguyen et al. 2021). In Vietnam, agroforestry plays a significant role in food security by restoring soil fertility and supporting the cultivation of drought-tolerant species, which helps provide essential food products such as fruits and edible oils (Do et al. 2020). Furthermore,

agroforestry reduces deforestation and mitigates climate change by increasing carbon sequestration (Mulia and Phuong 2021).

CSAF contributes to food security by producing a wide range of nutritious food products on the same land, often requiring minimal inputs. For example, the VAC system has been widely adopted in rural Vietnam, integrating livestock, crops, and aquaculture into a small area. This system enhances food production and supports household livelihoods while promoting sustainable land use practices (Tran and Tran 2024b). Agroforestry systems also align with national strategies for sustainable development in mountainous and rural regions by utilizing land efficiently and reducing reliance on chemical inputs (Hoang et al. 2018).

From an ecological perspective, agroforestry systems help conserve ecosystems and improve soil health. Well-managed systems reduce soil erosion, enhance water retention, and limit surface runoff, which are essential for maintaining soil fertility in regions prone to land degradation. By promoting nutrient cycling, agroforestry increases nutrient-use efficiency, reducing the demand for chemical fertilizers and mitigating groundwater contamination. Agroforestry also regulates stream flows, mitigates the risks of flash floods and landslides, and improves resilience to droughts (Nguyen et al. 2022).

In terms of biodiversity conservation, agroforestry reduces the pressure on natural forests by providing alternative sources of forest products such as timber and fuelwood, lessening the need for deforestation. Integrating trees into farming systems increases biodiversity at both the farm and landscape levels and helps maintain critical ecosystem services such as water regulation and carbon sequestration (Pham et al. 2020). Agroforestry plays a vital role in protecting buffer zones around nature reserves and promoting biodiversity conservation (Mulia and Phuong 2021). In mountainous regions of Vietnam, agroforestry has proven effective in reducing human pressure on natural forests and supporting forest regeneration (Do et al. 2020).

Finally, agroforestry contributes to climate change mitigation by sequestering carbon through tree planting and maintaining soil carbon levels. These systems enhance the capacity for carbon storage in both trees and soil, reducing atmospheric CO₂ levels and mitigating greenhouse gas emissions (Nguyen et al. 2021). Agroforestry also helps reduce deforestation, which plays a key role in Vietnam's efforts to combat climate change (Pham et al. 2020).

Institutional and policy mechanisms are essential for promoting agroforestry development in Vietnam. The 2017 Forestry Law provides a robust legal foundation for agroforestry by regulating land use and forest planting. Articles 57 and 60 of the law specifically address agroforestry in protective forests, supporting household and business participation in agroforestry systems (Vietnam Assembly 2017). These legal frameworks are critical in scaling up climate-smart agroforestry models across the country (Nguyen et al. 2022).

Circular No. 02/2020/TT-BNNPTNT (MARD 2020) defines the scale and legality of agroforestry models in Vietnam, recognizing those that meet specific size and product value criteria as farms. This recognition opens up access to financial support, technical assistance, and extension programs, promoting sustainable development. Recognized agroforestry farms can also benefit from state preferential policies, fostering growth and productivity.

Agroforestry is a key component of Vietnam's REDD+ strategy, as outlined in the National REDD+ Strategy until 2030 (Vietnam Gov. 2017b). This strategy prioritizes sustainable solutions like agroforestry to restore forests and improve local livelihoods. Extension and technology transfer policies have brought advanced practices from research institutions to farmers, enhancing productivity and environmental protection.

In Vietnam, agroforestry is mentioned or hidden in the policies on forest protection, reforestation, and sustainable resource, therefore these policies use promote agroforestry by reducing soil erosion, protecting biodiversity, and enhancing climate resilience. Water management policies also support agroforestry by encouraging efficient water use.

- CSAF models optimize land use, increase productivity, and boost household incomes. These models are particularly beneficial for ethnic minorities and poor households, contributing to poverty reduction. National climate change policies further encourage climate-smart agroforestry as a solution for land protection, biodiversity conservation, and greenhouse gas reduction.
- International cooperation and open-door policies have allowed Vietnam to access advanced technologies, experience, and funding, fostering the development of climate-smart agroforestry models. Investment incentives have attracted domestic and foreign businesses to participate in this growth.
- Training and decentralization policies have empowered local authorities, allowing flexibility in agroforestry model development to meet local needs.

Weaknesses and challenges. Alongside the proven advantages and opportunities, agroforestry models in Vietnam still face several challenges and risks. Many farmers lack concrete business strategies due to limited knowledge of production techniques and insufficient information on market demand forecasting for agroforestry products (Do et al. 2020). As a result, agroforestry products are often sold at 20-30% lower than the market price, leading to reduced profitability (Nguyen et al. 2021). Furthermore, farmers encounter difficulties related to land-use rights, as land allocation by local authorities is slow due to budget constraints and complex administrative procedures (Mulia and Phuong 2021). Extreme weather events caused by climate change, such as hailstorms, frost, dry season water shortages, and pest infestations, also heavily impact agroforestry in Vietnam, further complicating its sustainability (Nguyen et al. 2022).

The fragmented and small-scale nature of agroforestry production presents another challenge, as very few models have transitioned towards commercial-scale production (Do et al. 2020; Pham and Nguyen 2022; Tran and Tran 2024a). In some cases, the diversity of crops and livestock within agroforestry systems reflects a subsistence-level production system, limiting opportunities for market expansion. Additionally, many farmers lack access to modern technology and information on successful agroforestry practices, leading to inefficiencies in production (Hoang et al. 2018). Competition between industrial crops, annual crops, perennial crops, and livestock also threatens ecosystem diversity within agroforestry models (Nguyen et al. 2021).

Despite the existence of a legal framework supporting agroforestry, several challenges remain:

- Agroforestry is an interdisciplinary activity involving agriculture, forestry, livestock, and fisheries, yet comprehensive policies covering these fields are lacking. Agroforestry is primarily addressed in forestry-related policy documents, and there is a policy gap in promoting climate-smart agroforestry practices in agriculture (Do et al. 2020).
- Additionally, policies like Circular No. 02/2020/TT-BNNPTNT set criteria for farm recognition based on production scale and value but fail to reflect the unique benefits of climate-smart agroforestry, such as biodiversity conservation and ecosystem services. These economic criteria often overlook the non-economic benefits of agroforestry, reducing its appeal to potential investors (Hoang et al. 2018). The criteria are also unsuitable for small-scale and diverse production models, particularly in difficult rural areas, preventing many from qualifying for state support and incentives (Nguyen et al. 2021).

- As highlighted agroforestry models lack insurance mechanisms to protect against risks (Hoang et al. 2018). The flexible application of scientific and technological advancements in specific contexts is necessary to improve household capacity. Moreover, the lack of access to loan capital remains a significant barrier to advancing agroforestry development in Vietnam.

RECOMMENDATIONS

To fully realize the potential of CSAF in Vietnam, a multi-faceted approach is needed. First, policies must be refined to address the specific challenges facing smallholder farmers, particularly those related to land tenure, financial access, and technical knowledge. The government should introduce more targeted support through subsidies, low-interest loans, and grants for CSAF systems, ensuring that financial mechanisms are accessible to all farmers, especially those in remote areas. Expanding credit facilities, as well as developing insurance schemes to mitigate the risks from extreme weather events, are also crucial.

Second, coordination between the agricultural and forestry sectors should be strengthened. Given the interdisciplinary nature of agroforestry, new policies should promote integrated models that combine crops, livestock, and forestry within the same legal framework. A comprehensive strategy that links sustainable agriculture, forest management, and water resource conservation will provide a clearer direction for CSAF expansion.

Capacity-building programs are essential for farmers and local officials, providing them with the knowledge and skills needed to implement modern CSAF practices. Collaborations among research institutions, universities, and extension services can play a key role in disseminating technological innovations and successful CSAF examples. Such initiatives will help farmers optimize land use, diversify their production, and increase their resilience to climate change.

Finally, market access for CSAF products must be improved. This can be achieved by strengthening value chains, establishing cooperatives, and fostering partnerships with private companies. Encouraging investments from both domestic and international businesses, particularly in agroforestry-related value-added processing, will further enhance the profitability and sustainability of these systems.

CONCLUSIONS

This study underscores the critical role of agroforestry as a climate-smart cultivation system and helps in enhancing agricultural resilience, promoting environmental sustainability, and supporting rural livelihoods in Vietnam. CSAF systems, which integrate trees, crops, and livestock, offer multiple benefits, including improved land-use efficiency, carbon sequestration, and biodiversity conservation. These systems have been particularly effective in addressing soil erosion, enhancing water retention, and diversifying income sources for smallholder farmers.

However, the widespread adoption of CSAF remains constrained by several challenges. These include fragmented policy frameworks, limited technical support, insufficient financial resources, and small-scale production systems. Farmers often struggle with market access and face barriers to scaling agroforestry models to commercial levels. The impacts of climate change, such as extreme weather events, further complicate the sustainability of these models.

To overcome these challenges, it is essential to align policies across the agricultural and forestry sectors, provide targeted financial incentives, and improve farmers' access to technology and training. Strengthening value chains and enhancing market access for agroforestry products will also be crucial. By addressing these issues, Vietnam can fully leverage the potential of CSAF to meet its

climate adaptation and mitigation goals while promoting sustainable agricultural development and improving rural livelihoods.

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SHORT-TERM COLD STORAGE REGULATES NITROGEN METABOLISM AND SAFETY IN ICEBERG LETTUCE (cv. TURNOVER)

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ABSTRACT

Understanding postharvest metabolic regulation during short-term cold storage is essential for maintaining the quality and chemical safety of leafy vegetables in regional supply chains. This study investigated physiological and metabolic responses of iceberg lettuce (*Lactuca sativa* L. cv. Turnover) during a three-day postharvest period at Laboratory of Tropical Horticultural Sciences, Tokyo University of Agriculture in July 2025. Freshly harvested iceberg lettuce was stored at 5°C for 72 hours. Changes in nitrate (NO₃⁻), nitrite (NO₂⁻), ammonium (NH₄⁺), nitrate reductase (NR), and nitrite reductase (NiR) activities, vitamin C, γ -aminobutyric acid (GABA), putrescine, and organic acids were monitored, and integrated using principal component analysis (PCA). Despite declining NR and NiR activities, NO₃⁻ and NO₂⁻ contents decreased steadily, indicating sustained internal nitrogen assimilation and improved food safety. PCA revealed a distinct metabolic transition on day 2, characterized by transient NH₄⁺ accumulation, association with GABA and putrescine, and selective modulation of malic and citric acids, while succinic and fumaric acids remained relatively stable, indicating preservation of the core tricarboxylic acid (TCA) cycle. Vitamin C declined during this stress-responsive phase and partially stabilized as NH₄⁺ levels decreased. Overall, short-term cold storage at 5 °C induces coordinated metabolic reprogramming rather than deterioration, promoting controlled nitrogen turnover and chemical safety of iceberg lettuce during early storage.

Key words: ammonium, GABA, lettuce, nitrate, postharvest quality.

INTRODUCTION

Iceberg lettuce (*Lactuca sativa* L. var. *capitata*) is a significant leafy vegetable in Japan, with Nagano Prefecture being the foremost production area, accounting for about 33% of the overall domestic output (MAFF 2024). Within this area, the Kawakami highland, situated at heights between roughly 1,100 and 1,500 meters above sea level, is officially identified as the top center for lettuce farming during summer and autumn due to its cool temperatures and suitable alpine conditions for cultivation (JMA 2025; MAFF 2024; Nagano Prefectural Government 2024). These elevated regions are commonly recognized for producing lettuce known for its exceptional texture and high nutritional value; however, these benefits may not always be preserved during post-harvest processes and distribution.

In Japan, iceberg lettuce sourced from elevated areas is generally delivered through a "highland-to-metropolitan" distribution system, which entails refrigerated transportation over considerable distances to major urban markets. Throughout this procedure, lettuce experiences mechanical harvesting impacts, quick cooling, and prolonged exposure to cool temperatures, all of which can disrupt cellular balance and trigger oxidative stress. Thus, ensuring biochemical stability during the initial stages of post-harvest logistics presents a notable challenge (Gross et al. 2016). This logistic model closely resembles those in Southeast Asia, where vegetables cultivated in highland zones – such as Dalat in Vietnam and the Cameron Highlands in Malaysia – are transported under refrigeration to lowland city markets, highlighting the importance of enhancing cold-chain management practices regionally (Altaki and Launio 2025).

In the context of quality and safety issues associated with leafy vegetables, effectively managing inorganic nitrogen components is vital. While the accumulation of nitrate (NO_3^-) is closely monitored due to its possible health hazards, it should be noted that NO_3^- does not remain chemically inactive after being harvested. Instead, it can be enzymatically converted into nitrite (NO_2^-) and then further into ammonium (NH_4^+) (Meyer and Stitt 2001). This conversion process is significantly affected by factors such as storage temperature and the conditions under which the vegetables are handled after harvest (Chandra et al. 2006; Chandra et al. 2008; Cintya et al. 2018; Xu et al. 2022). Importantly, the production of NO_2^- during storage raises more significant health concerns compared to NO_3^- itself. This emphasizes the importance of comprehending the transformations of nitrogen that occur after harvesting, rather than merely concentrating on the NO_3^- levels present at the time of harvest.

However, most current research measures NO_3^- levels as a static parameter at harvest, often neglecting the ongoing transformation of inorganic nitrogen ($\text{NO}_3^- \rightarrow \text{NO}_2^- \rightarrow \text{NH}_4^+$) during storage. This transformation is mediated by the sequential activities of nitrate reductase (NR) and nitrite reductase (NiR), yet the behavior of these enzymes during the early post-harvest period has not been adequately examined (Chandra et al. 2006; Chandra et al. 2008; Coronel et al. 2009; Xu et al. 2022; Gulyás et al. 2025). Importantly, reduced or imbalanced NR and NiR activities under low-temperature storage may result in the transient accumulation of NH_4^+ , which represents a critical metabolic turning point rather than a passive end product. The first 72 hours after harvest – which includes harvesting, refrigerated transport, and initial distribution – constitute an essential, but underexplored window in which nitrogen assimilation, metabolic adjustment, and stress-responsive pathways may be rapidly reprogrammed.

Following inorganic nitrogen conversion, the accumulation of NH_4^+ during postharvest storage acts as a key metabolic signal that triggers downstream adjustments to maintain cellular homeostasis under low-temperature stress. Among these responses, γ -aminobutyric acid (GABA) and polyamines such as putrescine are closely associated with nitrogen rebalancing. GABA is a well-recognized stress-responsive metabolite that accumulates under mechanical injury and chilling and contributes to NH_4^+ assimilation, cytosolic pH regulation, and redox balance (Meyer and Stitt 2001). Likewise, putrescine, the simplest polyamine, is strongly linked to nitrogen availability and frequently increases under ammonium-rich conditions, supporting membrane stability and stress tolerance during postharvest storage (Gross et al. 2016).

In parallel, organic acids of the tricarboxylic acid (TCA) cycle serve as central integration points between carbon and nitrogen metabolism. Stress-induced modulation of malic and citric acids reflects metabolic flexibility and nitrogen redistribution, whereas the relative stability of succinic and fumaric acids indicates preservation of core respiratory function (Meyer and Stitt 2001). These metabolic adjustments are closely connected to cellular redox balance and antioxidant demand.

Within this framework, vitamin C functions as a primary antioxidant indicator of oxidative status and postharvest quality in leafy vegetables exposed to low temperature and mechanical stress (Smirnov)

2018). Although vitamin C depletion during cold storage has been widely reported (Cintya et al. 2018), its coordinated response with NH_4^+ accumulation and nitrogen-related metabolites during the early postharvest logistics period remains poorly understood.

To address these gaps, this study employed an experimental design that closely reflects commercial postharvest logistics. Iceberg lettuce cultivated in Nagano Prefecture was harvested at commercial maturity, transported under refrigeration to the Tokyo University of Agriculture, and stored at 5 °C in perforated polyethylene bags. Samples were analyzed immediately upon arrival at the laboratory (day 1), representing the post-logistics baseline condition. The remaining samples were maintained at 5 °C and analyzed over the subsequent two days, thereby encompassing the critical 72-hour postharvest logistics period.

Within this framework, three main contributions are presented. First, the study simultaneously monitors the complete inorganic nitrogen transformation ($\text{NO}_3^- \rightarrow \text{NO}_2^- \rightarrow \text{NH}_4^+$) together with its enzymatic regulators, NR and NiR, enabling an integrated evaluation of nitrogen turnover during early cold storage. Second, the accumulation of NH_4^+ is examined in relation to key nitrogen-responsive metabolites, including γ -aminobutyric acid (GABA) and putrescine, as well as selected tricarboxylic acid (TCA) cycle – related organic acids, thereby capturing coordinated carbon–nitrogen metabolic adjustments under low-temperature stress. Third, by defining the initial 72 hours after harvest as a critical logistics window, this work enhances the practical relevance of laboratory observations for cold-chain management in Japan and comparable highland-to-lowland supply systems in Southeast Asia (Altaki and Launio 2025; Gross et al. 2016).

In summary, this research investigated whether short-term storage at 5 °C during the critical 72-hour logistics window can maintain metabolic stability, nutritional quality, and chemical safety in iceberg lettuce, through the integrated assessment of nitrogen conversion, stress-related metabolites (GABA and putrescine), TCA cycle–associated organic acids, and vitamin C dynamics. The findings provide practical insights for improving cold-chain management in Japan and regional vegetable supply chains across Southeast Asia.

MATERIALS AND METHODS

Iceberg lettuce (*Lactuca sativa* L.) cultivar ‘Turnover’ was harvested at commercial maturity in July 2025 from Kawakami, Nagano Prefecture, Japan. Immediately after harvest, the lettuce was transported under refrigerated conditions to the Laboratory of Tropical Horticultural Sciences, Tokyo University of Agriculture. Upon arrival, samples were taken as the post-logistics baseline (day 1), and the remaining lettuces were stored at 5 °C in perforated polyethylene bags

Subsequently, samples were collected at 24 h intervals over the following two days. At each sampling point, the third fully expanded leaves were selected as representative tissues and divided for different analytical purposes. One portion of the fresh leaf tissue was used on the same day for the determination of inorganic nitrogen components (nitrate, nitrite, and ammonium), vitamin C content, and the activities of nitrate reductase and nitrite reductase.

The remaining portion of the leaf tissue was prepared for metabolite analysis by gas chromatography–mass spectrometry (GC–MS). Fresh tissues were finely chopped and immediately frozen with liquid nitrogen to rapidly quench metabolic activity, then ground into a fine powder using a pre-chilled mortar and pestle under liquid nitrogen. The resulting powders were transferred into cryogenic tubes and stored at –80 °C until subsequent extraction and GC–MS analysis of γ -aminobutyric acid (GABA), putrescine, and tricarboxylic acid (TCA) cycle–related organic acids.

Nitrate and nitrite content. The determination of NO_3^- and NO_2^- levels in vegetables was carried out using a reflectometric method following the application of a reducing agent and the Griess reaction (Merino 2009). This was performed with a reflectometer (RQ-flex Plus 10, Merck Inc., Darmstadt, Germany) in accordance with the research conducted by Nguyen et al. (2025). The concentrations of NO_3^- and NO_2^- were recorded as milligrams of NO_3^- and NO_2^- per kilogram of fresh weight (FW), respectively.

Ammonium content. The NH_4^+ concentration in the crude extract was assessed by utilizing a modified Berthelot reaction, following the procedure established by Weatherburn in 1967. A sample weighing 0.5 grams of lettuce leaf was powdered using a mortar and pestle in the presence of 3 mL of 0.3 mM sulfuric acid, while ensuring the pH remained at 3.5. The homogenized mixture was then subjected to centrifugation at a speed of 12,000 rounds per minute for a period of 10 minutes at a temperature of 25 °C. After centrifugation, 200 μL of the transparent supernatant was mixed with 3.8 mL of 0.3 mM sulfuric acid, resulting in a total solution volume of 4 mL. For the subsequent colorimetric reaction, 0.5 mL of solution A, which consists of 5 grams of phenol and 25 milligrams of nitroprusside dissolved in 100 mL of water, was incorporated, followed by the addition of 0.5 mL of solution B. Solution B was produced by combining 40 mL of 5% sodium hypochlorite with 2.5 grams of NaOH and diluting this mixture to a final volume of 100 mL with distilled water. The combined solution was left to incubate with gentle agitation in a water bath maintained at 37 °C for a duration of 20 minutes. The absorbance was subsequently measured at 625 nm against a control sample that lacked the extract. NH_4^+ levels were estimated using an extinction coefficient of $3.646 \mu\text{mol}^{-1}\cdot\text{cm}^{-1}$ and were expressed as mg NH_4^+ per kilogram of FW.

Vitamin C content. The content of vitamin C (ascorbic acid) in the vegetables was determined through a reflectometric technique, employing a reflectometer (RQ-flex Plus 10, Merck Inc., Darmstadt, Germany) in accordance with previous research of Nguyen et al. (2025). The ascorbic acid concentration was reported as milligrams per kilogram of FW.

Nitrate reductase activity. The assessment of nitrate reductase activity (NRA) was conducted according to the guidelines set forth by Neyra and Hageman in 1974, with adjustments as noted by Segura in 1990. A sample of 0.5 grams from the third leaves was acquired, finely minced, and subsequently introduced to 5 mL of incubation solution with a pH of 7.5. This procedure took place in a dark setting at ambient temperature, specifically at 28 ± 2 °C, over a period of 60 minutes. The incubation solution was composed of 1 mL of 0.1 M KNO_3 , 3.75 mL of a blend containing 0.1 M K_2HPO_4 and KH_2PO_4 , along with 0.25 mL of a 1% (v/v) n-propanol solution. Following the incubation phase, new solutions were prepared by mixing 2 mL of the incubation solution with 1 mL of nitrite reactive, which included Sulfanilamide at a concentration of 1% (w/v) in 3 M HCl and 0.02% N-(1-naftil) ethylene di-amine di-hydrochloride, alongside a control consisting of 2 mL of the incubation solution and 1 mL of distilled water. This combination was incubated in the dark for 15 minutes to facilitate color formation. The absorbance readings were obtained via a spectrophotometer set at a wavelength of 540 nm to establish a nitrites standard curve using a 10 ppm N solution (as NaNO_2). The findings were reported as one unit of NR activity in micromoles of NO_2^- per hour per gram of FW.

Nitrite reductase activity. The evaluation of nitrite reductase activity (NiRA) was performed in accordance with the protocol established by Wray and Fido in 1990, which utilized dithionite-reduced methyl viologen as an artificial electron donor.

Approximately 0.5 grams of the fresh specimen were pulverized in a pre-cooled mortar with a pestle, accompanied by 5 mL of distilled water. Following this, the resultant extract underwent centrifugation at a rate of 12,000 rounds per minute for a duration of 10 minutes at a temperature of 25°C, utilizing the TOMY MX-307 high-speed refrigerated microcentrifuge (Japan). For the assay procedures, 50 μL of the extract was mixed with 125 μL of a 50 mM potassium phosphate buffer adjusted to a pH of 7.5,

along with 125 μL of potassium nitrite (2.5 mM KNO_2) and 200 μL of a freshly prepared 20 mM sodium dithionite ($\text{Na}_2\text{S}_2\text{O}_4$) solution in 290 mM sodium bicarbonate. The reaction commenced upon the addition of sodium dithionite, succeeded by the incorporation of 125 μL of methyl viologen (3 mM methyl viologen), which resulted in the formation of a blue hue. Control samples, denoted as blanks, encompassed all assay components apart from methyl viologen. After permitting an incubation period of 15 minutes at 25°C in open tubes, the reaction process was terminated by thoroughly mixing the tube contents until both dithionite and the reduced methyl viologen were oxidized, as indicated by the loss of the blue coloration of the reduced dye. A 0.1 mL aliquot of the reaction mixture was then diluted with 2.9 mL of distilled water, in addition to 1 mL of each of the 1% (w/v) sulphanilamide solution in 3 M HCl and 0.02% (w/v) N-(1-naphthyl) ethylene-diamine dihydrochloride. This combination was incubated for a further 15 minutes. The absorbance was measured at a wavelength of 540 nm using an appropriate blank in a spectrophotometer, which enabled the determination of NiR activity. One unit of NiR activity was specified as the production of 1 μmol of NO_2^- per hour per gram of FW.

Stress-related metabolites and TCA cycle related organic acids. 100 mg of homogenized lettuce powder was used to prepare each sample. Each sample was combined with one zirconia bead and 250 μL of methanol, then mixed in a mixer mill MM400 for 2 minutes at 27 Hz. After that, 250 μL of chloroform was added, and then incubated in an Eppendorf thermomixer F2.0 for 3 minutes at 37 °C and 1200 rpm. Subsequently, 50 μL of standard solution (composed of 2 mg of ribitol in 1 mL of ultra-pure water) and 175 μL of ultra-pure water were added to each sample then vortexed until completely mixed by VORTEX GENIE 2. After this, the samples were centrifuged at 1,200 rpm for 10 minutes at 25 °C TOMY MX-307. 80 μL of supernatant was transferred into a new 1.5 mL tube and centrifugal evaporated for 2 hours in EYELA CVE-3110. Samples were then placed in a freeze-dryer machine EYELA FDM-100 at -45 °C overnight.

Following lyophilization, each sample received 40 μL of methoxamine hydrochloride (MAOI) (composed of 20 mg of MAOI mixed with 1 mL of pyridine solution), and then were placed back into the Eppendorf thermomixer F2.0 for 90 minutes at 37°C. Next, 50 μL of N-Methyl-N-trimethylsilyl trifluoroacetamide (MSTFA) was added and then centrifuged again in the Nichiryo C1008-B and subsequently placed back into the Eppendorf thermomixer F2. 0 for an additional 30 minutes at 37 °C. Next, 50 μL of the solution was extracted and transferred into small bottles designed for the Gas Chromatograph-Mass Spectrometer (GCMS) procedure in Shimadzu GC-2010 coupled with GCMS-QP 2010 Plus.

Statistical analysis. All data were analyzed using one-way analysis of variance (ANOVA) with storage time (day 1, day 2, and day 3) as the independent factor, followed by Tukey's multiple comparison test to determine significant differences among means at $p < 0.05$. Principal component analysis (PCA) was applied to integrated metabolic variables, including inorganic nitrogen components, enzyme activities, stress-related metabolites, organic acids, and vitamin C, to evaluate coordinated metabolic responses during short-term cold storage. All statistical analyses and graphical visualizations were performed using R software (version 4.4.1) and RStudio (version 2025.05.1+513).

RESULTS AND DISCUSSION

Visual change during storage. A noticeable change was observed in the appearance of iceberg lettuce from day one to day three (Fig. 1). The fresh samples retained a solid texture and substantial turgor on day one, while those collected on day two showed initial signs of wilting and a decrease in crunchiness. By day three, significant leaf curling, softening of the tissue, and a lackluster surface became apparent, signifying an aging symptom.

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These changes are characteristic of the stress that occurs after harvest during cold storage, where the lack of light inhibits photosynthesis and accelerates senescence processes, including the deterioration of membranes and oxidative damage (Toivonen and Brummell 2008).



Figure 1. Visual changes during storage of iceberg lettuce (cv. Turnover)

In leafy greens such as lettuce, the absence of light, as well as cold temperature, quickly impacts the metabolism of carbon and nitrogen, initiating physiological reactions that occur prior to biochemical alterations in nitrogen compounds and antioxidant systems (Canetti et al. 2002).

Nitrogen metabolism and antioxidant responses during storage. This section collectively describes the coordinated changes in inorganic nitrogen compounds (NO_3^- , NO_2^- , NH_4^+), nitrogen metabolic enzymes (NR and NiR), and antioxidant levels (vitamin C) in iceberg lettuce while it is kept in cold storage (Fig. 2).

Changes in nitrate, nitrite and their relationship with nitrate reductase and nitrite reductase activities. NO_3^- content declined steadily from day one to day three (Fig. 2A), which was accompanied by a notable reduction in the activity of NR (Fig. 2D). A similar declining trend was observed in NO_2^- levels and NiRA (Fig. 2B and 2E).

The simultaneous reductions in both NO_3^- levels and NRA can be mechanistically linked to the lack of light and coldness during the storage period. NR is an enzyme regulated by light, and its activity relies on reducing power generated through photosynthetically. Under dark storage, NR becomes rapidly inactivated through phosphorylation, often followed by a decrease in protein stability and proteolytic degradation, resulting in suppressed NO_3^- reduction capacity (Kaiser and Huber 2001). From a food safety perspective, the progressive decline in NO_3^- content observed during storage is favorable, as high NO_3^- intake from leafy vegetables is considered a major dietary exposure route (Santamaria 2006).

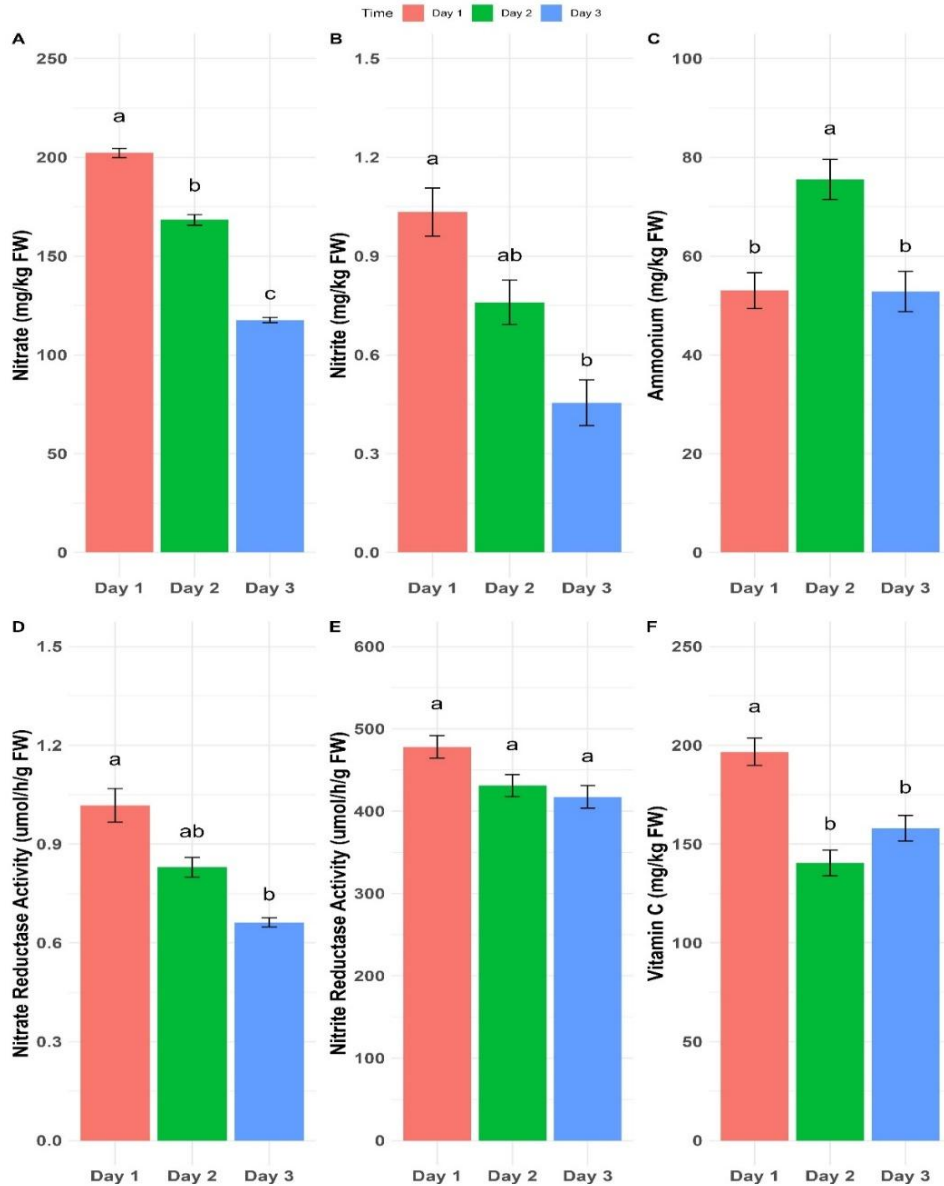


Figure 2. The effect of storage time on (A) Nitrate content, (B) Nitrate Reductase Activity, (C) Nitrite content, (D) Nitrite Reductase Activity, (E) Ammonium content and (F) Vitamin C content in iceberg lettuce (cv. Turnover)

Values are expressed as means (n = 3). Error bars represent standard error of the means. Different lowercase letters indicate significant differences according to the one-way ANOVA followed by the Tukey test (p < 0.05).

Similarly, NiRA decreased during the storage period, indicating a lower availability of NO_2^- substrate and a reduced metabolic requirement. In cold and dark environments, the coordinated downregulation of NR and NiR prevents the accumulation of NO_2^- . NO_2^- accumulation is of particular concern due to its higher toxicity compared with NO_3^- , emphasizing the importance of maintaining efficient NO_2^- reduction in leafy vegetables (Santamaria 2006). This observation clarifies why NO_2^-

levels did not rise in this study, in contrast to findings reported during storage at ambient temperature (Cintya et al. 2018).

The simultaneous reduction of NR, NiR, NO_3^- , and NO_2^- illustrates a strong metabolic linkage within the NO_3^- assimilation pathway. Similar patterns have been reported in postharvest leafy tissues stored under dark conditions, where reduced nitrate-reducing enzyme activities limit both NO_3^- utilization and NO_2^- formation (Xu et al. 2022).

Transient accumulation of ammonium and its physiological significance. A unique trend was identified concerning NH_4^+ , which exhibited a significant increase on day two, followed by a decrease on day three (Fig. 2C). This temporary rise indicates a metabolic imbalance between nitrogen reduction and assimilation during the initial storage phase.

The notable spike observed on day two may be associated with postharvest physiological stress, which promotes proteolysis and subsequent amino acid deamination induced by harvest injury and cold shock (Amodio et al. 2018). Simultaneously, the residual activity of NR and NiR during the early storage period may allow continue nitrogen reduction, potentially contributing to produce NH_4^+ (Kaiser and Huber 2001; Chandra et al. 2006). Together, these processes can induce a transient metabolic imbalance in which NH_4^+ generation may exceed the capacity of NH_4^+ assimilation via the GS/GOGAT pathway, thereby promoting NH_4^+ accumulation and postharvest physiological stress (Amodio et al. 2018; Forde and Lea 2007; Hachiya and Noguchi 2011).

The observed reduction in NH_4^+ levels on the third day is likely due to a diminished upstream supply originating from NO_3^- and NO_2^- , as extended storage is known to further suppress the activities of NR and NiR (Kaiser and Huber, 2001), together with a general decline in nitrogen metabolic capacity reported in stored lettuce (Chandra et al. 2006). This decrease may also indicate a combination of ammonia loss through volatilization (Amodio et al. 2018) and the gradual exhaustion of easily accessible protein reserves as senescence progresses (Masclaux-Daubresse et al. 2010). At the same time, the reassimilation of NH_4^+ through the GS/GOGAT pathway is essential for preventing NH_4^+ toxicity and sustaining cellular stability, particularly under conditions where nitrogen metabolism becomes increasingly constrained during postharvest senescence (Bittsánszky et al. 2015; Hachiya and Noguchi 2011). In summary, this trend suggests a shift from active nitrogen metabolism to a gradual metabolic shutdown, which is a characteristic of the late postharvest phase in leafy vegetables (Chandra et al. 2008; Gross et al. 2016).

Interaction between ammonium accumulation and vitamin C dynamics. Vitamin C content declined sharply from day one to day two, coinciding with the peak in NH_4^+ concentration, and then showed a slight recovery trend on day three (Fig. 2F), although the increase was not statistically significant.

This negative correlation implies that vitamin C may contribute to protective responses under elevated NH_4^+ conditions. It is established that high amounts of NH_4^+ can lead to serious physiological stress that disrupts pH gradients across membranes and increases the production of reactive oxygen species (ROS) (Bittsánszky et al. 2015; Li et al. 2021). To counteract ammonium-induced oxidative stress, plants primarily depend on ascorbic acid as a key ROS scavenger, leading to its swift depletion (Foyer and Noctor 2011; Smirnoff 2018). Therefore, the significant drop in vitamin C observed on day two likely indicates a rapid consumption of ascorbic acid due to oxidative stress caused by NH_4^+ .

As the levels of NH_4^+ decreased on day three, oxidative stress might have been lessened to some extent, potentially allowing vitamin C levels to stabilize or slightly recover due to a reduced antioxidant demand, despite limited de novo biosynthesis under dark storage conditions. This partial recuperation may reflect a physiological adjustment during later postharvest stages aimed at re-establishing cellular redox equilibrium as the impacts of proteolysis and NH_4^+ toxicity diminish (Foyer and Noctor 2011;

Smirnov 2018). Similar interactions between ammonium-induced oxidative stress and antioxidant depletion have been documented under nitrogen imbalance conditions in plants (Li et al. 2021).

Changes in amino acid, polyamine and organic acids during cold storage. Significant changes over time were noted in metabolites related to stress and organic acids in iceberg lettuce during cold storage (Fig. 3).

The content of γ -aminobutyric acid (GABA) showed a substantial increase from day one to day two ($p < 0.05$) and maintained a significantly elevated level at day three when compared to day one (Fig. 3A). Putrescine demonstrated a notable temporary accumulation, reaching its peak on day two before experiencing a sharp decline by day three (Fig. 3B).

Among the intermediates of the tricarboxylic acid (TCA) cycle, succinic acid and fumaric acid showed no significant differences among the three storage days (Fig. 3C and 3D). In contrast, malic acid content decreased progressively from day one to day three, with significantly lower values on day three compared to day one (Fig. 3E).

Citric acid exhibited a distinct transient pattern, with a significant increase on day two followed by a decrease on day three, although day three values remained higher than those measured on day one (Fig. 3F).

The metabolic patterns observed indicate that iceberg lettuce underwent a transient but coordinated metabolic adjustment during cold storage, with day two representing a critical phase of physiological response rather than progressive deterioration (Fig. 3).

The sharp increase in GABA and putrescine on day two reflects a rapid activation of stress-responsive nitrogen metabolism pathways. GABA accumulation is widely recognized as an early response to abiotic stress, functioning both as a metabolite linking carbon and nitrogen metabolism and as a signaling molecule involved in stress responses (Forde and Lea 2007; Ramesh et al. 2015). Similarly, putrescine accumulation is associated with enhanced polyamine biosynthesis under stress conditions, contributing to membrane stabilization and cellular protection (Groppa and Benavides 2008).

The subsequent decline of both metabolites on day three suggests that this response was transient and regulated, consistent with an adaptive adjustment to cold storage rather than irreversible metabolic disruption.

A notable result is the absence of significant differences in succinic and fumaric acid contents across the three storage days. As both metabolites are core intermediates of the TCA cycle, their stability indicates that mitochondrial respiratory metabolism remained largely intact during short-term cold storage, suggesting maintenance of basal respiratory activity under appropriate postharvest handling conditions (Cantwell and Suslow 2002; Gross et al. 2016). In contrast, the dynamic changes observed for malic and citric acids indicate flexible regulation of specific TCA cycle branches, allowing metabolic adjustment without compromising basal respiration.

The metabolic configuration observed on day two provides a mechanistic basis for the transient increase in NH_4^+ content observed in Figure 2. NH_4^+ accumulation is a sensitive indicator of postharvest physiological stress rather than a symptom of metabolic failure (Amodio et al. 2018). In the present study, the NH_4^+ pulse coincided with maximal levels of GABA and putrescine, suggesting that excess NH_4^+ was, at least in part, actively reassimilated and diverted into nitrogen-rich protective metabolites. Such metabolic redirection is consistent with the established roles of GABA and polyamines in linking nitrogen and carbon metabolism and in enhancing cellular protection under stress conditions (Forde and Lea 2007; Groppa and Benavides 2008; Ramesh et al. 2015).

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The stability of succinic and fumaric acids further suggests that NH_4^+ detoxification did not disrupt basal respiratory metabolism, supporting the concept of a controlled metabolic stress response (Bittsánszky et al. 2015; Gross et al. 2016).

The metabolic adjustments are closely linked to the changes in NO_3^- , NO_2^- , (Fig. 3) and the activities of NR and NiR (Fig. 2). The coordinated accumulation of organic acids and nitrogenous metabolites on day two suggests that residual NRA and NiRA remained functional, allowing continued NO_3^- and NO_2^- reduction despite cold-induced stress.

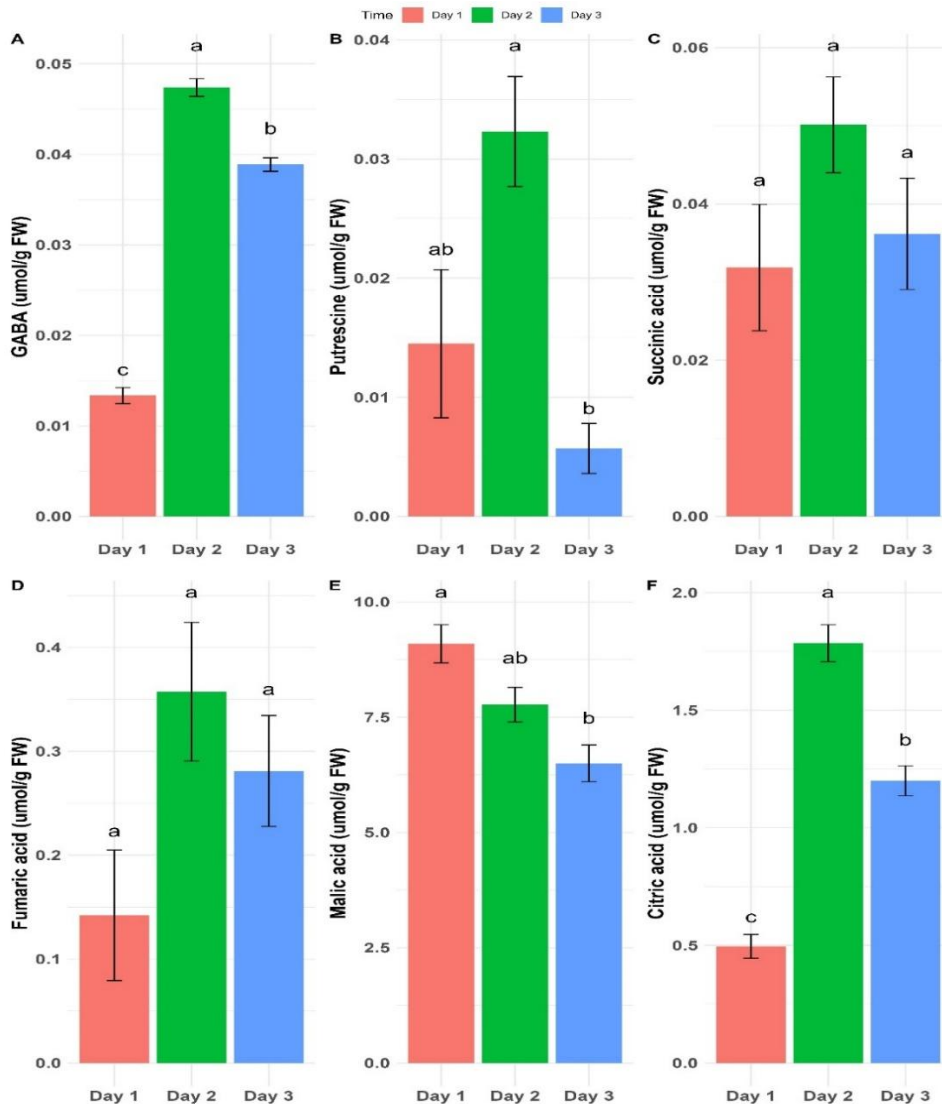


Figure 3. The effect of storage time on (A) GABA, (B) Putrescine, (C) Succinic acid, (D) Fumaric acid, (E) Malic acid and (F) Citric acid in iceberg lettuce (cv. Turnover)

Values are expressed as means ($n = 3$). Error bars represent standard error of the means. Different lowercase letters indicate significant differences according to the one-way ANOVA followed by the Tukey test ($p < 0.05$).

Previous studies have demonstrated that NRA can be modulated through post-translational regulation under stress conditions, depending on the availability of carbon skeletons and reducing power (Kaiser and Huber 2001; Meyer and Stitt 2001). The observed metabolic balance in the present study likely prevented excessive NO_2^- accumulation, a phenomenon frequently associated with postharvest metabolic impairment (Santamaria 2006; Xu et al. 2022).

The progressive decrease in vitamin C content observed in Figure 2 can be interpreted in the context of the metabolic responses (Fig. 3). Ascorbate plays a central role in cellular redox homeostasis and is actively consumed during stress adaptation (Foyer and Noctor 2011; Smirnov 2018). The peak metabolic activity on day two, characterized by enhanced nitrogen assimilation and organic acid turnover, likely increased cellular oxidative pressure and antioxidant demand, thereby contributing to vitamin C depletion.

Similar trends have been reported in leafy vegetables during cold storage, where vitamin C loss accompanies metabolic adjustment under refrigerated conditions rather than uncontrolled senescence (Cintya et al. 2018; Gross et al. 2016).

The short-lived metabolic pulse observed in this study reflects a rapid but controlled physiological response following harvest. The maintenance of respiratory stability and nitrogen assimilation capacity supports the effectiveness of the postharvest handling strategy applied to iceberg lettuce (Cantwell and Suslow 2002; Gross et al. 2016).

The noted alterations in GABA, putrescine, and organic acids provide significant mechanistic insight into the nitrogen absorption processes of iceberg lettuce during cold storage. Previous findings indicated a coordinated reduction in the levels of NO_3^- and NO_2^- , which was coupled with maintained activities of NR and NiR, alongside a temporary increase in NH_4^+ observed by day two. NH_4^+ serves as a vital metabolic convergence point, as it requires prompt reassimilation to prevent cellular toxicity (Amodio et al. 2018; Bittsánszky et al. 2015).

The prominent accumulation of GABA from day two onwards strongly suggests the engagement of the GABA shunt, a key metabolic route linking NH_4^+ assimilation with carbon metabolism. GABA is produced from glutamate, a central product of NH_4^+ assimilation via the GS/GOGAT cycle, and its accumulation has been widely reported as a stress-responsive mechanism contributing to pH regulation, redox balance, and the integration of carbon and nitrogen metabolism (Forde and Lea 2007; Li et al. 2021). The sustained presence of GABA on day three indicates that iceberg lettuce did not undergo irreversible metabolic disruption but instead entered a phase of metabolic stabilization during cold storage.

Putrescine exhibited a notable transitory increase on day two, in alignment with heightened NH_4^+ levels and the initial restructuring of carbon metabolism. Polyamines like putrescine are recognized for their rapid accumulation under abiotic stress, contributing to protective functions such as membrane stabilization and scavenging of reactive oxygen species (Han et al. 2025). The following decrease in putrescine by day three implies that the initial stress response was effectively resolved, in agreement with the lack of significant senescence signs.

Putrescine exhibited a notable transitory increase on day two, in alignment with heightened NH_4^+ levels and the initial restructuring of carbon metabolism. Polyamines such as putrescine are known to rapidly accumulate under abiotic stress and contribute to cellular protection, including membrane stabilization and mitigation of oxidative damage (Groppa and Benavides 2008; Han et al. 2025). The subsequent decline in putrescine levels by day three suggests that the initial stress response was effectively resolved, consistent with the absence of pronounced senescence symptoms.

The redistribution of TCA cycle intermediates further reinforces this viewpoint. The rises in citric, succinic, and fumaric acids by day two may reflect an increased requirement for carbon skeletons to facilitate nitrogen reassimilation and other metabolic processes associated with stress. The

accumulation of citrate has been linked to a heightened flow through the TCA cycle during NH_4^+ assimilation, which provides energy and carbon scaffolding for amino acid production (Masclaux-Daubresse et al. 2010; Li et al. 2021). In contrast, the gradual reduction of malic acid implies a transition from a high-respiration, fresh-harvest metabolic condition toward a more organized and energy-efficient metabolism during storage (Cantwell and Suslow 2002; Gross et al. 2016).

From a postharvest viewpoint, these results illustrate that iceberg lettuce has the ability to integrate nitrogen metabolism with carbon metabolism that responds to stress, enabling it to sustain physiological stability during cold storage. This metabolic synchronization is likely significant in postponing degradation processes related to senescence, which are frequently linked to unregulated nitrogen remobilization and the breakdown of nucleic acids (Canetti et al. 2002; Masclaux-Daubresse et al. 2010). This finding underlines the efficacy of cold-chain management in maintaining both nitrogen safety and metabolic integrity in Iceberg lettuce, in alignment with recognized principles of postharvest handling (Cantwell and Suslow 2002; Gross et al. 2016).

Principal component analysis of nitrogen metabolism. The first principal component analysis (PCA 1) concerning nitrogen metabolism, which includes nitrate (NO_3^-), nitrite (NO_2^-), nitrate reductase activity (NRA), nitrite reductase activity (NiRA), and ammonium (NH_4^+), distinctly classified lettuce samples based on the length of storage (Fig. 4). The initial two principal components (Dim1 and Dim2) accounted for 64.5% and 21.0% of the overall variance, respectively, indicating a strong differentiation in storage time.

Dim1 primarily represented the general ability for NO_3^- reduction. Samples from Day 1 were located on the positive axis of Dim1 and were closely linked to higher levels of NO_3^- and NO_2^- as well as increased NRA and NiRA activities, indicating an efficient NO_3^- assimilation system. Conversely, Day 3 samples were found on the negative side of Dim1, which correlates with a substantial decrease in NO_3^- reduction capability due to extended storage time.

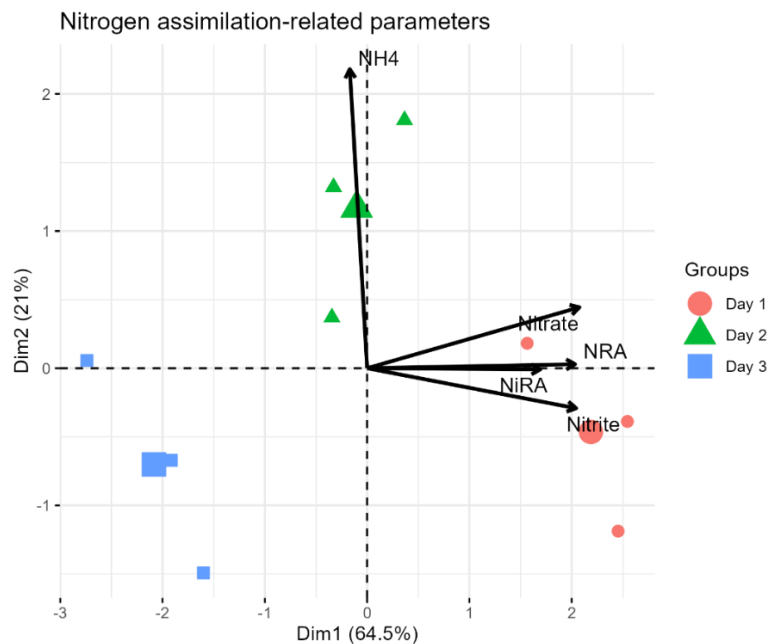


Figure 4. Principal component analysis of nitrogen metabolites during storage of iceberg lettuce (cv. Turnover)

Samples from Day 2 created a unique cluster that was mainly differentiated along Dim2, influenced by heightened NH_4^+ accumulation and changes in the relationship between NRA and NiRA. This arrangement signifies that the metabolic alterations observed on Day 2 are not a straightforward progression from Day 1 to Day 3, but rather indicate a temporary metabolic phase.

In summary, the PCA indicates a non-linear pathway of nitrogen metabolism throughout the storage period, with Day 2 representing a brief metabolic surge. The distinct but intermediate position of the Day 2 samples points to an immediate physiological reaction shortly after the start of storage, confirming metabolic reorganization induced by postharvest stress (Cantwell and Suslow 2002; Gross et al. 2016). The strong correlation between NH_4^+ accumulation and Day 2 reinforces the concept of NH_4^+ as a sensitive marker for postharvest stress, as suggested by Amodio and coworkers (2018).

Integration of the PCA with the temporal patterns observed in Figure 2 suggests that NH_4^+ accumulation at Day 2 arises from multiple internal sources, including not only ongoing NO_3^- and NO_2^- reduction but also enhanced protein and amino acid catabolism triggered by postharvest stress. Dark- and stress-induced proteolysis has been reported to release free NH_4^+ during early senescence and metabolic adjustment (Masclaux-Daubresse et al. 2010). Although NRA and NiRA remain active, limitations in carbon skeleton availability and energy supply likely constrain further incorporation of NH_4^+ into amino acids, leading to its transient accumulation (Hirel et al. 2007).

Principal component analysis of metabolites stress and antioxidant status. The second principal component analysis (PCA 2) included vitamin C, organic acids (citric, malic, succinic, and fumaric acids), GABA, and putrescine (Fig. 5). The first two components explained 62.4% (Dim1) and 18.0% (Dim2) of the total variance, accounting for 80.4% cumulatively, and clearly separated samples according to storage duration.

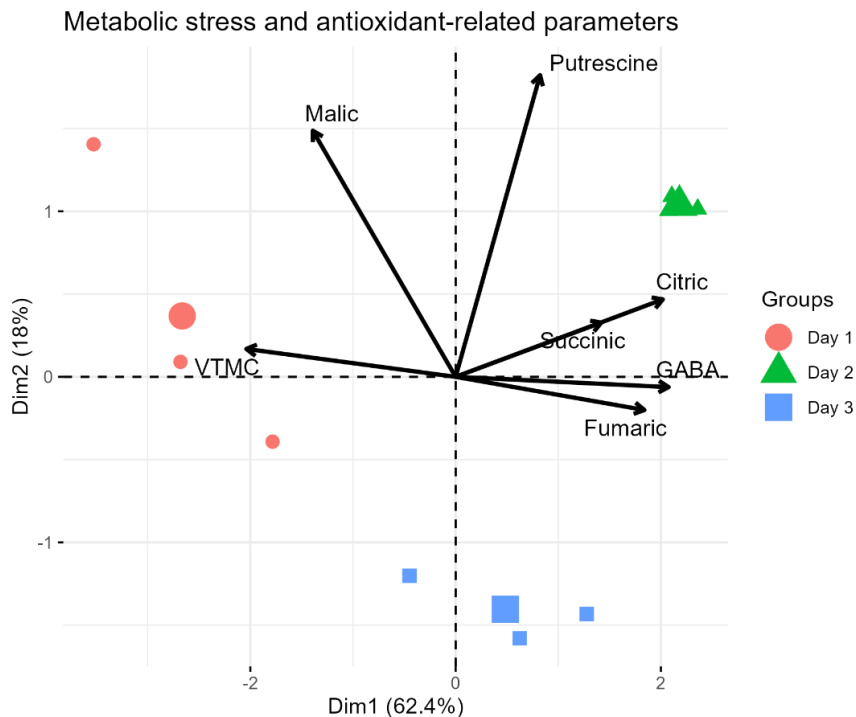


Figure 5. Principal component analysis of metabolic stress and antioxidant status during storage of iceberg lettuce (cv. Turnover)

Day 1 samples clustered on the negative side of Dim1 and were closely associated with higher vitamin C content and relatively balanced organic acid profiles. In contrast, Day 3 samples shifted toward the positive Dim1 region, characterized by lower vitamin C levels and reduced contributions from organic acids, indicating progressive metabolic decline during storage.

Day 2 samples occupied a distinct position, mainly separated along Dim2, and were associated with GABA and putrescine, suggesting activation of stress-responsive metabolic pathways. Among organic acids, citric and malic acids contributed to sample separation, whereas succinic and fumaric acids showed minimal influence, consistent with their lack of significant variation among storage days.

The spatial separation of Day 2 samples in PCA 2 reflects active metabolic reprogramming rather than metabolic deterioration. The relative stability of succinic and fumaric acids suggests maintenance of the core TCA cycle, while marked changes in malic and citric acids indicate selective regulation of carbon fluxes, particularly at branch points of the TCA cycle.

Malate and citrate serve as major carbon skeleton donors for NH_4^+ reassimilation via the GS/GOGAT pathway (Forde and Lea 2007; Masclaux-Daubresse et al. 2010). The increased demand for carbon skeletons during the NH_4^+ pulse at Day 2 likely promotes utilization of these intermediates, whereas the stable succinate–fumarate pool reflects structural integrity of the TCA cycle rather than enhanced flux. Such selective modulation of organic acid metabolism under nitrogen stress has been widely reported (Bittsánszky et al. 2015; Li et al. 2021).

The close association of Day 2 samples with GABA and putrescine further supports activation of alternative nitrogen sinks. The GABA shunt provides a rapid route for temporary nitrogen sequestration and redox stabilization, while polyamine synthesis represents a well-established protective mechanism against NH_4^+ toxicity (Forde and Lea 2007; Bittsánszky et al. 2015).

Vitamin C clustered with Day 1 samples and progressively diverged from Day 2 and Day 3, indicating antioxidant depletion during storage. This pattern is mechanistically linked to carbon metabolism, as ascorbate biosynthesis and regeneration depend on carbohydrate and organic acid availability (Smirnoff 2018). Enhanced utilization of malate and citrate for NH_4^+ detoxification, combined with increased reactive oxygen species under elevated NH_4^+ , likely accelerates vitamin C consumption (Foyer and Noctor 2011; Cintya et al. 2018).

Overall, PCA 2 captures a coordinated trade-off between nitrogen detoxification and antioxidant maintenance, revealing a dynamic metabolic trajectory: Day 1 represents a homeostatic antioxidant-protected state; Day 2 reflects a transient stress-induced metabolic pulse dominated by carbon reallocation and engagement of GABA and polyamine pathways; and Day 3 marks the onset of metabolic downregulation associated with early senescence. This pattern is consistent with postharvest physiological models described by Cantwell and Suslow (2002), Chandra et al. (2008), and Amodio et al. (2018).

Based on the integrated interpretation of PCA 1 and PCA 2, a conceptual metabolic scheme is proposed to summarize the coordinated nitrogen–carbon reprogramming occurring during cold storage (Fig. 6). While PCA 1 identifies the onset of nitrogen imbalance and transient NH_4^+ accumulation as an early postharvest event, PCA 2 reveals the downstream redistribution of carbon fluxes, activation of stress-responsive pathways, and depletion of antioxidant capacity. The schematic framework links these multivariate patterns into a unified mechanistic model, illustrating how nitrogen metabolic disruption propagates into carbon metabolism, GABA and polyamine engagement, and vitamin C decline during storage.

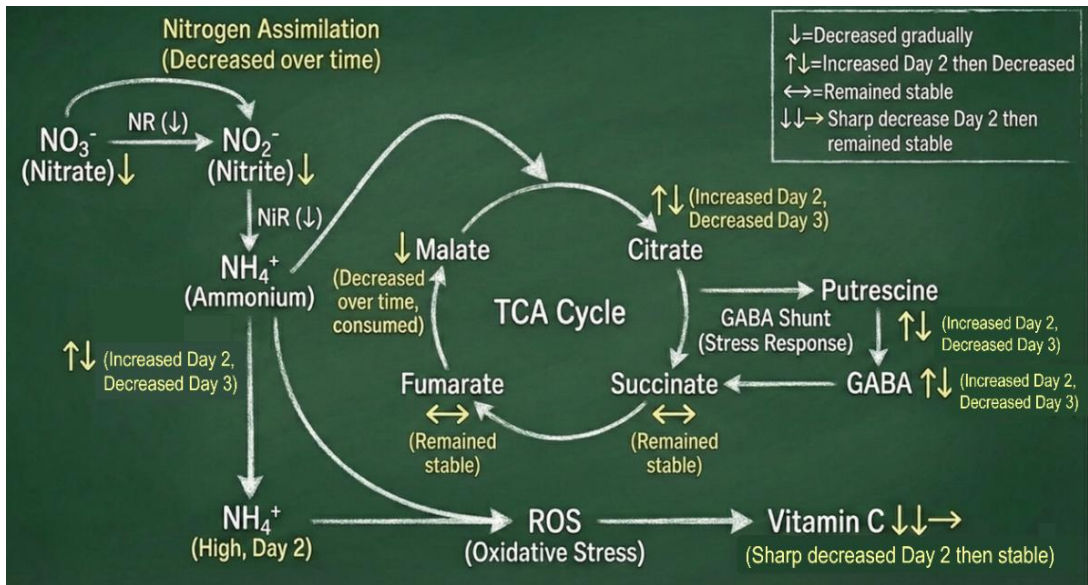


Figure 6. Metabolic responses linking nitrogen assimilation, carbon metabolism, and stress-related pathways during storage in iceberg lettuce (cv. Turnover)

The scheme integrates the multivariate patterns observed in PCA 1 and PCA 2. Early storage (Day 1) is characterized by active NR, NiR, balanced NH_4^+ assimilation, stable TCA cycle function, and high antioxidant capacity. At Day 2, partial decoupling between nitrogen reduction and NH_4^+ assimilation, combined with stress-induced protein degradation, leads to a transient NH_4^+ pulse. To mitigate NH_4^+ toxicity, carbon skeletons derived mainly from malate and citrate are redirected toward reassimilation pathways, while alternative nitrogen sinks such as the GABA shunt and polyamine (putrescine) synthesis are activated. These adjustments occur without collapse of the core TCA cycle, as indicated by stable succinate and fumarate pools. Enhanced nitrogen detoxification and redox buffering at Day 2 impose a trade-off with antioxidant maintenance, contributing to progressive vitamin C depletion. Prolonged storage (Day 3), NH_4^+ levels decline, indicating recovery of nitrogen reassimilation and metabolic stabilization.

The schematic model illustrates that short-term cold storage induces an active and transient metabolic reprogramming rather than a linear decline. Day 2 represents a critical metabolic pulse characterized by NH_4^+ accumulation, selective carbon reallocation toward citrate and malate, and activation of alternative nitrogen sinks (GABA and polyamines), at the expense of antioxidant maintenance.

CONCLUSION

This study examined whether short-term cold storage at 5 °C during the critical 72-hour logistics window can maintain metabolic stability, nutritional quality, and chemical safety in iceberg lettuce (*Lactuca sativa* L. cv. Turnover). The results demonstrate that storage under these conditions induces coordinated metabolic regulation rather than passive deterioration. Nitrate (NO_3^-) and nitrite (NO_2^-) concentrations declined progressively, indicating sustained internal nitrogen conversion and effective detoxification through residual nitrate and nitrite reductase activity. A transient increase in ammonium (NH_4^+) on Day 2 likely reflected temporary imbalance between nitrogen release and reassimilation under cold stress, accompanied by the accumulation of stress-related metabolites (GABA and putrescine) and selective adjustments in TCA cycle-associated organic acids. By Day 3, the decline in NH_4^+ together with stabilization of vitamin C and organic acid profiles suggested recovery of metabolic balance. Importantly, NO_3^- and NO_2^- levels remained well below established safety thresholds

throughout storage. The compact head morphology of iceberg lettuce may further contribute to this stability by buffering environmental stress and preserving enzymatic functionality in inner tissues.

This study highlighted an integrated metabolic framework linking nitrogen conversion, stress-associated metabolites, carbon metabolism, and antioxidant dynamics during short-term postharvest storage. Maintaining storage at 5 °C for up to 72 h therefore represents a reliable strategy for preserving both chemical safety and metabolic integrity in iceberg lettuce. These findings provide practical insights for improving cold-chain management in Japan and regional vegetable supply systems across Southeast Asia. Integrating enzyme activity, metabolomic profiling, and storage physiology will further refine postharvest strategies aimed at optimizing both nutritional quality and food safety.

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Authorship Contributions:

Conceptualization: NTTN, KK; Study Design: NTTN, KK; Sample collection: NTTN, KK; Conduct of experiment: NTTN, NT; Data curation: NTTN, NT, AS, KK; Visualization: NTTN, NT, AS, KK; Formal analysis: NTTN, NT, AS, KK; Supervision: KK; Writing – Original draft preparation: NTTN.; Writing – Review and Editing: NTTN, NT, AS, KK.

EXPLORING INDIVIDUAL ENTREPRENEURIAL ORIENTATION AMONG INDONESIAN ALUMNI OF JAPAN'S TECHNICAL INTERN AND TRAINING PROGRAM IN THE AGRICULTURE SECTOR

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ABSTRACT

Although Japan's Technical Intern Training Program (TITP) was originally designed for workforce development rather than entrepreneurship, many Indonesian alumni have returned home and started their respective own agricultural enterprises. To understand this transformation, the study examined the Individual Entrepreneurial Orientation (IEO) of TITP alumni who have returned to Indonesia. Using exploratory factor analysis (EFA) on data collected from 75 respondents across Indonesia between November 2021 and August 2023, the study identified the key factors shaping their entrepreneurial orientation. The two main dimensions that emerged are: Autonomy–Leadership and Innovativeness–Risk Orientation. These dimensions together explain how training experiences influenced entrepreneurial behavior. Alumni from a Japanese host farm that provides regular financial and entrepreneurial classes (NT Farm), showed notably higher IEO levels. While the Technical Intern Program (TIP) alumni reported the highest average monthly income, their IEO scores did not align (correlate) with profit levels, suggesting different patterns of decision-making and enterprise management. Overall, the findings indicate that TITP's impact seemed to extend beyond technical skill transfer. Exposure to these structured, professional farming environments fostered autonomy, innovation, and confidence among returnees. Thus, strengthening post-return entrepreneurship support and financial literacy programs could help sustain this momentum and nurture a new generation of capable agripreneurs in Indonesia.

Key words: agriculture training, *agripreneur*, autonomy-leadership

INTRODUCTION

In recent years, Japan has been facing a significantly pressing challenge—a declining domestic population coupled with a lack of interest among its youth to pursue careers in the agricultural sector. According to MAFF Japan, the number of core persons mainly engaged in farming declined from approximately 1.36 million in 2020 to 1.23 million in 2022, where about 70% were aged 65 or older with an average age of 68.4 years (MAFF 2024). The 2025 (preliminary) figures show that the number of core agricultural workers is approximately 1.02 million, resulting to a further decline of about 25% from 2020 (MAFF Japan 2025). This level threatens production capacity if there are no new entrants or policy reforms that enhance

productivity (MAFF Japan 2022). Policy reports emphasize that securing agriculture labor has become increasingly difficult, stimulating a turn to foreign workers and technology while re-evaluating rural revitalization strategies. This situation raises deep concerns towards the sustainability of the agricultural sector. To secure it, the Japanese government has taken proactive steps to strengthen strategic cooperation with countries around the world. Among these measures is the long-standing instrument, the Foreign Technical Intern and Training Program (TITP) established in 1993. TITP plays a pivotal role as a bilateral instrument for skill transfer and human resource program in the agriculture sector.

TITP was legally designed to facilitate transfer of skills, technologies, and knowledge through on-the-job training to support human resource development in partner (mostly developing) countries; not to adjust Japan's domestic labor force (OTIT 2023). Yet, the program has evolved into a major labor and development path. By the end of 2023, around 400,000 technical intern trainees reside across Japan. However, it is important to note that TITP is currently undergoing major transformation. In February of 2024, the Japanese government formally resolved to replace TITP with the new Employment for Skill Development (ESD/Ikusei Shūrō Seido) scheme that is expected to come into effect between April to June 2027 (Japan Times 2024 and 2025). These reforms mark the importance of evaluating TITP's actual human capital and entrepreneurial impacts before its full replacement. Understanding how TITP alumni have developed entrepreneurial orientation and capabilities provides timely insights that help shape the design of the upcoming ESD framework.

Surprisingly, in the case of Indonesia, despite TITP's primary role for workforce development initiative, a significant number of Indonesian alumni were reported to establish various enterprises after returning home from Japan. Previous studies like Horiguchi (2019) describes the program as a platform for international cooperation and cultural exchange between Japan and the developing regions. Several have observed that participants often gain limited technical expertise but do develop strong Japanese work ethics, discipline (the Japanese 5S principles; *Seiri, Seiton, Seiso, Seiketsu, Shitsuke*), initial capital, and business networks that support post-return entrepreneurship (Faruq 2018; Ratnayake et.al. 2016; Syaukat and Hatanaka 2024). Ironically, the Indonesian government program explicitly designed to promote agriculture entrepreneurship (agripreneurship) has shown lesser success rates and shorter sustainability compared to TITP experiences. This contrast raises a crucial question: what specific factors are associated with the entrepreneurial behavior of TITP alumni, especially in agriculture? To address this question, this study adopted the Individual Entrepreneurial Orientation (IEO) framework, which captures the behavioral and psychological capabilities that shape how individuals recognize opportunities, take initiative, and manage risk under resource and institutional constraints (Bolton and Lane 2012; Lumpkin and Dess 1996).

Unlike firm-level Entrepreneurial Orientation (EO), IEO conceptualizes entrepreneurship as an individual-level capability, making it particularly suitable for analyzing agripreneurs who operate under uncertainty, limited capital, and incomplete market access (McElwee 2008). Prior research shows that individuals with stronger IEO tend to be more adaptable, innovative, and resilient; qualities crucial for sustaining farm-based enterprises (Mitchelmore and Rowley 2010; Rauch et al. 2009).

Following Bolton and Lane (2012), IEO comprises five dimensions: autonomy, risk taking, innovativeness, proactiveness, and competitive aggressiveness. In the agricultural context, these dimensions correspond respectively to self-directed farm management, willingness to adopt new technologies and crops, value-adding innovation, anticipatory market behavior, and persistent competitive effort under structural disadvantage.

For TITP alumni, such entrepreneurial capabilities may develop not through formal entrepreneurship training, but through prolonged exposure to Japan’s disciplined work culture, standardized production systems, and management practices. These experiences may later translate into the ability to organize, lead, and innovate agribusiness ventures after returning home — providing a plausible mechanism explaining the unusually high incidence of agriprenurship among Indonesian TITP alumni.

Despite growing policies of interest in linking labor mobility and entrepreneurship, quantitative analyses of TITP alumni’s EO remain limited. Most prior studies have been descriptive or qualitative, focusing on migration experiences rather than measuring entrepreneurial attributes (Syafitri et al. 2024; Syaukat et al. 2024; Yuniarto 2018). Therefore, this study aims to (1) evaluate the IEO levels of Indonesian TITP alumni engaged in agribusiness ventures, (2) determine the key variables that are associated with shaping their EO, and (3) examine how specific training characteristics and experiences relate to the development of IEO. Rather than testing causal models, this study sought to identify underlying behavioral patterns and policy-relevant implications found from the observed data, emphasizing interpretation over prediction. By doing so, this study contributes empirical evidence on how cross-national training experiences increase entrepreneurial capabilities in agriculture, insights that are vital for designing more effective human resource strategies under the forthcoming ESD framework.

RESEARCH METHODOLOGY

Conceptual framework. This research conceptualizes IEO as a psychological antecedent of entrepreneurial capabilities and activities. High levels of IEO can enhance a person’s capacity to lead, recognize opportunities, and make prompt strategic decisions, collectively referred to as entrepreneurial capability. These aspects of IEO are often seen as predictors of entrepreneurial success and can indeed reflect an individual's entrepreneurial capabilities. Entrepreneurs with a strong IEO are likely to be more innovative, adaptable, and resilient – qualities that are crucial in the dynamic field of agriculture. At the same time, these individuals may also engage directly in entrepreneurial activities even without extensive training support, suggesting both direct and indirect pathways between IEO and entrepreneurial capabilities. Figure 1 summarizes this conceptual framework. IEO forms the behavioral foundation that shapes entrepreneurial capabilities and ultimately leads to entrepreneurial activity. In this study, this model is applied to assess how agriculture TITP training experiences influenced the EO and capability development of Indonesian alumni, particularly those who have ventured into agribusiness after returning.

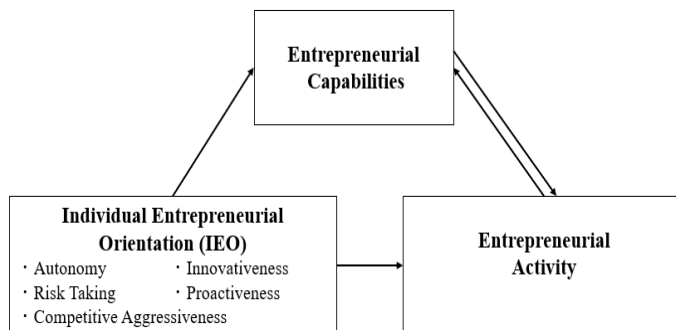


Figure 1. Conceptual framework of the study

Note: adapted from Bolton and Lane (2012), Lumpkin and Dess (1966), and Mitchelmore and Rowley (2010)

Respondents and data collection. Respondents consisted of Indonesian TITP alumni who had completed their agricultural training in Japan and returned to Indonesia. Primary data were collected through in-depth interviews and online questionnaires administered between November 2021 and August 2023. Recruitment of respondents presented significant challenges such as the absence of an alumni database and the total number of TITP alumni in agriculture. Although the questionnaire’s Google Form link was distributed through alumni networks and social media groups of TITP returnees, the most effective approach proved to be the snowball sampling technique, wherein initial respondents referred to subsequent alumni within their network. This referral chain method resulted in a relatively limited sample size with a total of 75 valid respondents. These respondents represented alumni from various provinces across Indonesia, where more than 50% reside in Java Island.

Description of TITP sub-programs. Respondents in this study participated in one of three sub-programs under Japan’s TITP in agriculture: the Industrial Training Program (ITP), the Technical Intern Program (TIP) which is the general pathway of TITP, and the NT Farm; a private farm in Fukui Prefecture that serves as a distinctive model combining technical and entrepreneurship learning for the trainees. At NT Farm, trainees are carefully selected among alumni of a top ranked agricultural vocational school (SMK Tanjung Sari) located in West Java, Indonesia. NT Farm was chosen as a study site because it is the only known farm in Japan that provides foreign trainees with structured financial literacy discussions and entrepreneurship classes, making it a unique and relevant example for examining enhanced learning opportunities within the TITP framework. Although the three programs share the same overall framework, they have slight differences (Table 1). The ITP program organized under the Indonesian Ministry of Agriculture, typically lasts up to one year and emphasizes practical training for young Indonesian farmers and is basically considered as pure internship hence the allowance, not wage. In contrast, the TIP operates through registered private Indonesian training organizations (*LPK - Lembaga Pelatihan Kerja*) focusing primarily on the development of on-the-job skills without formal education. The NT farm program differs remarkably; since it is a 3-year specialized training program for an agriculture vocational high school graduate that combines technical practice and entrepreneurship sessions.

Table 1. Comparison of Sub-Programs under TITP Examined in this Study

Main Difference	Kenshu (ITP)	Ginou Jisshu-TIP (TITP in General)	NT Farm (Ideal Model Farm)
Pre-departure Training	PS4/Organization under the Indonesian Ministry of Agriculture (MA)	Registered Training Organization (LPK), pays a min. of IDR 10 million	Not required, must study basic Japanese language before departure
Trainee Candidate	Young farmers or family member of farmer in Indonesia	Anyone who registered for training under official LPK	Alumni of Tanjung Sari Agriculture Vocational High School (SMK)
Selection of the Trainee	Selected by P4S (farmer group) under MA	Selected by farmer host (in Japan) via LPK through online interview	Selected by the principal of Tanjung Sari SMK
Length of Training	Possible up to < 3 years; majority < 1 year	2-5 years	3 years
Agriculture Training in	At the beginning and in the middle of program	None	Yes, around twice a month

Main Difference	Kenshu (ITP)	Ginou Jisshu-TIP (TITP in General)	NT Farm (Ideal Model Farm)
during Training (in Japan)			
Financial Literacy Education	Yes (starting from 2021)	None	Yes
Income	Allowance (around ¥40,000/month)	Wage (hourly; at least ¥100,000/month net)	Wage (hourly; at least ¥100,000/month net)
Accommodations (Lodging and Meals)	Free; provided by host farmer	Not provided; borne by the trainee	Not provided; borne by the trainee
Overtime	Not allowed, not paid	Allowed and paid	Allowed and paid

Source: Survey data 2021-2023

Measurement and IEO. IEO was measured using 26 statements adapted from established EO and IEO literature, contextualized to the agricultural sector. Each statement was rated on a five-point Likert scale ranging from 1 (“strongly disagree”) to 5 (“strongly agree”). The items captured the five dimensions of IEO, innovativeness, proactiveness, risk-taking, autonomy, and competitive aggressiveness, reflecting behavioral tendencies relevant to agripreneurship. The questionnaire was pre-tested with a small group of TITP alumni for clarity, language accuracy, and internal consistency prior to final distribution.

Data analysis. Factor Analysis is a statistical technique that seeks to identify underlying relationships between observed variables. This method aims to simplify a large set of observed variables into fewer latent factors, which can then explain the observed correlations or covariances among the variables. This study employed a quantitative descriptive approach supported by exploratory factor analysis (EFA) to examine the underlying dimensions of IEO among the Indonesian alumni of TITP in agriculture. The analysis aimed to identify which behavioral and attitudinal factors most strongly characterize IEO within the agriculture trainees, without testing causal hypothesis. This approach is distinctive in the context of TITP since the primary objective of the program is not explicitly geared towards enhancing entrepreneurial skills. However, Indonesia stands out, potentially as one of the few, if not the only, sending country that recognizes TITP as a human resource development initiative. Given that a significant number of TITP alumni return and embark on entrepreneurial ventures, this analysis explores whether their experiences fostered entrepreneurial aptitude to effectively manage their agricultural enterprises.

Reliability and validity. To ensure the robustness of the measurement instruments and the appropriateness of the data for factor analysis, this study employed several diagnostic tests following standard procedures recommended in multivariate analysis literature (Field 2018; Hair et al. 2010). The Kaiser-Meyer-Olkin (KMO) test, Bartlett’s Test of Sphericity, and Cronbach’s Alpha were applied to ensure sampling adequacy, construct validity, and internal consistency of the IEO measurement items.

RESULTS AND DISCUSSION

Characteristics of farm and enterprises managed by TITP alumni. In this study, farmers are defined as individuals who cultivate their land and sell their produce through conventional channels such as intermediaries (the middleman) or directly to the local market. In contrast,

agripreneurs (farmer entrepreneurs) are those who not only engage in cultivation but also add value by processing their products and/or adopting innovative marketing strategies, including online platforms and direct-to-customer approaches. Understanding the structural characteristics of enterprises operated by the trainee alumni is essential to contextualize income disparities and entrepreneurial outcomes. On average, respondents owned 1.1 hectares of land, with agripreneurs managing slightly larger plots (an average of 1.5 ha) compared to conventional farmers. Prior to TITP, the average landholding was only 0.51 ha, indicating significant expansion post-training. More than 80% of alumni practice diversified farming, combining horticulture, livestock, and food processing to optimize returns and avoid relying on only one source of income (Syaukat and Hatanaka, 2024). The enterprises managed typically included vegetables, livestock/fishery, catering services, and agricultural input businesses, with some alumni managing up to four distinct enterprises. While there are 55 entrepreneurs, the total number of enterprises managed was 74. As to the combination of enterprises, it is known that alumni who combined farming with selling agriculture inputs or services earned the highest monthly profit from their enterprises, with more than IDR 8-15 million, far exceeding the national farmer average of IDR 1.28 million with those who cultivate 2 ha or less (Indonesian Census 2021). The diversification strategy, driven by land constraints and market opportunities, significantly influences profitability. These findings suggest that farm size and enterprise diversification are critical factors explaining income variation across TITP subprograms.

Overview of IEO among Agricultural TITP trainee alumni. The majority of the respondents were found to be engaged in agricultural production, processing, or agribusiness activities at the time of the survey. This research adopts the five-dimensional framework of IEO, encompassing autonomy, innovativeness, risk-taking, proactiveness, and competitive aggression. The analysis revealed that TITP alumni, though trained primarily for technical skill transfer rather than entrepreneurship, show measurable levels of IEO. This supports previous findings (Bolton and Lane 2012) that EO can manifest at the individual level, independent of formal business training.

IEO Scores based on entrepreneurial status. Respondents were first categorized according to their engagement in entrepreneurial activities. Approximately 90% derived income from the agricultural sector, and more than 80% are identified as entrepreneurs. In this study, "farmers" (conventional farmers) are defined as individuals engaged in land cultivation, distributing their produce conventionally through intermediaries or directly to the traditional markets. While "farmer entrepreneurs" or agripreneurs are those involved in land cultivation who employ innovative methods to market their products through digital platforms and other channels or process them to enhance their value.

- (i) **Non-entrepreneurial respondents.** Sixteen percent of respondents reported non-entrepreneurial status, mostly working as conventional farmers or agricultural laborers. Among them the average IEO score was 78, the lowest among all groups. However, five respondents within this group achieved notably high IEO scores (≥ 120). This indicates that TITP participation may cultivate autonomy and proactive behaviors even among those engaged in traditional farming or wage-based agricultural work, consistent with the individual-level conceptualization of IEO. Several non-entrepreneurial respondents nevertheless reported expanding their farmland, adopting Japanese production methods, or improving management practices after returning. These cases suggest that exposure to structured work systems in Japan can foster an entrepreneurial mindset even in a non-enterprise context. Prior research from migration studies indicates that oversea work experience can facilitate skill and mindset transfer upon return, leading to adaptive and entrepreneurial practices (McCormick and Wahba, 2001)
- (ii) **Entrepreneurial respondents.** Around 84% of respondents identified themselves as entrepreneurs or agripreneurs, primarily managing agribusinesses from production,

processing, to marketing of their products. Their average IEO score was 110. Notably higher than those who are non-entrepreneurs. Most of them operated small to medium scale enterprises such as vegetable farms, dairy and poultry operations, food processing units, and online product sales. A small number diversified into input trading, agriculture machinery rental, or agrotourism. This finding suggests that participation in TITP can translate into concrete entrepreneurial behavior when combined with post-return access to land, capital, or networks. Evidence from the return migration literature shows that returnees are significantly more likely to initiate entrepreneurial ventures when they have accumulated assets and resources such as land and savings (Bao et al. 2022). Another study mentions that migration serves as a household strategy for accumulating resources that facilitates entrepreneurial investment back home once they return (Zhou et al. 2024).

IEO Score by TITP sub-program. In this section, the respondents were categorized based on the specific sub-programs they undertook in Japan. These respondents were grouped into three distinct groups: ITP, TIP, and NT farm alumni. These programs differ in training duration, content, and learning structure as outlined earlier in the methodology section. Table 2 provides a summary of the IEO scores and average monthly profit of alumni across the sub-programs. In general, all groups showed relatively high IEO scores ranging from 110.5~113, indicating a relatively strong entrepreneurial mindset among returnees.

Table 2. Grouping of IEO Score of Entrepreneurs based on TITP Program

Program	n	IEO score (/130)	%	Ave. Monthly Agrib.* Profit (IDR)	Ave. Monthly Income (IDR)
ITP	31	110.5	85	1,330,000	3,635,000
TIP	27	111.9	86	5,216,667	6,616,667
NT Farm	10	113.0	87	2,280,000	4,700,000

Note: *Agrib. = Agribusiness; Total score of IEO is 130

Source: Survey data (2021-2023)

Although NT farm alumni have the highest average IEO score, the differences across programs were modest. This suggests that participation in TITP in general effectively cultivates EO, regardless of the program type. However, differences in program structure offer an important interpretive nuance. The NT Farm program, which combines technical practices with regular entrepreneurship classes, may foster a more balanced development of autonomy and innovativeness among other respondents. This tendency may reflect the structured nature of NT Farm’s training system that encourages independent decision making and exposure to entrepreneurial thinking, dimensions that later emerge as two dominant factors shaping IEO in this study.

Regarding the average monthly profit of respondents, TIP alumni appear to have a marginally higher profit at approximately IDR 5,216,667. This is more than double the average earnings of ITP alumni (IDR 1,330,000) and NT Farm alumni (IDR 2,280,000). A potential explanation for this disparity could be the earnings of TIP alumni during their time in Japan. They earn a monthly wage between 90,000-200,000 JPY net (depending on season and overtime) for 2-5 years, potentially allowing them to save a significant amount. This capital could later be invested in their enterprises, in contrast to ITP alumni who received a stipend of just 40,000 JPY over 11 months during their training in Japan. Regarding the NT Farm alumni, the standard deviation for the average monthly profit and income is notably higher due to the limited number of alumni, rendering predictions less reliable. Also, over 80 % of NT Farm alumni have an additional source of income, not solely relying on their enterprise.

IEO scores of entrepreneurs based on profit. For a more comprehensive insight, the entrepreneurs were grouped into five groups based on their average monthly agribusiness profit (Table 3). Among the groups, a positive trend was observed; respondents with higher profits generally have higher IEO scores. This pattern suggests that IEO may contribute to improved enterprise performance. However, this pattern is not strictly linear. The group with the highest average profit (more than IDR 11,000,000) recorded slightly lower IEO scores (mean= 109.8) compared to those in the mid profit categories (Group 2-4, IEO=112.5-121). Closer examination revealed that these top-earning respondents were engaged in mixed enterprises, combining agriculture with service sectors, such as pharmacies, selling agricultural machinery, and managing an *LPK*. These diversified enterprises often employed several workers, suggesting that decision-making responsibilities were distributed, not concentrated in the owner, potentially explaining the lower IEO scores.

Table 3. Grouping of IEO score based on the average profit of enterprise.

Group	Ave. Monthly Agrib.* Profit (IDR)	n	Ave. IEO Score (/130)	%	Ave. Monthly Income (IDR)	± SD
1	900,000	8	104.2	80	2,536,364	± 1,332,989
2	2,000,000	30	112.5	87	4,471,429	± 2,563,321
3	4,500,000	13	114.4	88	5,566,667	± 2,528,944
4	8,000,000	3	121.0	93	6,166,667	± 1,649,916
5	11,000,000	4	109.8	84	11,000,000	± 1,082,532

Note: *Agrib. = Agribusiness;

Source: Survey Data (2021-2023)

In contrast, mid-range earners (Group 3 and 4) tend to remain deeply involved in production, marketing, and financial management. These individuals demonstrated more active problem-solving and creativity in improving their businesses, which may explain higher IEO scores. Several respondents also mentioned during interviews that their training experience in Japanese farms has reshaped their perception of farming. Before TITP, they did not think of farming as a business, but exposure to Japan’s work ethics and structured farm management systems inspired them to approach farming as a business and a profession to take pride in. This shift in attitude seems to have strengthened their motivation and confidence to innovate after returning home.

Overall, these findings show that IEO not only reflects entrepreneurial intention but also behavioral engagement and mindset transformation. Alumni who adopted Japan’s disciplined farming practices tended to develop a more proactive and improvement-oriented approach in managing their business, an attitude that, as shown in the next section, aligns with the key dimensions identified through factor analysis.

Factor analysis of trainee alumni IEO. Exploratory Factor Analysis (EFA) was employed using 26 items representing the five IEO dimensions. Prior to extraction, the dataset was tested to confirm suitability. The Kaiser–Meyer–Olkin (KMO) measure of sampling adequacy yielded a value of 0.88, exceeding the recommended threshold of 0.60, while Bartlett’s Test of Sphericity was statistically significant ($\chi^2 = 1140.52$, $p < 0.001$), confirming that correlations among

variables were adequate for factor analysis. To ensure internal consistency, Cronbach's Alpha was calculated for the 26 items, producing a coefficient of 0.97, indicating excellent reliability. Each extracted factor also demonstrated strong construct reliability, with alpha values above 0.70.

Following the latent root criterion (eigenvalue > 1) and examination of the scree plot, two key factors were extracted, explaining 51% of the total variance. Ideally, a cumulative variance exceeding 60% is preferred. However, the scree plot (Fig. 2) indicates an elbow after just two factors. The objective of factor analysis is to elucidate the most variance using the fewest factors (Nunnally and Bernstein 1994). Given this, it was determined that the two-factor solution is adequate. Table 4 provides detailed information on factor loadings. The two dominant dimensions were labeled as:

- (i) *Autonomy-Leadership*: capturing independence in decision-making, interpersonal management, and the ability to lead teams.
- (ii) *Innovativeness-Risk Orientation*: reflecting openness to experimentation, creativity, and the willingness to take calculated risks in pursuing new opportunities.

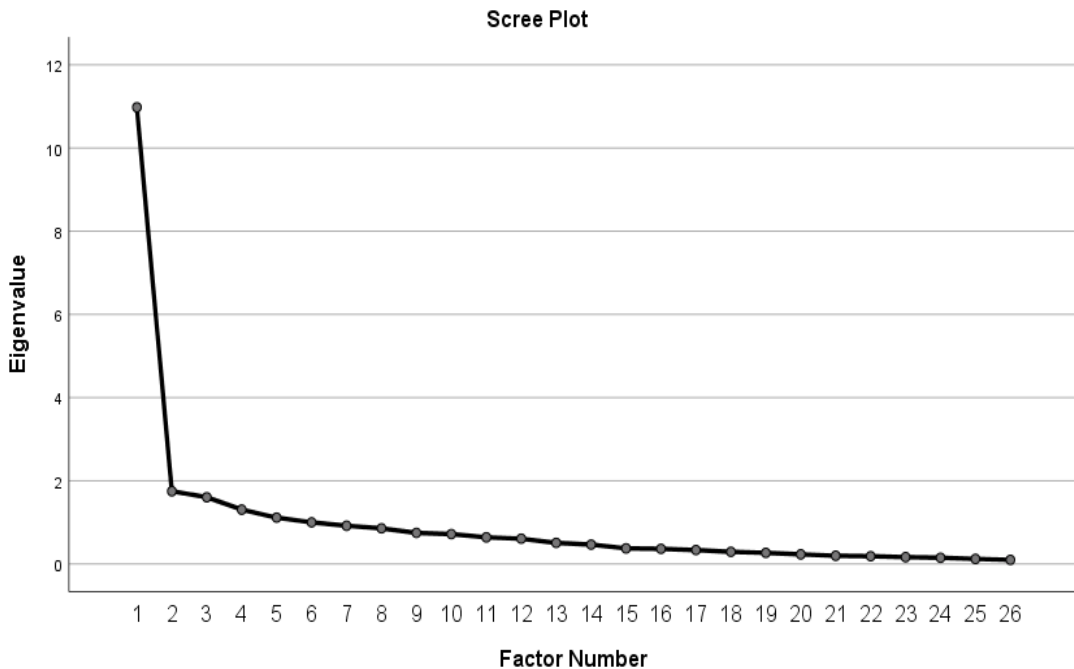


Figure 2. Scree plot of factor analysis results

Table 4. Factor analysis results

Dimension	Factor 1		Factor 2	
	Autonomy - Leadership		Innovativeness- Risk Orientation	
Factor Loading				
“I can accept critics and suggestions from others”	-	0.73	-	-
“I have good relationships with other people”	-	0.67	-	-
“I can manage team work well”	-	0.66	-	-
“I often find new ideas for my business”	-	-	-	0.81
“I find different ways to achieve the same result”	-	-	-	0.69
“I often find new innovations in the field I am in”	-	-	-	0.68
Kaiser-Meyer-Olkin Measure of Sampling Adequacy				0.88
Bartlett's Test of Sphericity	Approx. Chi-Square			1140.52
	df			325
	Sig.			0.000

Based on the factor scores, respondents were categorized into four groups (Fig. 3). The majority of the respondents (32%) belonged to Group 1, characterized by high scores in both Autonomy-Leadership and Innovativeness-Risk Orientation. This study found that 82% of the NTF farm alumni belong in Group 1, and the remaining 18% belong in Group 2. NTF farm is the only farm that gives routine financial and entrepreneurial education to its trainees. This shows that financial and entrepreneurial education during training in Japan has helped foster both confidence and innovative thinking. These findings align with Japanese research emphasizing that the management philosophy of host farms plays a crucial role in skill and mindset transfer. Nikaido (2021) found that agricultural employers who view trainees as future collaborators rather than temporary laborers foster stronger autonomy and proactive learning—conditions that appear to resonate with the “Autonomy–Leadership” and “Innovativeness–Risk” dimensions identified in this study.

However, respondents in Groups 3 and 4 were mainly composed of slightly older alumni with longer post-return experience, displaying lower Innovativeness-Risk Orientation but moderate Autonomy-Leadership scores. This suggests that age and accumulated managerial experience may shift focus from innovation toward operational stability and team coordination, a trend also reported in prior entrepreneurship research (Rauch and Frese 2007).

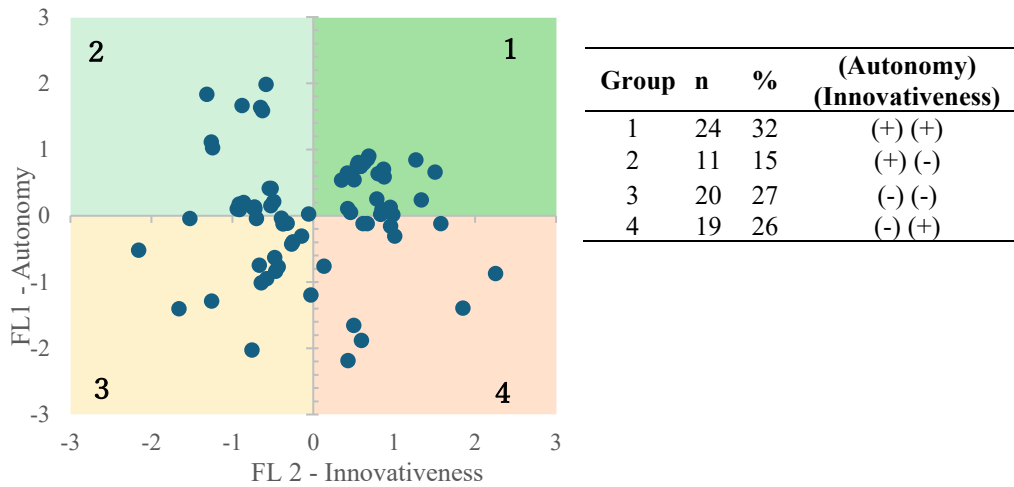


Figure 3. Grouping of respondents based on autonomy-managements and innovativeness-risk factor loading

Table 5 shows the distinct demographic patterns across the four groups derived from factor analysis. Groups 1 and 2 are dominated by younger alumni. These people show higher Autonomy-Leadership and Innovativeness-Risk Orientation, suggesting that young returnees tend to apply skills obtained from TITP more dynamically in their enterprises. In contrast, Group 3 and 4, members with average age of 35 years and have been back in Indonesia for more than 10 years, show lower Innovativeness-Risk Orientation but maintain moderate (better) Autonomy, indicating a shift toward managerial stability and operational control with experience.

Table 5. General demographic profile of the FA groups

Group	Autonomy - Leadership	Innovative-Risk	Age	Training Length (Years)	Years After Return	Entp.* Experience (years)	Land Owned (Ha)
1	0.736	0.196	31.6	1.77	7.97	5.9	1.31
2	0.776	-0.112	31.4	1.68	7.88	4.9	1.24
3	-0.664	0.006	35.7	1.86	11.09	7.9	1.21
4	-0.732	-0.035	35.3	1.78	10.38	7.7	1.28

Note: *Entrepreneurship

Source: Survey data (2021-2023)

Interestingly, the length of training (1.6-1.8 years) is consistent across all groups, implying that training quality gives stronger influence on IEO outcomes compared to the duration of training. It is worth noting that the average effective duration for the successful alumni is around 1.7 to 1.8 years. This may indicate that programs with a very short duration, such as those under one year, are less effective in fostering an entrepreneurial orientation. Future programs, such as the ESD, should consider the duration of training more thoroughly.

CONCLUSION

This study provides quantitative evidence that participation in TITP fosters stronger autonomy-leadership, and innovativeness-risk orientations among Indonesian alumni. Exposure to Japan's structured agricultural environment and professional work culture has contributed to developing a stronger sense of responsibility, initiative, and adaptive thinking among trainees; traits that remain vital after returning home. These behavioral transformations suggest that TITP seems to serve not only as a platform to transfer technical skills but also as a formative experience that cultivates entrepreneurial mindset development. This confirmed the importance of entrepreneurship education and mentorship within technical training programs. Specifically, fostering autonomy and innovativeness can enhance rural livelihoods and sustain the growth of agripreneurship in Indonesia. It is worth noting that the average effective duration for successful alumni is approximately 1.7 to 1.8 years, suggesting that programs shorter than one year may be less effective in fostering entrepreneurial orientation.

This research is limited by its relatively small sample size and focuses on Indonesian alumni of the Japanese agricultural TITP, which may restrict the generalization of findings to other countries or programs. Moreover, the use of self-reported data could introduce response bias. Despite these constraints, the identification of Autonomy-Leadership and Innovativeness-Risk Orientation as dominant IEO dimensions suggests a clear policy direction: integrating entrepreneurship-focused modules and ensuring post-return support within TITP and similar programs could significantly improve their long-term impact on agribusiness development.

For further studies, comparative studies between TITP and the newer Specified Skilled Workers (SSW) program would also help clarify how differences in program design and structure could influence long-term employability, entrepreneurial orientation, and local economic contribution. Multi-country approaches would further explain how institutional and cultural contexts mediate the experience of overseas training into sustainable agribusiness development. As for the upcoming ESD program revision expected in 2027, the findings indicate the value of retaining and strengthening entrepreneurial development components, including structured learning modules and post-return support systems to enhance the long-term developmental impact of overseas agricultural training.

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FARMER PARTICIPATION IN AGRICULTURAL TRAINING DURING THE COVID-19 PANDEMIC: INSIGHTS FROM THE FARMER-SCIENTISTS TRAINING PROGRAM IN LUZON, PHILIPPINES

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ABSTRACT

The COVID-19 pandemic disrupted agricultural training and extension services essential for sustained farmer development. This study used a qualitative multiple case design, guided by Park's Adult Dropout Model and Self-Determination Theory, to examine two Farmer-Scientists Training Program cases in Luzon, Philippines, with contrasting completion rates and identify factors influencing participation and training completion. Data were collected from all 43 farmer-participants using semi-structured interviews, focus group discussions, key informant interviews with implementers, and relevant documents, with face-to-face sessions conducted consecutively from May to July 2023. The intrinsic motivation, particularly the desire to gain knowledge and improve farm productivity, was the primary driver of participation, supported by extrinsic motivation, such as recognition as "Farmer Scientists" and incentives. However, sustaining training participation and completion depended on the interplay of external factors, including pandemic-related restrictions, abiotic stresses, and health concerns, which interacted with internal factors such as training design limitations and reduced trainer interaction, undermining participants' sense of competence, autonomy, and relatedness. Conversely, family and organizational support, strong peer relationships, and adaptive program modifications promoted social and academic integration, enabling continued engagement. The study highlights the need for flexible, context-responsive agricultural training that strengthens social support and employs adaptable delivery strategies.

Key words: motivation, training completion, psychological needs

INTRODUCTION

Agriculture was among the several industries severely disrupted by the COVID-19 pandemic, which was declared a worldwide health emergency in the first quarter of 2020. Lockdowns and mobility restrictions disrupted supply chains, threatened food security, reduced labor availability, and constrained agricultural extension and advisory services (Delos Reyes and Padrid 2024; World Bank 2020). In the Philippines, Proclamation No. 922, which declared a state of public health emergency nationwide, was issued on March 8, 2020 (Republic of the Philippines 2020). A nationwide lockdown imposed on March 15, 2020, further limited mobility, prompting immediate government interventions such as the provision of farm inputs, essential services, and measures to secure food supplies while

enforcing health protocols (World Bank 2020). From 2020 to 2023, recovery efforts were pursued in line with Republic Act No. 8435, or the Agriculture and Fisheries Modernization Act (AFMA) of 1997, with training and education programs serving as a key strategy. Although initially suspended due to health restrictions, training activities eventually resumed, underscoring their vital role in agricultural recovery and long-term development. The Department of Agriculture’s Agricultural Training Institute (DA-ATI), the country’s lead provider of training and extension services, sustained program implementation in partnership with government agencies, Local Government Units (LGUs), and State Universities and Colleges (SUCs) (Baconguis 2022).

While previous studies have documented the broader impacts of the pandemic on agriculture, limited attention has been given to how training programs adapt during crises and, more importantly, to the factors that influence training completion. Previous research on the Farmer-Scientists Training Program (FSTP) in the Philippines during the COVID-19 pandemic by Cayabyab et al. (2024) showed that, despite the pandemic, training participants remained satisfied with the training content, resulting in improved technical competencies and farm productivity, while emphasizing the need for institutional and logistical support post-training to sustain training effectiveness. However, limited information exists on how such programs were implemented and sustained under mobility restrictions and public health protocols. Thus, this study examined the implementation of agricultural training programs during the COVID-19 pandemic within the context of the Farmer-Scientists Training Program, analyzed factors associated with training completion, and identified strategies to strengthen training delivery beyond the pandemic.

CONCEPTUAL FRAMEWORK

The study adopted the *Adult Dropout Model (ADM)* (Park 2007), which was modified and contextualized (Fig. 1) using findings from related empirical studies on farmers’ participation and attrition (Akinmusola et al. 2016; Azumah et al. 2022; Bahtera et al. 2016; Baynes et al. 2011) and guided by the *Self-Determination Theory (SDT)* (Ryan and Deci 2000).

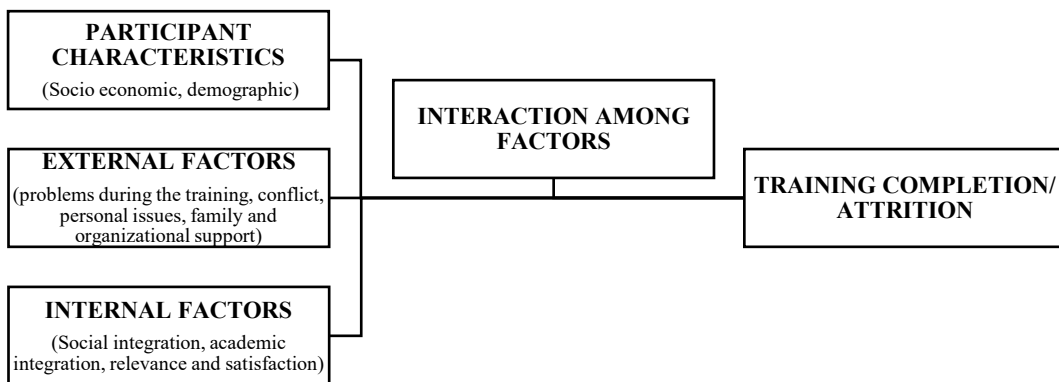


Figure 1. A conceptual framework showing the different factors influencing training completion/attrition.

The ADM is derived from the *Composite Persistence Model*, which was developed to explain learners’ perseverance in distance education settings (Rovai 2003). Rovai’s model, in turn, integrates key elements from *Student Attrition Model* (Bean and Metzner 1985) and the *Student Integration Model* (Tinto 1993), both of which were originally designed to explain student retention in formal education contexts.

According to the ADM, an individual's decision to complete training is influenced by three main factors: participant characteristics (socioeconomic and demographic), and external and internal factors. Empirical evidence suggests that participant characteristics alone exert only a limited or indirect influence on training attrition or completion but become significant when combined with other factors (Park 2007). The three factors are not mutually exclusive; rather, they are interconnected, and their interaction may lead to either training attrition or completion (Park and Choi 2009).

External factors refer to environmental elements outside the training program that may influence participant's decision-making regarding training completion. Identified factors include *scheduling conflicts, financial constraints, family and organizational support, personal issues, and other external challenges* beyond the control of both participants and trainers (Park 2007).

Internal factors encompass elements within the training program that directly affect participant's motivation, such as *social integration*, which is defined as the relationship between participants, their peers, and trainers, and *academic integration*, which includes aspects of training design such as mode of delivery, accessibility of training sites, and training duration (Tinto 1993). These also involve the *perceived relevance and satisfaction* derived from the program (Park and Choi 2009).

To further understand motivation and its relationship with training completion, this study draws on the *Self-Determination Theory (SDT)*, which divides motivation into intrinsic and extrinsic forms (Ryan and Deci 2000). Intrinsic motivation refers to behaviors driven by personal interest and the inherent satisfaction, fulfillment, or joy derived from the activity itself, while extrinsic motivation refers to acts motivated by external factors such as rewards, avoidance of punishment, or social pressure. SDT posits that maintaining motivation requires supporting three basic psychological needs: autonomy, competence, and relatedness. By applying this framework, the study aims to identify specific factors that may contribute to higher training completion rates and offers insights for strengthening agricultural training programs beyond the COVID-19 pandemic.

MATERIALS AND METHODS

The study employed a multiple qualitative case study approach focusing on two municipalities in Luzon, Philippines. Luzon was selected because it hosts several established sites of the Farmer-Scientists Training Program (FSTP) and experienced varying completion rates during the COVID-19 pandemic (2020 to 2022), making it an appropriate setting to examine factors influencing program participation and completion. Two municipalities were purposively selected, one with a low completion rate and another with a high completion rate, to identify key factors affecting training outcomes.

The multiple case study design allowed for an in-depth investigation of the phenomenon using a variety of data sources, in line with Creswell (2014). Credibility and validity were ensured through personal interviews, focus group discussions (FGDs), and key informant interviews (KIIs) (Creswell and Miller 2000), complemented by secondary data from the Agricultural Training Institute Regional Training Center (ATI-RTC) and the University of the Philippines Los Baños (UPLB).

Before data collection, the study protocol underwent an ethics review process through the UPLB Research Ethics Board. A complete enumeration of 43 farmer-participants from both municipalities was conducted due to the relatively small population. For the FGDs, at least six farmers from each municipality participated to enrich the data and allow sufficient time for sharing. KIIs were conducted with one representative each from the ATI-RTC, UPLB, and the Local Government Unit (LGU) overseeing FSTP implementation in the respective municipalities. Table 1 presents the number of participants from each case according to data collection method.

Data collection from the two sites was conducted consecutively, with the researcher personally facilitating face-to-face sessions from May to July 2023. Relevant secondary data were also gathered simultaneously. Informed consent forms were obtained from all the participants to ensure compliance with ethical standards. A structured questionnaire was administered prior to the interviews to collect the farmers' socioeconomic and demographic characteristics, while guided questions were used during the interviews, FGDs, and KIIs. The collected data were summarized and analyzed using thematic analysis, guided by the study's conceptual framework to identify and group recurring themes, trends, similarities, and differences. Notable themes, translated direct quotations, and participant narratives were integrated into the analysis and discussion. The names of the municipalities were omitted to protect participants' confidentiality and privacy.

Table 1. Number of participants per case by data collection procedure.

Data collection procedure	Case 1 Low training completion	Case 2 High training completion
Farmer interviews	16	27
Focus group discussions	6	8
Key informant interviews	3	3

RESULTS AND DISCUSSION

Case study context. The Farmer-Scientist Training Program (FSTP) is a nationwide initiative of the Department of Agriculture's Agricultural Training Institute (DA-ATI), implemented in partnership with the University of the Philippines Los Baños (UPLB), local government units (LGUs), and other agencies. Institutionalized through Executive Order No. 710 in 2008, the program develops farmer-scientists through a three-phase framework focusing on corn research and experimentation, technology adoption, and farmer-to-farmer knowledge transfer (Davide et al. 2016). The FSTP was implemented in both cases during the peak of the COVID-19 pandemic. Case 1 was conducted from December 2020 to 2022, while Case 2 took place from September 2020 to 2022. Participant attrition occurred primarily during Phase II. In Case 1, 50 percent of participants who completed Phase I advanced to the next phases, compared with 77.78 percent in Case 2 (Table 2).

Table 2. Training participants per phase.

Variable	Category	Case 1		Case 2	
		Low training completion	High training completion	Low training completion	High training completion
		F	%	F	%
Participants	Phase I	16	100	27	100
	Phase II	8	50	21	77.78
	Phase III	8	50	21	77.78

Participant's profile. Participants in both cases were predominantly women, aged 40 to 77, married, with household sizes exceeding three members. Most were seasoned farmers with 20 to 40 years of experience and owned farms of 1 to 2 hectares. Differences were observed in education and income

levels. Half of Case 1 participants attained tertiary education compared with only 18.52 percent in Case 2. Similarly, 50 percent of Case 1 participants had monthly household incomes above ₱10,000, whereas most Case 2 participants earned less than ₱10,000 and relied primarily on farming (Table 3).

Table 3. Key characteristics of 43 farmer-participants from two municipalities in Luzon, 2023.

Dominant characteristic	Case 1	Case 2
	Low training completion	High training completion
Women (%)	50	59.26
Average age (years)	58	55
Age (range)	41-70	41-77
With tertiary education (%)	50	18.52
Married (%)	88.50	100
Average household size	4	5
Sole income from farming (%)	31.25	62.96
Monthly household income > ₱10,000 (%)	50	7.41
With 20-40 years of farming experience (%)	43.75	74.07
Owns farm (%)	75	62.96
Farm size of 1-2 ha (%)	50	62.96

Motivation of training participants. Across both cases, intrinsic motivation emerged as the primary driver of participation. Participants sought to acquire new knowledge, enhance farm productivity, and improve their families’ livelihoods, consistent with the conceptualization of intrinsic motivation (Ryan and Deci 2000). In Case 1, many were motivated by their desire to learn and explore innovations in corn production to improve farming practices. A 61-year-old male participant stated, *“The changing agricultural landscape requires us farmers to adapt, and we can only do so by participating in various training programs offered by the LGU,”* while a training implementer added that “farmers are yearning for appropriate technologies and practices suited to their farming needs.”

Similarly, participants in Case 2, many of whom were shifting from rice to corn production, expressed curiosity about the scientific methods introduced in the program. A 69-year-old male participant explained, *“We aim to learn the scientific ways of farming to enhance our yield and income, thus we value every training.”* Some couples also joined to learn directly rather than rely on their spouses, and others were motivated by positive experiences in previous LGU-led programs.

Intrinsic motivation in both cases was complemented by extrinsic motivation, such as the challenge of sharing knowledge with fellow farmers, aspirations to gain recognition as “Farmer

Scientists,” and the receipt of farming materials as incentives, all of which have been shown to support farmer participation in training programs (Akinmusola et al. 2016; Was et al. 2021). Likewise, previous studies highlight that farmers motivated by learning, self-improvement, and the perceived relevance of training are more likely to participate, remain engaged, and complete their training (Akinmusola et al. 2016; Bahtera et al. 2016; Charatsari et al. 2017; Mariyono et al. 2022; Zhu and Yang 2012).

External factors. In Case 1, participation was primarily constrained by the COVID-19 pandemic. Lockdowns caused the cancellation or rescheduling of sessions, while travel restrictions limited attendance and prevented trainers from conducting regular monitoring. These disruptions undermined participants’ sense of autonomy and reduced motivation despite strong intrinsic motivation. A 59-year-old male discontinued training participation due to COVID-19 concerns, and a 70-year-old participant explained that although he was “very eager and inspired to participate in the first phase,” worsening conditions during the second phase heightened his fear of infection, which eventually “overshadowed his interest in the training” and led to withdrawal. Distance and mobility constraints also discouraged participation; a 48-year-old female participant reported, “I live far away from the training, and sudden lockdowns and rescheduling of classes became a nuisance for me.” Lockdowns further prevented participants whose farms were outside their barangays from conducting Phase II field experiments, resulting in automatic dropout for those unable to comply.

Unfavorable weather conditions, including typhoons, drought, and pest infestations, posed additional challenges, consistent with the identification of common abiotic stresses in Philippine corn production (Gerpacio et al. 2014). Personal circumstances also reduced participation. A 41-year-old male cited business commitments and time constraints from off-farm and non-farm work, similarly limited involvement, leading to discontinuation due to opportunity costs (Azumah et al. 2022; Praneetvatakul and Waibel 2001). Involvement in multiple livelihood activities can interfere with training activities and prompt individuals to prioritize immediate income-generating tasks (Alemu 2021; Azumah et al. 2022). Collectively, these external factors weakened motivation even among participants who initially demonstrated strong intrinsic motivation.

In Case 2, the pandemic had minimal impact and the program proceeded without lockdown-related disruptions. However, unfavorable weather and pest infestations required repetition of experiments and limited the involvement of older individuals in field activities. Despite a generally high completion rate, some participants were unable to finish the program. Attrition largely involved older female participants whose household responsibilities hindered their ability to maintain Phase II on-farm experiments. As one 55-year-old participant stated, she wished to complete the training but “could not comply with the on-farm setup,” citing childcare and household chores. Another participant, aged 64, withdrew due to age-related health concerns. These patterns align with observation that farmers with limited labor resources are more likely to discontinue training (Waddington and White 2014). Additional withdrawals were due to competing professional or personal commitments; barangay officials struggled to fulfill training requirements alongside official duties, while a 44-year-old male participant exited after relocating to pursue business opportunities. This case illustrates how labor constraints, competing responsibilities, and livelihood transitions continue to shape participation even without pandemic-related disruptions.

Across both cases, family and organizational support helped sustain participation despite the challenges faced. This is consistent with earlier studies that revealed family encouragement reinforced adult learners’ motivation and commitment (Terry 2007). In Case 1, participants came from diverse organizations, whereas in Case 2 most were siblings, relatives, or couples from farming households who collaborated and supported one another. Case 2 participants also belonged to the same farming association, fostering group cohesion and engagement. Peer and organizational support similarly promoted sustained participation (Park and Choi 2009). These findings indicate that participants’

motivation was strengthened through the fulfillment of the psychological need for relatedness, as described in Self-Determination Theory.

Internal factors. The lockdowns imposed during the COVID-19 pandemic constrained program implementation and prevented the training from being delivered according to its intended design. Although participants in both cases completed Phase I, which involved group-based experiments, attrition emerged in Phase II when individual on-farm experimentation was required. In Case 1, continuous lockdowns prevented most participants from conducting their individual experiments, and implementers were unable to provide regular monitoring or timely guidance, further limiting participants' ability to meet program requirements. One 43-year-old female participant withdrew due to miscommunication with implementers, highlighting the need for clearer support during experiment setup. The loss of contact during a period of heightened uncertainty contributed to feelings of hopelessness, reduced morale, and demotivation (Baynes et al. 2011). These disruptions also hindered the fulfillment of key psychological needs identified in Self-Determination Theory: competence, autonomy, and relatedness. Participants' sense of competence was weakened by their inability to carry out experiments effectively, their autonomy was constrained by limited control over the training process, and relatedness declined due to reduced interaction with implementers and peers.

To address these challenges, training implementers revised the program design by reverting to group-based experiments and organizing participants by barangay. However, this strategy remained infeasible for some participants due to miscommunication and conflicting commitments. As a 54-year-old female participant explained, "I wished to continue the training with my groupmates, but some were reluctant to proceed due to competing activities, which prevented us from conducting the experiment."

Despite these constraints, social integration played a critical role in sustaining participation among those who continued. Supportive peer relationships were an important motivational resource, particularly in overcoming logistical barriers. As one 48-year-old female participant described:

I live far from the training site, and I find participating challenging since I do not have a means of transportation. But, my co-trainees, who turned into friends, exerted their efforts and even picked me up to ensure I would participate. Had it not been for their support, I would not have been able to complete the training.

This finding is consistent with earlier observations which demonstrated that social capital, fostered through training interactions, enhances sustained engagement by reinforcing collective commitment (Bahtera et al. 2016). Some participants were also motivated by a strong desire to learn, improve production, and derive satisfaction from the program's relevance to their needs. As a 47-year-old female participant explained:

As fortunate farmers selected as participants, it seemed only fitting to finish what we started. We had invested our time and effort and were committed to completing all three phases of FSTP. Moreover, I wanted to gain the experience of teaching our fellow farmers to test if I have what it takes to serve as a "Farmer-Scientists-Teacher."

In Case 2, participants faced challenges related to unsuitable land and ongoing rice production during Phase II, prompting adjustments such as using alternative participants' farms and conducting on-farm experiments concurrently with Phase III. Consistent support and regular interaction with implementers inspired perseverance. Participants valued implementers' visits, which made them feel valued and provided an opportunity to voice concerns. The empathy demonstrated by implementers, along with field trip activities, encouraged active participation. Commitment to completing the program

was driven by a desire to learn, the relevance of the content to farming needs, and overall satisfaction with the training. These factors contributed to the high completion rate observed. A 48-year-old female participant shared that, despite being teased by younger neighbors for studying at an older age, she felt proud to gain practical knowledge beneficial to her livelihood.

CONCLUSION

The case of the Farmer-Scientist Training Program during the COVID-19 pandemic demonstrates that while intrinsic and extrinsic motivations effectively draw farmers into agricultural training, sustaining participation and achieving completion require supportive conditions across both external and internal domains. Pandemic-related restrictions, weather and pest pressures, and health concerns interacted with limitations in training design and implementation, creating barriers that were especially pronounced among participants facing mobility constraints, household responsibilities, or health vulnerabilities. Even in the case less affected by the pandemic, labor demands, competing responsibilities, and livelihood transitions continued to influence participation. These dynamics reveal that training completion depends not only on participants' motivation to engage but also on their ability to fulfill the psychological needs for competence, autonomy, and relatedness. The cases further showed that external factors such as family and organizational support, along with internal factors such as relationships with co-participants and trainers through social integration, play an important role in fostering a training environment that satisfies the need for relatedness. Likewise, modifications made by trainers to the program design, such as allowing group experiments, the use of other farms for on-farm experiments, and the simultaneous conduct of these activities alongside Phase III in consultation with participants, promoted adaptability and continuity. This reflected academic integration that allowed the training to proceed despite pandemic disruptions. These adjustments resulted in a program that was relevant and satisfactory to participants, supporting the fulfillment of competence and autonomy and ultimately contributing to training completion.

Moving forward beyond the pandemic, the findings highlight the importance of designing agricultural training programs that are both flexible and responsive to participants' needs and the contextual challenges that may arise over time. Mechanisms that strengthen social support, promote adaptive training design, and ensure relevance to the improvement of farmers' livelihoods should be prioritized. By addressing the various factors influencing participation, engagement and completion in agricultural training can be enhanced, delivering more effective programs that promote sustained learning, practical application, and long-term benefits for farmers and their communities.

Although this study identified factors influencing participation and completion in agricultural training, its qualitative design limits the generalizability of the findings. Future research could build on these insights by employing a quantitative or mixed-methods approach, which would provide a broader understanding of the determinants of participation and completion and enable more targeted strategies for improving agricultural training programs.

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**BIOLOGY AND MASS REARING OF THE ARMYWORM,
Spodoptera pecten Guenée, 1852 (Lepidoptera: Noctuidae)
IN THE PHILIPPINES UNDER LABORATORY CONDITIONS**

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ABSTRACT

The armyworm, *Spodoptera pecten* Guenée, is a polyphagous pest of crops across a wide distribution range in the tropics, including regions such as Japan, Hawaii, and the Philippines. This species is considered an emerging pest of corn and other crops in Southeast Asia, and its increasing occurrence in the Philippines poses potential risks to crop productivity and pest management programs. Understanding its biology is therefore important for accurate identification, monitoring, and development of effective control strategies. Hence, the biology of the pest was investigated using corn leaves (IPB var. 6) as a substrate. The observed developmental periods revealed that eggs hatched within 3–5 days ($\bar{x} = 3.15 \pm 0.53$), first instar, 3-5 days ($\bar{x} = 3.05 \pm 0.31$), second instar, 3-4 days ($\bar{x} = 3.02 \pm 0.16$), third instar, 2-5 days ($\bar{x} = 3.27 \pm 0.71$), fourth instar, 1-4 days ($\bar{x} = 2.10 \pm 0.74$), fifth instar, 1-4 days ($\bar{x} = 2.76 \pm 0.66$), sixth instar, 3-6 days ($\bar{x} = 4.39 \pm 1.09$), pre-pupa, 1-2 days ($\bar{x} = 1.22 \pm 0.47$), and pupa, 8-11 days ($\bar{x} = 9.48 \pm 0.77$). Post-development periods for female adults included pre-oviposition, 0-7 days ($\bar{x} = 3 \pm 2$), oviposition, 0-4 days ($\bar{x} = 2.27 \pm 1.71$), and post-oviposition, 0-2 days ($\bar{x} = 0.83 \pm 0.72$). Female fecundity ranged from 91 to 1,278 eggs ($\bar{x} = 477 \pm 381.58$ eggs per female). Adult male longevity was 7.47 ± 1.35 days, and female longevity was 6.93 ± 2.10 days, and the sex ratio (male: female) was 1.2:1. Mass rearing of *S. pecten* under laboratory conditions was also discussed. These results may be useful for predicting population dynamics of *S. pecten* and improving its management.

Key words: corn, defoliator, IPM, polyphagous pest

INTRODUCTION

The genus *Spodoptera* (Lepidoptera: Noctuidae) comprises 31 species, half of which are significant crop pests and have become major invaders, colonizing areas outside their native range, as seen with the fall armyworm, *Spodoptera frugiperda* (J.E. Smith) (Brown et al. 2009; Kergoat et al. 2021). These species are widely distributed throughout tropical and temperate Asia, Australia, and the Pacific Islands (CABI 2022). Known by various names such as fall armyworm, corn leafworm, grass worm, and southern grassworm, their larvae feed on a broad range of host plants- a total of 353 *S. frugiperda* larval host plant records belonging to 76 plant families (Montezano et al. 2018).

Spodoptera pecten Guenée is a highly adaptable species with a wide distribution range in the tropics, including regions such as Japan, Hawaii, and the Philippines. Guerrero et al. (2024) reviewed the distribution of *S. pecten*, which included India, Cambodia, Pakistan, Nepal, Bhutan, Bangladesh,

Sri Lanka, Myanmar, Vietnam, Malaysia, China, Brunei, Taiwan, South Korea, Japan, and Papua New Guinea. Known for its polyphagous nature, the larvae of *S. pecten* are notorious for feeding on the foliage of various crops, including rice, corn, and different grass species.

The Philippines experienced outbreaks of several *Spodoptera* species, including *S. exigua* (Hubner), or onion or beet armyworm, which caused an outbreak in 2016 (Navasero 2017; Navasero et al. 2019), and remains a significant pest problem in onion cultivation in Central Luzon. The fall armyworm (FAW), *S. frugiperda*, caused damage in 2019 and remains an invasive pest of corn (Navasero et al. 2019).

The life cycle of *Spodoptera* species follows the typical pattern of lepidopteran insects, passing through egg, larval, pupal, and adult stages. Larvae, commonly known as armyworms due to their tendency to move in large groups resembling an advancing army, are the most destructive stage of the insect. Feeding voraciously on plant foliage, particularly during early crop stages, can cause significant defoliation and yield losses.

The economic impact of armyworm infestations can be severe, resulting in reduced yields, increased production costs, and economic losses to farmers, especially in regions where agricultural crop cultivation is a primary source of livelihood (Sampiano 2026; Navasero et al. 2019; Navasero 2017; Nueva Ecija Provincial Agriculture 2016). Among these species, *S. pecten* is considered an emerging pest of corn and other crops in Southeast Asia, and its increasing occurrence in the Philippines poses potential risks to crop productivity and pest management programs. Moreover, the reliance on chemical insecticides for pest control raises concerns about environmental pollution, human health risks, and the development of insecticide resistance in armyworm populations. Understanding the biology of *S. pecten* is therefore important for accurate identification, monitoring, and the development of effective control strategies.

Efforts to manage armyworm infestations often involve integrated pest management (IPM) strategies incorporating cultural, biological, and chemical control methods (Machado et al. 2020). Cultural practices such as crop rotation, intercropping, and the use of resistant crop varieties can help reduce the vulnerability of crops to infestation. Biological control agents, including natural enemies such as parasitoids and predators, offer environmentally friendly alternatives to chemical pesticides.

Despite these control efforts, the adaptability, high mobility, polyphagous nature, and rapid reproductive potential of armyworms present challenges for effective pest management (Sampiano 2026). For example, the rapid spread of the fall armyworm (*S. frugiperda*) across the Philippines and its invasion into the Davao Region, feeding aggressively on young leaves, whorls, tassels, and ears causing visible damage such as window paning, ragged cuts, and heavy defoliation that can lead to great losses; coupled with vulnerability of Davao Region's agricultural system across diverse cropping systems, and risks on over reliant to chemical -based control, led to urgent need for region-specific management strategies (Sampiano 2026). Continued research into the biology, ecology, genetics, and behavior of this species is essential for the development of sustainable and resilient agricultural systems capable of mitigating the threats posed by armyworms to global food security and livelihoods.

Recently, egg masses of *S. pecten* from leaves of yellow duranta and mulberry plants in the Philippines were collected for the first time, but these were initially mistaken for the eggs of *Spodoptera litura*, a highly polyphagous and destructive pest in the Philippines (Gabriel 2000) due to the profuse covering of the egg masses. Reports show this species is similar to *Spodoptera mauritia* but slightly smaller (Holloway 1976) and has been reported as a pest of corn in Malaysia and rice in several Asian countries (CABI 2022). Adult males of *S. pecten* are characterized by bipectinate antennae, a feature that distinguishes them from several related *Spodoptera* species with filiform antennae. The adults also exhibit brown forewings with relatively less variegated patterning compared with *S. mauritia*, and

hindwings lacking the strong dark delineation of veins present in that species. In addition, genitalic characters provide reliable identification, with the species exhibiting distinctive structures in both male and female genitalia that are commonly used in taxonomic diagnosis of *Spodoptera* species (Holloway 1976). It was later identified as *Spodoptera pecten* Guenée by molecular analysis (Guerrero et al. 2024).

This study sought to investigate some basic aspects of the biology and rearing of *S. pecten* under laboratory conditions in the Philippines. As a major pest of corn and other crops, understanding its developmental stages and morphological characteristics is important for improving pest management strategies. Specifically, this study aimed to: (1) determine the different life stages, fecundity, longevity and sex ratio of *S. pecten* on a native variety of corn; (2) describe the changes in color, size, and habits during development; (3) determine morphometric measurements at specific growth stages.

MATERIALS AND METHODS

Test insects. Eggs masses of *S. pecten* were collected on leaves of *Duranta erecta* L. (Verbenaceae) and reared in the laboratory from August to December 2024 at the National Crop Protection Center, College of Agriculture and Food Science, University of the Philippines Los Baños.

Fresh corn leaves (IPB var 6) were washed thoroughly and air-dried to ensure cleanliness before offering as food for the neonate larvae (Navasero and Navasero 2020). Once the larvae reached the third instar stage, they were reared individually in Petri plates to avoid any potential cannibalism, competition or interference during feeding and development. Fresh corn leaves, which were both fresh and surface-sterilized, and offered to the larvae daily until pupation.

Pupae were carefully managed and placed in Petri plates for holding before transferring to Mylar cages to facilitate adult eclosion. Adults mated, and females laid eggs on leaves of corn, establishing a colony inside these cages.

Throughout the rearing process, the setups were kept within a temperature range of 27-29°C, with a relative humidity (RH) maintained at 60-70%, as in FAW (Navasero and Navasero 2020). Additionally, a photoperiod of 12 hours of light followed by 12 hours of darkness (12D:12L) was maintained to mimic natural light cycles and support normal developmental processes.

Biological Characterization

Life history. A pair of adults was caged, with 10 pairs prepared in this manner following the method of Navasero and Navasero (2020) for *S. frugiperda*. These cages, with a diameter of 9 cm, were lined with wax paper above, below, and along the sides to serve as a substrate for oviposition.

The cluster of eggs was individually placed in a Petri dish lined with filter paper moistened with distilled water, where it remained until hatching. From these eggs, 60 neonates were individually transferred onto Petri plates, and fresh corn leaves were offered as food until pupation. The molting, growth, and development of the larva, the need to replace food, were observed and recorded daily. Pupation and eclosion to the adult stage were also recorded. Details in the appearance, color, and hair cover of the egg/egg mass, including the incubation period, characteristics of each larval instar, and the pupal period, were observed and described.

Furthermore, the pre-oviposition, oviposition, and post-oviposition for female adults and the longevity of both male and female adult individuals were recorded by monitoring their lifespan from emergence to death. During the oviposition periods of female adults, fecundity was monitored daily until females stopped laying eggs. Egg hatchability was another parameter monitored and recorded.

Laboratory mass rearing technique. The rearing setup consisted of improvised rearing pans (45 cm long, 10 cm high, and 30 cm wide), with aeration windows (22 cm x 14 cm) covered with fine-mesh muslin (used for rearing *S. frugiperda* in Navasero and Navasero 2020). The container was provided with a paper towel, although plain paper could also be used as a lining, which served to collect larvae's excreta and absorb excess moisture, making disposal easier. Before reuse, the containers were properly cleaned and disinfected. A paper towel was placed over the top of the pan before securing the cover to prevent small larvae from escaping.

Rearing procedure

Adult pairing. Newly emerged adults (a female and a male moth) were placed in mating/oviposition cages with cotton balls soaked in a 20% sugar solution for nourishment, following the method of Navasero and Navasero for *S. frugiperda*. Once the females started to lay eggs, each pair was gently moved to a different cage equipped with the same setup, and the egg masses were then collected in a Petri plate for holding. For mass rearing, eggs laid up to the 3rd or 4th day were used.

Larval feeding and pupation. Ten to fifteen young corn seedlings, cut at the base and aged 10-15 days after sowing (DAS), were provided per pan to feed approximately 500-1,000 neonate larvae. After 24 hours, five pieces of newly harvested corn stalks were added to replace the spent ones. This routine was repeated every 24 hours, with fresh corn stalks replacing the old ones, which were then carefully removed. At the 3rd instar stage, the larvae in culture were divided into two groups. Another division occurred after an additional 3-4 days, and further splitting was performed as needed. When pre-pupae were observed, these were separated into rearing containers for holding until pupation. Pupae were then transferred to a separate cage for eclosion to adults, initiating another rearing cycle.

Statistical analysis. Mean values and standard deviations for the data on life history, body measurements of *S. pecten* were calculated using Microsoft Excel.

RESULTS AND DISCUSSION

Life history of *S. pecten*

Eggs. Eggs of *S. pecten* exhibited distinctive characteristics, being spherical or slightly flattened, with a smooth surface and initially displayed a pale coloration. As these matured, their color gradually darkened (Fig. 1 A-C). These eggs were typically laid in clusters, covered with thick hairs. These were commonly found on the undersides of leaves of various host plants, such as corn, mulberry, yellow duranta, or other suitable substrates like muslin cloth, wax paper, or Mylar plastic, within the oviposition cage. On average, the eggs measured 0.44 ± 0.01 mm (Table 1). In the laboratory setting, the incubation period for the eggs typically ranged from three to five days ($X=3.15 \pm 0.53$) (Table 2).

Table 1. Measurements (mm) of the egg, larval instars, pupae, and adults of *Spodoptera pecten* reared on corn under laboratory conditions.

Developmental Stage	Parameter	Mean±SD
Egg	Width	0.44±0.01
Larva		
1 st instar		
Head capsule	Width	0.25±0.01
Body	Length	2.17±0.20

Developmental Stage	Parameter	Mean±SD
	Width	0.34±0.04
2 nd instar		
Head capsule	Width	0.43±0.07
Body	Length	3.28±0.20
	Width	0.55±0.05
3 rd instar		
Head capsule	Width	0.72±0.09
Body	Length	6.31±0.57
	Width	1.08±0.17
4 th instar		
Head capsule	Width	0.96±0.09
Body	Length	9.09±0.75
	Width	1.51±0.13
5 th instar		
Head capsule	Width	1.52±0.35
Body	Length	15.34±1.83
	Width	2.42±0.32
6 th instar		
Head capsule	Width	2.50±0.13
Body	Length	25.59±3.81
	Width	4.31±0.27
Pupa		
Male	Length	13.17±0.70
	Width	4.50±0.20
Female	Length	13.52±0.85
	Width	4.69±0.33
Adult		
Male		
Wing expanse	Wing expanse	31.45±1.25
Female		
Wing expanse	Wing expanse	30.68±3.88



Figure 1. *Spodoptera pecten*: A. egg-mass, B. Egg, C. eggs hatching, D. and E. 1st instar, F. 2nd instar, G. 3rd instar, H. 4th instar, I. 5th instar, J. 6th instar, K. pre-pupa, L. pupa, M. male adult, N. female adult

Larval stage. During the larval stage, newly hatched larvae were tiny, hairy, and pale in color with olive brown heads and whitish V-shaped sutures (Fig. 1D-E). These often exhibited gregarious behavior, congregating in large groups, and displayed a characteristic looping motion when agitated. As the larvae progressed through development, they underwent distinct instar stages, with each instar marked by specific morphological, size, and behavioral changes. For instance, the second instar (Fig. 1F) appeared less hairy and lacked the looping habit when crawling, until the third instar (Fig. 1G). Upon reaching the fourth instar until the sixth (Fig. 1H-J), larval skin became smooth. The coloration of larvae varied, encompassing shades of green, brown, or black, often with intricate patterns and markings.

One notable feature was the presence of distinct longitudinal stripes that run along the body, providing camouflage and aiding in their concealment among foliage. Additionally, rows of tubercles, small protuberances on the larvae's body, were observed, each bearing setae or tiny hairs.

Pupal stage: Non-feeding stage, typically oblong, reddish-brown or dark brown in color, and had a smooth, cylindrical shape, with distinct segmentation and appendages (Fig. 1H). Inside the pupal case, the adult structures developed, including wings, legs, antennae, and reproductive organs. The duration of the pupal stage varied. Initially, the pupa was greenish yellow, turning reddish-brown and finally blackish, before eclosion into the adult stage.

Adult stage: Upon emergence from the pupal case, adult moths had wings covered in scales, which varied in coloration and pattern but often included shades of brown, gray, or tan, with distinctive markings (Fig. 1 I-J), darker in males. The wingspan of adult moths ranged from approximately 30-40 mm for males and females. The antennae of the male moth are combed-like. Adult moths are equipped with mouthparts adapted for feeding on nectar from flowers, although they did not feed extensively. Moths are nocturnal. The adults exhibited brown forewings with relatively less variegated patterning compared with *S. mauritia*, and hindwings that lack the strong dark delineation of veins present in that species (Holloway 1976).

The genitalia of the male and female adults are shown in Figure 2, similar to those illustrated by Holloway (1976) for *S. pecten*.

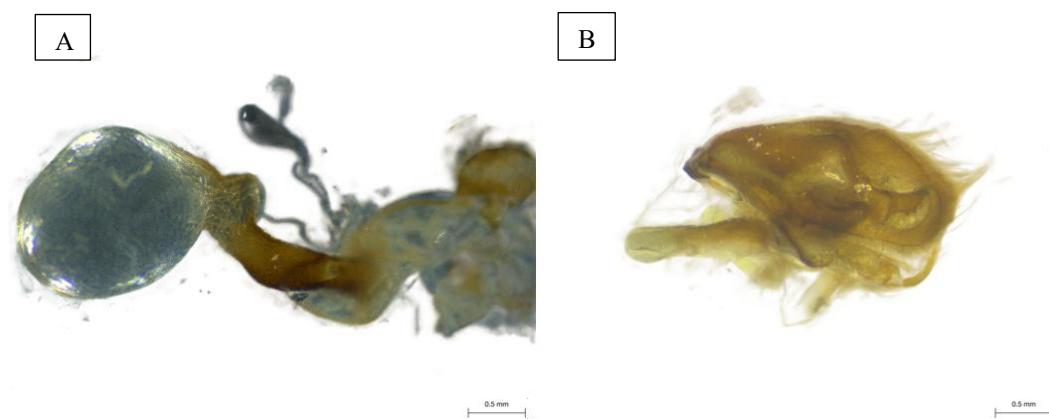


Figure 2. Genitalia of *Spodoptera pecten*: A) female and B) male. (Photo credits: Maricon dP. Javier).

Table 2 shows the durations of the different life stages of *S. pecten*. The eggs and the first three larval instars had the same durations. The combined duration of the fourth and fifth instar was as long as the 6th instar. The pre-pupal period was about 1.22 ± 0.47 d while the pupal period was 9.48 ± 0.77 d. Total larval period was 17.71d and total development period was 30.32 ± 0.54 d.

The pre-oviposition (3 ± 2 days) and post-oviposition (0.83 ± 0.72 d) periods were observed on *S. pecten*. The oviposition period was 2.27 ± 1.71 d.

Fecundity of females exhibited a wide variability in the number of eggs laid throughout their lifetime, ranging from 91 to 1278 eggs, with a mean of 477 ± 381.58 eggs). Adult male longevity was 7.47 ± 1.35 days, and female longevity was 6.93 ± 2.10 days; the sex ratio (male:female) was 1.2:1.

Table 2. Duration (in days) of the egg, larval instars, pupa, and post developmental stages of *Spodoptera pecten*.

Developmental Stage	Range (days)	Mean \pm SD
Egg	3-5	3.15 ± 0.53
Larva		
First instar	3-5	3.05 ± 0.31
Second instar	3-4	3.02 ± 0.16
Third instar	2-5	3.27 ± 0.71
Fourth instar	1-4	2.10 ± 0.74
Fifth instar	1-4	2.76 ± 0.66
Sixth instar	3-6	4.39 ± 1.09
Pre-Pupa	1-2	1.22 ± 0.47
Total larval period	14-18	17.71 ± 1.01
Pupa	8-11	9.48 ± 0.77

Developmental Stage	Range (days)	Mean \pm SD
Pre-oviposition period	0-7	3 \pm 2
Oviposition period	0-4	2.27 \pm 1.71
Post oviposition	0-2	0.83 \pm 0.72
Total developmental period (Egg-Adult)	30-32	30.34 \pm 0.54

Mass rearing of *S. pecten*. Survivability of larvae was 90 percent, pupation of survivors was 100 percent, and eclosion into adults was 100 percent (Fig. 3).

Only approximately 54.7% of the eggs laid by females of *S. pecten* in this study are fertile, indicating that a significant portion of the eggs may not successfully hatch or develop into viable offspring. This observation underscores the importance of factors such as mating success, environmental conditions, and physiological state in determining the fertility and reproductive output of female *S. pecten*. Likewise, the lifespan of male and female *S. pecten* individuals reveals interesting patterns. While both sexes exhibit relatively short lifespans, with males typically living between 4 to 12 days and females between 4 to 10 days, males tend to live slightly longer on average than females. This disparity in lifespan between the sexes may reflect differences in energy allocation, reproductive strategies, or susceptibility to environmental stressors (Cui et al. 2018).



Figure 3. Set-up for mass rearing *Spodoptera pecten*: a) fresh young corn leaves, b) young corn leaves in a rearing pan, c) larvae with newly replenished food, d) covered rearing pan, e) sorting of larvae based on instar, f) pupation in rearing pans, g) pooled pupae from rearing pans, h) oviposition cage with adult males and females on young leaves of corn as oviposition substrates.

The immature feeding stages (larvae) of *S. pecten* underwent six instars on corn. However, in other species of *Spodoptera*, some authors have reported five to eight larval instars, on corn for *S. exigua*, attributed to the quality of the host plant, differences in geographic population, presence of hairs on leaves, variability or reduction of nutritional quality of host plant species (Azida and Sofian-Azirun 2006).

The duration of the immature stages of *S. pecten* resembled those described of the same genus for other species of *Spodoptera*, and whose larvae fed with various host plants such as *S. frugiperda*, and *S. albula* (Montezano et al. 2013), *S. frugiperda* on corn and *S. exigua* on cabbage leaves (Azidah and Sofian-Azirun 2006) *S. litura* on castor leaves (Sharma et al. 2025), asparagus (Ye et al. 2022), and other host plants (Sultan et al. 2020). Despite the similarities, several authors have shown a great variation in the duration of the life cycle of the *Spodoptera* species, as influenced by the larval diet (Ye et al. 2022; Mehta et al. 2021; Silva et al. 2019).

The pre-oviposition and post-oviposition periods, as described, are integral components of the reproductive cycle of *S. pecten*, shedding light on the timing and dynamics of egg-laying behavior. With a mean duration of 3 ± 2 days, the pre-oviposition period denotes the timeframe leading up to egg-laying, during which females prepare for reproduction. Similarly, the post-oviposition period, averaging 0.83 ± 0.72 days, occurs immediately after egg-laying and likely involves recovery or recuperation. Notably, both these periods are slightly shorter than the oviposition period itself, which spans approximately 2.27 ± 1.71 days. This discrepancy suggests that the act of egg-laying is the most time-intensive phase within the reproductive cycle of *S. pecten*.

Moreover, the observation that the pre-oviposition period in *S. pecten* is longer than the post-oviposition period implies a significant aspect regarding the sexual maturation of females. A longer pre-oviposition period indicates a more extended period required for females to reach sexual maturity and readiness for reproduction (Milonas et al. 2011). This suggests that females undergo a process of physiological development and preparation before they become capable of laying eggs. This finding underscores the importance of understanding the reproductive biology and life history traits of *S. pecten*, as it provides insights into the factors influencing population dynamics, reproductive success, and potentially, strategies for pest management or conservation efforts.

CONCLUSION

Some basic aspects of the biology and rearing of *S. pecten* under laboratory conditions in the Philippines were investigated. The species completed its development from egg to adult in about 33 days under laboratory conditions, with eggs hatching in about 3 days, six larval instars lasting about 2–4 days each, and a pupal period of about 9 days. High larval survival, pupation, and adult emergence demonstrated its adaptability to corn, despite moderate egg viability. The rearing protocol provides a foundation for future studies on host range, natural enemies, and integrated pest management strategies, and the biological data generated here are essential for predicting population outbreaks and designing effective control measures for this emerging pest in the Philippines.

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Conceptualization: MMN, MSG, MdPJ; Study design: MMN, MSG, MdPJ; Sample collection: MMN, MSG, MdPJ; Conduct of experiment: MMN, MSG, MdPJ; Data curation: MdPJ; Visualization: MMN, MSG, MdPJ; Formal analysis: MdPJ; Supervision: MMN, MSG; Writing – Original draft preparation: MMN, MSG, MdPJ; Writing – Review and editing: MMN, MSG

MARKET POWER OF INDONESIAN AND MALAYSIAN PALM OIL EXPORTS IN MAJOR IMPORTING MARKETS: AN ANALYSIS OF RESIDUAL DEMAND ELASTICITY

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ABSTRACT

Indonesia and Malaysia dominate global palm oil exports; however, large market shares did not necessarily imply pricing power. This study examined the extent of market power exercised by Indonesian and Malaysian crude palm oil (CPO) exports in three major importing markets—India, Pakistan, and China—by applying a structural residual demand elasticity (RDE) framework within a simultaneous equation system. Using annual data from 1994 to 2023, the analysis employed Seemingly Unrelated Regressions (SUR) and Three-Stage Least Squares (3SLS) to address endogeneity and cross-market interdependence. The results indicated that Indonesia exercised stronger market power in India and Pakistan, while market power was weaker in China due to greater substitution among vegetable oils. Malaysia exhibited statistically significant but consistently lower market power across destination markets. Export restriction policies, including export duties and related trade measures, significantly affected residual demand elasticity and export pricing behavior, particularly in markets with high import dependence. These findings provided a comparative and policy-relevant assessment of pricing power in the international palm oil trade.

Key words: export duty, oligopoly, market power

INTRODUCTION

Indonesia and Malaysia are the two largest producers and exporters of palm oil in the world. In 2023, Indonesia produced more than 50 million tons of palm oil, with export volumes reaching approximately 36 million tons and generating foreign exchange earnings of USD 25 billion. Malaysia ranked second, producing around 20 million tons and exporting 18 million tons valued at USD 16 billion (BPS-Statistics Indonesia 2024; World Bank 2024). The leading position of these two countries underscores the strategic role of palm oil in global agricultural trade. Crude palm oil (CPO) represents one of the most important plantation commodities in international markets and serves as a key input in multiple industries, including food processing, renewable energy, cosmetics, and oleochemicals. Global

demand for CPO continues to expand due to its versatility and relatively high production efficiency compared with other vegetable oils such as soybean, sunflower, and rapeseed oil.

Oil palm cultivation is widely recognized for its superior land productivity, yielding approximately 3.7 tons of oil per hectare annually, substantially higher than soybean yields of about 0.4 tons per hectare. Relatively low production costs and a long economic lifespan of 25 to 30 years further strengthen its competitiveness in international markets (Wibowo et al. 2023; Winardi et al. 2017; Singh and Zhu 2008). These structural advantages explain why palm oil remains one of the most extensively traded vegetable oils worldwide, with Indonesia and Malaysia jointly accounting for more than eighty percent of global CPO exports. Asia constitutes the principal destination region for Indonesian CPO exports. In 2023, India, Pakistan, and China emerged as the three largest importers, accounting for 16.94 percent, 13.16 percent, and 9.96 percent of Indonesia's total palm oil exports, equivalent to USD 5.335 billion, USD 4.143 billion, and USD 3.137 billion, respectively (UN Comtrade 2024).

These figures confirm the central importance of these markets for Indonesia's export performance. Demand structures differ substantially across importing countries. India imports large volumes of crude palm oil (CPO) primarily for food processing, particularly for ghee production. China places greater emphasis on refined palm oil for both food consumption and industrial applications, while Pakistan relies heavily on CPO imports to sustain its domestic cooking oil industry. These differences in demand structures reflect the diverse roles of palm oil across national food systems and industrial uses, which in turn shape import dependence and market responsiveness in each country (Lee et al. 2020; Suroso 2022; Suryana 2016). Previous studies also emphasize that global palm oil trade patterns are strongly influenced by structural demand conditions, trade policies, and the competitiveness of major exporting countries (Nugrahapsari et al. 2024). In addition, export performance is closely linked to factors such as production levels, export policies, and macroeconomic conditions that affect international market dynamics (Rifai et al. 2015).

Such heterogeneity in demand patterns implies that Indonesia's competitive position and pricing influence are unlikely to be uniform across destination markets. Despite their dominance in production and export shares, Indonesia and Malaysia do not necessarily act as price setters in the global palm oil market. International CPO prices are influenced by multiple factors, including fluctuations in substitute vegetable oil prices such as soybean and sunflower oil, macroeconomic conditions in importing countries, trade policies, and climate-related production shocks. Domestic policy instruments in exporting countries, including export duties, export levies, and downstream development strategies, further affect export supply incentives and competitiveness (Immanuel et al. 2019; Ministry of Agriculture 2024; Rifin 2010). These policies are intended to stabilize domestic supply and promote value-added processing, yet they may also influence export volumes and international price dynamics.

In economic theory, market power refers to the ability of a market participant to influence prices or quantities within a particular market. In the context of international trade, exporter market power reflects the extent to which an exporting country can affect the price of its products in destination markets. One approach widely used to analyse exporter market power is the residual demand framework (Goldberg and Knetter 1999). Residual demand refers to the demand faced by a particular exporter after the supply responses of competing exporters have been considered. In other words, it represents the portion of total market demand that remains available to a specific exporter once competitors have supplied their quantities to the market. Residual demand elasticity (RDE) differs from conventional demand elasticity. Traditional demand elasticity measures the responsiveness of total market demand to changes in price. By contrast, residual demand elasticity measures the responsiveness of the demand faced by an individual exporter after accounting for the reactions of competing suppliers (Baker and Bresnahan 1988; Knetter 1989).

This distinction is important in markets where a small number of exporters dominate global supply. In such settings, the elasticity of residual demand becomes a direct indicator of market power. When residual demand is relatively inelastic, exporters can increase prices without experiencing a proportional reduction in export quantities, implying stronger pricing power. Conversely, when residual demand is highly elastic, exporters face intense competition and behave more like price takers in the market (Carter and MacLaren 1997; Goldberg and Knetter 1999). The residual demand elasticity framework is particularly relevant for analysing international agricultural commodity markets that exhibit oligopolistic characteristics. In these markets, a limited number of large exporters interact strategically and influence price formation in destination markets. Previous studies show that such market structures can generate varying degrees of exporter market power in international trade (Go and Lau 2017; Zhu et al. 2019). The RDE approach therefore provides a useful analytical tool for measuring export competitiveness and identifying the extent to which exporters can influence prices in international markets.

Although extensive research has examined palm oil trade, most empirical studies focus on comparative advantage, export performance, or price transmission rather than directly estimating exporter market power. Rifin (2010), for example, analysed the impact of Indonesia's export duty policy on CPO exports and found that the policy tends to reduce export competitiveness. However, the study did not quantify the degree of pricing power exercised by Indonesian exporters in major destination markets. Other studies have emphasized that Indonesia exhibits stronger comparative advantage than Malaysia in markets such as India and Spain, but these analyses primarily evaluate trade performance indicators rather than directly measuring exporter market power through structural demand estimation.

Empirical studies using Granger causality analysis also indicate strong linkages between domestic and international palm oil prices. For example, Lee et al. (2020) and Rifin (2010) document price interactions between major reference markets such as Rotterdam and Bursa Malaysia, suggesting a high degree of price integration across markets. Such interdependence may reflect strategic interactions among dominant exporters and indicates the possibility of oligopolistic behaviour in the international palm oil market. Nevertheless, the magnitude of exporter market power in the global palm oil market remains largely unexplored. Several research gaps therefore remain. Empirical evidence directly estimating the market power of Indonesian and Malaysian CPO exports using a structural residual demand elasticity framework is still limited. Comparative analysis of both exporters across multiple major importing markets while accounting for cross-market interdependence is rarely conducted. Furthermore, the interaction between export restriction policies and exporter market power has not been rigorously analysed within a unified econometric framework.

Indonesia and Malaysia together account for more than eighty-five percent of global CPO exports, making the assessment of their pricing influence particularly important for understanding global vegetable oil markets. Competitive interaction between these two exporters further complicates price dynamics. Indonesia exports larger volumes, whereas Malaysia benefits from trade agreements such as the Malaysia–India Comprehensive Economic Cooperation Agreement, which facilitates preferential access to the Indian market. Non-price factors such as trade agreements, exchange rate movements, and economic diplomacy also influence export competitiveness. Substitution between palm oil and other vegetable oils is relatively high in China, which may reduce pricing power compared with India and Pakistan where import dependence is stronger. These structural differences suggest that exporter market power may vary significantly across destination markets.

This study therefore examines the extent of market power exercised by Indonesia and Malaysia in the global crude palm oil market using a structural residual demand elasticity framework. The analysis focuses on three major importing markets—India, Pakistan, and China—which together represent the largest destinations for Indonesian palm oil exports. Specifically, the study pursues two

objectives. First, it estimates and compares the degree of exporter market power of Indonesian and Malaysian CPO exports across the three major importing markets using a simultaneous equation system estimated through Seemingly Unrelated Regression (SUR) and Three-Stage Least Squares (3SLS) techniques. Second, it evaluates the impact of export restriction policies, including export duties and related policy measures, on residual demand elasticity and export pricing behaviour. By integrating exporter competition and policy variables within a unified econometric framework, this study provides a comparative and policy-relevant assessment of pricing power in the international palm oil market. The findings contribute to the literature on agricultural trade and industrial organization by offering empirical evidence on how export policy instruments interact with market structure in a highly concentrated commodity market.

RESEARCH METHODS

The Residual Demand Elasticity (RDE) model was formally introduced in the international trade literature by Goldberg and Knetter (1999) as a structural framework for measuring exporter market power using aggregate trade data. The model estimates the demand faced by an exporter after accounting for the supply responses of competing exporters in the same destination market. Within this framework, exporters face residual demand rather than total market demand. The elasticity of this residual demand reflects the degree of pricing power exercised by exporters in international markets. The RDE framework is therefore particularly appropriate for analysing the market power of Indonesia and Malaysia in the global palm oil market, where a small number of dominant exporters interact strategically and compete across major importing markets. This study uses annual data covering the period 1994 to 2023. The analysis focuses on two major exporting countries, Indonesia and Malaysia, and three principal importing markets, namely India, Pakistan, and China. These countries represent the largest destinations for Indonesian and Malaysian crude palm oil (CPO) exports and together account for the majority of global palm oil trade. Using these markets allows the analysis to capture variations in demand structures and competitive interactions across importing countries.

Export price and export volume data for CPO were obtained from the UN Comtrade database, which provides detailed bilateral trade statistics. Macroeconomic indicators for importing countries, including real GDP and the Consumer Price Index (CPI), were obtained from the World Bank World Development Indicators database. Exchange rate data were collected from the IMF International Financial Statistics database. Policy variables, including export duties, non-tariff measures (NTM), and free trade agreements (FTA), were compiled from official government publications, WTO trade policy reports, and international trade policy databases. All price variables were converted into consistent units, and yearly series were transformed into natural logarithms to ensure comparability across countries and to reduce heteroskedasticity in the estimation. Prior to estimation, the dataset was organized into a panel time-series structure by exporter–importer pairs. Export prices and quantities were matched by year for each exporting country (Indonesia and Malaysia) and each destination market (India, Pakistan, and China). Missing observations were checked and corrected using official trade records where available. Continuous variables were expressed in logarithmic form to interpret estimated coefficients as elasticities and to stabilize variance across the time series.

The empirical model is estimated separately for each importing market of Indonesian and Malaysian CPO, namely India, Pakistan, and China. To capture the strategic interaction between the two dominant exporters and the potential interdependence across destination markets, the model is specified as a system of simultaneous equations (Gafarova et al. 2023; Pall et al. 2013; Uhl 2021). The baseline estimating equation is defined as:

$$\ln P_{mt}^n = \gamma_m^n + \eta_m^n \ln Q_{mt}^n + \alpha_m^n \ln GDP_{mt} + \sigma_m^n \ln CPI_{mt} + \delta_m^n T_{mt} + \beta_m^k \ln e_{mt}^k + \varphi_m^k \ln PPW_{mt}^k + \vartheta_{mt}^n ER_{mt}^{n,ET} + \vartheta_{mt}^k ER_{mt}^{k,ET} + \vartheta_{mt}^m ER_{mt}^{m,NTM} + \vartheta_{mt}^m ER_{mt}^{m,FTA} + \varepsilon_{mt}$$

Information

n	:	Exporting countries (Indonesia/Malaysia)
m	:	Importing countries (India/Pakistan/China)
k	:	Competitor countries (Malaysia for the Indonesian equation and vice versa)
P_{mt}^n	:	Export price of CPO exporter to the importer market (INR/PKR/CNY per Ton)
Q_{mt}^n	:	Export volume of CPO exporters to importer markets (Tons)
η_m^n	:	Elasticity of Indonesia's residual demand in India, Pakistan, China at t
GDP_{mt}	:	Real GDP India, Pakistan, China at t time (USD)
CPI_{mt}	:	Consumer Price Index for Food Goods in the importer's market
T_{mt}	:	Linear time trends
e_{mt}^k	:	Competitor exchange rate to importer market (MYR/INR, MYR/PKR, MYR/CNY)
PPW_{mt}^k	:	Price of CPO producers in competing countries (MYR/Ton)
$ER^{n,ET}$:	CPO Export Duty of Exporting Countries (US\$/ton)
$ER^{k,ET}$:	Competitor Countries' CPO Export Duties (US\$/ton)
$ER^{m,NTM}$:	Dummy of Non-Tariff Measure (NTM) in the importer's market in the period t (0 = no NTM; 1 = NTM)
$ER^{m,FTA}$:	Dummy enforced Free Trade Area (FTA) in importer market (0 = no FTA; 1 = FTA)
ε_t	:	Error term

The primary parameter of interest is η_m^n , which represents the elasticity of residual demand faced by the exporter in each destination market. A statistically significant and relatively inelastic residual demand elasticity indicates that exporters can increase prices without experiencing a proportional reduction in export quantities, reflecting the presence of market power. Because export prices and quantities are jointly determined in international trade, the empirical estimation is conducted within a simultaneous equation framework to address potential endogeneity. The estimation procedure follows several steps. First, residual demand equations are specified for each exporter–importer pair, allowing the demand faced by Indonesia and Malaysia to be estimated separately for India, Pakistan, and China. Second, the system of equations is initially estimated using Seemingly Unrelated Regressions (SUR) introduced by Zellner (1962). SUR allows the disturbance terms across destination markets to be correlated, which is plausible in global commodity markets where shocks in one market may influence prices in others.

However, SUR does not correct for simultaneity bias arising from the joint determination of prices and quantities. Therefore, the final estimation employs Three-Stage Least Squares (3SLS), which combines instrumental variable estimation with system estimation. This method allows endogenous regressors to be instrumented while simultaneously accounting for cross-equation correlations. Instrumental variables are constructed using exporter-side supply shifters. Producer prices (PPW) are used as instruments because they capture domestic production conditions such as input costs, productivity, weather shocks, and domestic policy interventions. These factors affect export supply but are not directly determined by demand conditions in specific importing markets. Consequently, producer prices serve as valid instruments within the residual demand framework (Knetter 1989; Carter and MacLaren 1997; Goldberg and Knetter 1999). Similar approaches have been applied in empirical studies of agricultural commodity trade (Pall et al. 2013; Uhl 2021).

Model validity is evaluated through several diagnostic procedures. The Durbin–Wu–Hausman test is used to detect the presence of endogeneity. The Hansen–Sargan test evaluates the validity of over-identifying restrictions and confirms instrument exogeneity. Additional diagnostic tests include heteroskedasticity testing using the Breusch–Pagan or White tests, multicollinearity assessment using the Variance Inflation Factor (VIF), and serial correlation testing using the Breusch–Godfrey test. Within this framework, the magnitude and statistical significance of the estimated residual demand elasticity provide direct evidence of exporter market power. A residual demand elasticity close to zero

indicates highly elastic demand consistent with competitive market conditions, while a larger negative elasticity indicates stronger pricing power. The larger the absolute value of η_m^n , the greater the exporter's ability to influence export prices in the corresponding destination market.

RESULTS AND DISCUSSION

CPO market overview. The global crude palm oil (CPO) market is largely dominated by Indonesia and Malaysia, which together account for more than 80 percent of global production and exports. Data from the World Bank (2024) indicate that Indonesia contributes approximately 58 percent of global output, while Malaysia accounts for around 25 percent. UN Comtrade (2024) reports that Indonesia's export value in 2023 exceeded 24 billion US dollars, compared with approximately 14 billion US dollars for Malaysia. These figures confirm the central role of the two countries in shaping international CPO supply and influencing global price dynamics. Such a high level of market concentration is consistent with Winardi and co-workers (2017), who described the palm oil industry as an oligopolistic market structure in which a small number of dominant exporters influence trade flows and international prices. To provide preliminary insights into the behavior of the international palm oil market, graphical presentations of time-series export prices are presented for both Indonesia and Malaysia across the major importing markets of India, Pakistan, and China. These graphical illustrations allow an initial observation of price dynamics before the econometric analysis is conducted.

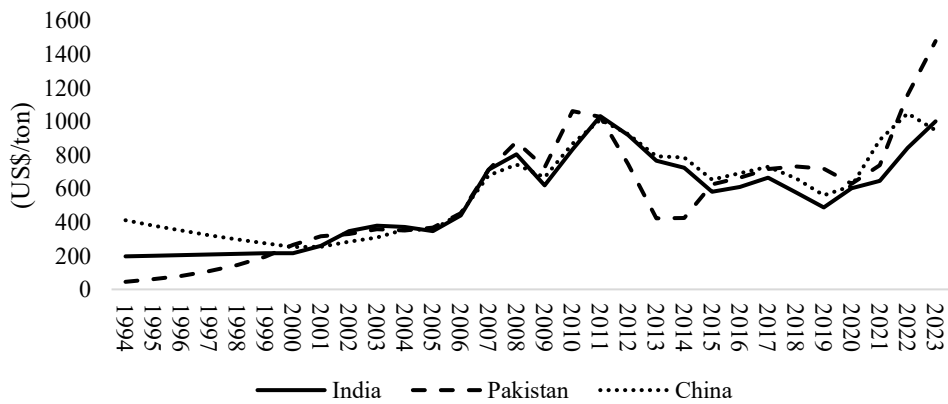


Figure 1. Trend of Indonesian CPO export prices in major import markets (1994–2023) (India, Pakistan, and China).

Source: UN Comtrade (2024)

Figure 1 presents the trend of Indonesia's CPO export prices in the three major importing markets over the period 1994–2023. The price movements across India, Pakistan, and China generally follow a similar pattern, indicating a strong degree of integration in the global palm oil market. Major price increases occurred during the global commodity boom between 2007 and 2008 and again after 2020. These periods correspond to global supply disruptions, increasing demand for vegetable oils, and shocks originating from energy markets that affected biofuel demand. Despite the broadly similar price trends, differences in the magnitude of price fluctuations are observed across markets. Pakistan shows the most pronounced price increases in recent years, which may reflect a stronger dependence on imported palm oil. In contrast, China exhibited relatively smoother price movements, suggesting the presence of broader substitution possibilities with other vegetable oils such as soybean oil and sunflower oil. These observations indicate that while global supply conditions largely determined the general direction of prices, country-specific demand structures contributed to variations in price dynamics across importing markets.

Figure 2 presents the corresponding price trends for Malaysia’s CPO exports to the same importing markets. Similar to the Indonesian case, Malaysia’s export prices across India, Pakistan, and China display closely related movements over time. The consistency of price trends across exporters and markets further indicates that the global palm oil market operates as an integrated commodity market where international shocks are transmitted rapidly across trading partners. Beyond price dynamics, the distribution of export market shares across importing countries also illustrates the structural position of the two exporters. Table 1 reports the average market share of Indonesian and Malaysian CPO exports in India, Pakistan, and China over the period 1994–2023. Indonesia commands a dominant share of the Indian market (55.3 percent) and the Pakistani market (64.7 percent), both considerably higher than Malaysia’s shares in these markets. These findings are consistent with Suroso (2022), who highlights the strong reliance of India and Pakistan on Indonesian palm oil due to competitive pricing and established bilateral trade relationships. The prominent role of Indonesia in Pakistan is also supported by Lee et al. (2020), who note that Pakistan’s refining and food processing industries depend heavily on imported crude palm oil.

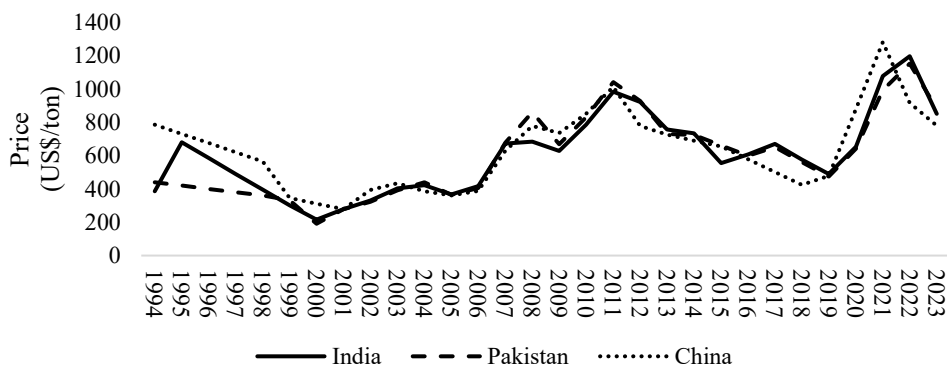


Figure 2. Trend of Malaysian CPO Export Prices in major import markets (1994–2023) (India, Pakistan, and China). Source: UN Comtrade (2024)

The Chinese market exhibits a more balanced structure, with Indonesia accounting for 48.5 percent and Malaysia 40.6 percent of imports. The relatively even distribution of market shares indicates stronger competition between the two exporters. Singh and Zhu (2008) explain that China’s vegetable oil market is characterized by a high degree of substitutability among palm oil, soybean oil, and sunflower oil. Such substitution possibilities reduce the dominance of any single supplier and contribute to more elastic import demand for palm oil. As a result, Chinese buyers tend to adopt flexible procurement strategies in response to price changes.

Table 1. Average market share of Indonesian and Malaysian CPO exports in major importing markets, 1994–2023

Importing Country	Indonesia (%)	Malaysia (%)	Rest of World (%)
India	55.3	37.8	6.9
Pakistan	64.7	30.2	5.1
China	48.5	40.6	10.9

Source: UN Comtrade (2024)

These differences across importing markets highlight the heterogeneous structure of international demand for palm oil. Indonesia’s dominance is strongest in India and Pakistan, where import dependence and supply chain linkages are more pronounced, whereas the Chinese market

reflects stronger competitive interaction between Indonesia and Malaysia. The variation in market structures across destination markets underscores the importance of analyzing exporter market power within specific market contexts and supports the application of the residual demand elasticity framework.

Indonesia's CPO export market power in major importer markets. The residual demand equations for Indonesian CPO exports to India, Pakistan, and China are estimated simultaneously because price formation across these destination markets is closely interconnected. These three countries represent the largest importing markets for Indonesian palm oil and rely heavily on two dominant global suppliers, Indonesia and Malaysia. As a result, changes in export supply conditions or pricing strategies in one market can influence price dynamics in other markets through integrated trade flows and competitive interactions between exporters. The graphical evidence presented in Figures 1 and 2 illustrates this interdependence. The time-series trends of export prices for both Indonesian and Malaysian CPO in India, Pakistan, and China during the period 1994–2023 display broadly similar movements over time. Major price increases occur during the global commodity boom of 2007–2008 and again after 2020, while price declines are observed during periods of global economic adjustment. The parallel movement of prices across the three importing markets suggests a high degree of integration in the international palm oil market, where global supply shocks, demand expansion, and energy market developments affect multiple destination markets simultaneously.

Table 2. Endogeneity test results for the RDE model of Indonesian CPO exports

Destination Market	With Export Restrictions			Without Export Restrictions		
	India	Pakistan	China	India	Pakistan	China
Number of instruments	16	16	18	10	10	12
Number of excluded instruments	2	2	2	2	2	2
Excluded instruments	PPW ^{INA} , TQ ^{INA}	PPW ^{INA} , TQ ^{INA}	PPW ^{INA} , TQ ^{INA}	PPW ^{INA} , TQ ^{INA}	PPW ^{INA} , TQ ^{INA}	PPW ^{INA} , TQ ^{INA}
Wu–Hausman F statistic	12.8451	18.3927	11.7246	9.8673	14.5832	10.2157
p-value	(0.0000)	(0.0000)	(0.0362)	(0.0485)	(0.0000)	(0.0417)
Durbin–Wu–Hausman χ^2 statistic	10.3158	16.4752	9.8652	7.9463	13.2715	8.4521
p-value	(0.0015)	(0.0000)	(0.0284)	(0.0392)	(0.0000)	(0.0473)

Note: PPW^{INA} denotes the domestic producer price of crude palm oil in Indonesia (US\$/ton), representing supply-side production costs. TQ^{INA} denotes the total quantity of Indonesian CPO exports (tons). ***, **, * significance level

Such price co-movement is consistent with previous empirical studies that document strong linkages among international palm oil markets and other vegetable oil markets. Palm oil prices in major trading hubs exhibit significant transmission effects across markets, reflecting the globally integrated nature of the commodity (Lee et al. 2020; Rifin 2010). Similar findings argue that price interactions across destination markets are typical in oligopolistic export industries where a small number of exporters dominate global supply (Goldberg and Knetter 1999). In this context, estimating the residual demand equations within a simultaneous equation framework is appropriate because export prices and quantities are jointly determined across markets. The simultaneous system captures cross-market interdependence and accounts for the strategic interaction between competing exporters, particularly Indonesia and Malaysia. By allowing the error terms across destination-market equations to be correlated, the model better reflects the structure of international commodity trade where global shocks

and policy changes may affect several importing markets at the same time. This approach therefore improves the efficiency and consistency of the estimated parameters when evaluating Indonesia's market power in major importing markets.

Table 2 presents the results of the endogenous regressor tests applied to the RDE model of Indonesian CPO exports to India, Pakistan, and China under scenarios with and without export restrictions. The Wu–Hausman F statistics and the Durbin–Wu–Hausman chi-square statistics consistently reject the null hypothesis that the regressors are exogenous at the 1–5 percent significance level. These results confirm the presence of endogeneity between export prices and quantities, supporting the use of instrumental variable estimation in the system. Use of limited but relevant instruments, namely export prices and total export quantities, prevents over-identification and enhances reliability of estimates. Table 2 presents the results of endogeneity tests for the RDE model across India, Pakistan, and China under both specifications. The Wu-Hausman F test and Durbin-Wu-Hausman chi-square test confirm instrument validity. P-values associated with PPW^{INA} and TQ^{INA} are generally below 0.05, indicating statistical significance at the 1–5 percent level and confirming instrument relevance and exogeneity. Variation in Wu-Hausman and Durbin-Wu-Hausman statistics across markets reflects differences in instrument strength. Pakistan exhibits stronger instrument relevance compared with India and China, consistent with its higher dependence on Indonesian CPO imports.

RDE estimation results are presented using 3SLS and SUR methods for India, Pakistan, and China under both specifications. R-squared values range from 0.58 in China to 0.72 in Pakistan, indicating satisfactory explanatory power (Tables 3, 4, and 5). Durbin-Watson statistics lie between 1.96 and 2.08, suggesting absence of serious autocorrelation. Hansen-Sargan statistics confirm instrument validity because the null hypothesis of over-identifying restrictions cannot be rejected. The coefficient of primary interest is the residual demand elasticity (η). According to the Lerner index relationship, $(P - MC)/P = 1/|RDE|$, implying that the markup over marginal cost is inversely related to the absolute value of residual demand elasticity. Therefore, when residual demand is more elastic (larger $|RDE|$), exporters have limited ability to raise prices, whereas when residual demand is inelastic (smaller $|RDE|$), exporters can maintain higher price markups and stronger market power.

Estimation results indicate that Indonesia exhibits significant market power in India and Pakistan. In India, η ranges from -0.61 to -0.49 (Table 3). This implies that a 1 percent increase in Indonesia's export price reduces import demand by approximately 0.49–0.61 percent, indicating relatively inelastic residual demand and allowing Indonesia to maintain a positive markup. In Pakistan, η ranges from -0.69 to -0.56 (Table 4), meaning that a 1 percent increase in price reduces demand by about 0.56–0.69 percent, which also reflects inelastic demand and substantial pricing influence. In contrast, the Chinese market exhibits more elastic residual demand. Estimates range from -0.30 to -0.22 (Table 5), implying that a 1 percent increase in Indonesia's export price reduces demand by approximately 0.22–0.30 percent. Although still inelastic in absolute terms, these smaller elasticities suggest weaker pricing influence due to stronger substitution with other vegetable oils such as soybean and sunflower oils.

Other model variables display theoretically consistent effects. Real GDP exerts a positive and statistically significant influence across markets, indicating that higher income levels increase import demand for vegetable oils. CPI generally shows a negative effect, particularly in China, suggesting that domestic inflation reduces purchasing power and dampens import demand. Exchange rate movements also influence competitiveness. The coefficient of the Malaysian exchange rate is negative in both India and Pakistan, indicating that a depreciation of the Malaysian ringgit increases Malaysia's export competitiveness relative to Indonesia. Malaysian CPO export prices also exert a positive effect on Indonesian export demand. For example, in India the coefficient ranges between 0.1860 and 0.2617, implying that a 1 percent increase in Malaysian CPO export prices raises demand for Indonesian CPO by about 0.19–0.26 percent, reflecting substitution between the two exporters.

Table 3. RDE estimation results using Indonesia's 3SLS and SUR approach in Indian market

Parameters	With Export Restrictions				No Export Restrictions			
	3SLS		SUR		3SLS		SUR	
	Coef	t-stat	Coef	t-stat	Coef	t-stat	Coef	t-stat
η_{IND}^{INA}	-0.6079**	-3.0146	-0.5712**	-2.8754	-0.5417**	-2.8123	-0.4948**	-2.5392
α_{IND}^{INA}	0.4046**	4.0218	0.3821**	3.8849	0.3787**	3.7426	0.3581**	3.5984
σ_{IND}^{INA}	-0.0697	-1.1415	-0.0598	-1.0340	-0.0479	-0.9002	-0.0451	-0.8641
δ_{IND}^{INA}	0.0189	1.2847	0.0170	1.1906	0.0152	1.0291	0.0135	0.9662
β_{MYR}^{INR}	-0.0816*	-1.6383	-0.0712*	-1.5480	-0.0684*	-1.6035	-0.0605*	-1.5076
φ_{IND}^{MAL}	0.2617**	2.5872	0.2329**	2.3781	0.2013**	1.9984	0.1860*	1.9347
$\vartheta_{IND}^{INA,ET}$	-0.2916**	-2.0854	-0.2634**	-1.9873				
$\vartheta_{IND}^{MAL,ET}$	-0.0841*	-1.6129	-0.0735*	-1.5317				
$\vartheta_{IND,NTM}$	-0.0769	-1.1527	-0.0664	-1.0892				
$\vartheta_{IND,FTA}$	0.1887**	2.0145	0.1729**	1.9723				
γ_{IND}^{INA}	0.6285***	4.2516	0.5934***	4.0407	0.5831***	3.8720	0.5624***	3.7339
R-square	0.6745		0.7063		0.6412		0.6895	
DW-stat	2.0526		2.1041		1.9843		2.0127	
Hansen-Sargan stat	4.0836		3.8619		2.7264		2.4983	

Note: **, and * express significance at the 1%, 5%, and 10% levels.

Table 4. RDE estimation results using Indonesia's 3SLS and SUR approach in Pakistani market

Parameters	With Export Restrictions				No Export Restrictions			
	3SLS		SUR		3SLS		SUR	
	Coef	t-stat	Coef	t-stat	Coef	t-stat	Coef	t-stat
η_{PAK}^{INA}	-0.6891**	-3.4562	-0.6543**	-3.2121	-0.6018***	-3.0057	-0.5664***	-2.8649
α_{PAK}^{INA}	0.3952***	3.9985	0.3764***	3.8011	0.3549***	3.6123	0.3415***	3.4769
σ_{PAK}^{INA}	-0.0815	-1.2951	-0.0726	-1.1839	-0.0619	-1.0746	-0.0587	-1.0224
δ_{PAK}^{INA}	0.0274*	1.7013	0.0231	1.5026	0.0197	1.3482	0.0176	1.2425
β_{MYR}^{INR}	-0.0938**	-2.0457	-0.0827**	-1.9786	-0.0786*	-1.8453	-0.0719*	-1.6991
φ_{PAK}^{MAL}	0.2886***	2.9364	0.2547**	2.5147	0.2268**	2.1864	0.2129*	1.9741
$\vartheta_{PAK}^{INA,ET}$	-0.3125**	-2.2467	-0.2849**	-2.1036				
$\vartheta_{PAK}^{MAL,ET}$	-0.0982*	-1.6882	-0.0867*	-1.6054				
$\vartheta_{PAK,NTM}$	-0.0921	-1.3226	-0.0804	-1.2073				
$\vartheta_{PAK,FTA}$	0.2178**	2.1546	0.1997**	2.0183				
γ_{PAK}^{INA}	0.6574***	4.5231	0.6128***	4.1983	0.5972***	3.9964	0.5721***	3.8436
R-square	0.6927		0.7215		0.6541		0.7036	
DW-stat	2.0834		2.1279		1.9745		2.0258	
Hansen-Sargan stat	4.3981		4.1027		2.8961		2.6039	

Note: **, and * express significance at the 1%, 5%, and 10% levels

Trade policy variables also influence market outcomes. Indonesian export duties show negative coefficients, indicating that higher export taxes reduce export competitiveness by increasing export prices. Malaysian export duties produce the opposite effect by weakening Malaysia’s competitive position. Non-tariff measures generally exhibit negative but statistically weak effects, suggesting that regulatory requirements affect trade primarily through compliance costs rather than direct quantity restrictions. Free trade agreements show positive and statistically significant effects in India and Pakistan, reflecting improved market access and reduced trade barriers. Overall, the empirical results indicate that Indonesia maintains stronger market power in India and Pakistan than in China, consistent with differences in import dependence and substitution possibilities. These findings are consistent with the residual demand framework, where market power emerges when exporters face relatively inelastic demand in destination markets.

Table 5. RDE estimation results using Indonesia’s 3SLS and SUR approach in the Chinese market.

Parameters	With Export Restrictions				No Export Restrictions			
	3SLS		SUR		3SLS		SUR	
	Coef	t-stat	Coef	t-stat	Coef	t-stat	Coef	t-stat
η_{CHI}^{INA}	-0.3027**	-2.0419	-0.2784**	-1.9675	-0.2516*	-1.7851	-0.2297*	-1.6423
α_{CHI}^{INA}	0.2763***	3.1842	0.2581***	3.0357	0.2415**	2.8246	0.2279**	2.6938
σ_{CHI}^{INA}	-0.1254**	-2.2187	-0.1128*	-1.9047	-0.1085*	-1.8371	-0.0962	-1.6942
δ_{CHI}^{INA}	0.0145	1.0923	0.0129	0.9815	0.0112	0.8739	0.0095	0.7926
β_{MYR}^{INR}	-0.0579	-1.2964	-0.0527	-1.2084	-0.0486	-1.1456	-0.0442	-1.0825
φ_{CHI}^{MAL}	0.1897*	1.9184	0.1724*	1.8142	0.1582	1.6358	0.1445	1.5283
$\vartheta_{CHI}^{INA.ET}$	-0.1457	-1.4936	-0.1318	-1.3872				
$\vartheta_{CHI}^{MAL.ET}$	-0.0962	-1.2837	-0.0845	-1.2019				
$\vartheta_{CHI.NTM}$	-0.0674	-1.0974	-0.0598	-1.0421				
$\vartheta_{CHI.FTA}$	0.1289	1.4736	0.1173	1.3827				
γ_{CHI}^{INA}	0.4287***	3.5619	0.4029***	3.2971	0.3895***	3.1526	0.3667***	2.9981
R-square	0.5836		0.6129		0.5417		0.5875	
DW-stat	1.9681		1.9872		1.9435		1.9637	
Hansen-Sargan stat	3.2197		2.9874		2.1075		1.9186	

Note: **, and * express significance at the 1%, 5%, and 10% levels.

Differences in market power across destination markets are consistent with empirical evidence on competitiveness and revealed comparative advantage. Zuhdi et al. (2021) demonstrate strong Indonesian competitiveness in India and Pakistan using RCA measures. Rosyadi et al. (2021) identify GDP growth and export volumes as key drivers of CPO export performance. High structural dependence in these markets supports the inelastic residual demand estimates. Evidence from China emphasizes substitution effects. Cross-price interactions are strong among vegetable oils (Kojima et al. 2016), while competitive dynamics exists within China’s edible oil market (Wang 2018). These findings align with the more elastic RDE estimates observed for China. Lugo-Arias et al. (2024) identify exchange rates and competing oil prices as determinants of export competitiveness, consistent with substitution effects observed in this study. GDP, exchange rates, non-tariff measures, and trade agreements are important (Pratiwi 2021). The negative competitiveness effects of palm oil taxation in Malaysia have been documented (Hamzah et al. 2015). The present results are consistent with these findings, as export duties reduce Indonesia’s pricing flexibility while free trade agreements enhance market access. Taken together, these empirical comparisons reinforce the conclusion that Indonesia’s

market power varies systematically across destination markets due to differences in import dependence, substitution possibilities, macroeconomic conditions, and trade policy instruments.

Market power Malaysia's CPO exports in major importer markets. The endogeneity test results presented in Table 6 indicate that Malaysia's CPO export quantities to India, Pakistan, and China are endogenous. Estimation therefore requires a simultaneous equation system approach. This finding is consistent with the interdependent structure of the global CPO market, which is strongly influenced by two dominant suppliers, Indonesia and Malaysia. Such interdependence justifies the application of Seemingly Unrelated Regressions (SUR) and Three-Stage Least Squares (3SLS) to obtain efficient estimates and correct for potential simultaneity bias. The instruments employed are Malaysian producer prices (PPW^{MAL}) and total Malaysian CPO export quantities (TQ^{MAL}). Wu-Hausman F statistics confirm strong instrument relevance, particularly in India ($F = 13.90$) and Pakistan ($F = 19.47$), reflecting Malaysia's strategic role in these markets. In China, the F-statistics are lower (11.18 with export restrictions and 9.86 without restrictions), indicating that the instruments remain valid but relatively weaker. This outcome corresponds to the more diversified structure of the Chinese vegetable oil market, where substitution among palm oil, soybean oil, and sunflower oil is more pronounced.

Table 6. Endogeneity test results for the RDE model of Malaysian CPO exports.

Destination Market	With Export Restrictions			Without Export Restrictions		
	India	Pakistan	China	India	Pakistan	China
Number of instruments	16	16	18	10	10	12
Number of excluded instruments	2	2	2	2	2	2
Excluded instruments	PPW^{MAL} , TQ^{MAL}	PPW^{MAL} , TQ^{MAL}	PPW^{MAL} , TQ^{MAL}	PPW^{MAL} , TQ^{MAL}	PPW^{MAL} , TQ^{MAL}	PPW^{MAL} , TQ^{MAL}
Wu-Hausman F statistic	13.9024	19.4762	11.1839	10.2385	15.3279	9.8641
p-value	(0.0000)	(0.0000)	(0.0387)	(0.0412)	(0.0000)	(0.0529)
Durbin-Wu-Hausman χ^2 statistic	11.2845	17.0381	9.2746	8.1563	12.9842	7.3185
p-value	(0.0008)	(0.0000)	(0.0261)	(0.0376)	(0.0003)	(0.0628)

Note: PPW^{MAL} denotes the domestic producer price of crude palm oil in Malaysia (US\$/ton), representing supply-side production costs. TQ^{MAL} denotes the total quantity of Malaysian CPO exports (tons). ***, **, * significance level.

Durbin-Wu-Hausman chi-square results further confirm endogeneity of Malaysian export quantities in India and Pakistan at the 1 percent significance level. In China, statistical significance is weaker but remains acceptable at conventional levels. These findings indicate that Malaysia's export decisions materially influence price formation in India and Pakistan, whereas its pricing influence in China is shared with Indonesia and non-palm oil competitors. Instrument validity within the 3SLS framework therefore, ensures that RDE estimates are not biased by simultaneity.

RDE estimation results for Malaysia. RDE estimates for Malaysia are presented using 3SLS and SUR methods across India, Pakistan, and China (Tables 7, 8, and 9). Residual demand elasticity coefficients (η^{MAL}) are consistently negative and statistically significant at the 5 percent level. A lower, more inelastic residual demand implies a greater potential mark-up over marginal cost, indicating stronger market power. The negative and significant coefficients demonstrate that Malaysia does not

behave as a pure price taker; instead, it retains the ability to influence export prices through adjustments in export quantities. In the Indian market, residual demand elasticity ranges from -0.28 to -0.25 and is statistically significant (Table 7). These values suggest measurable pricing influence despite strong competition from Indonesia. India’s status as the world’s largest CPO importer enhances the strategic importance of Malaysia’s market position. The Indian vegetable oil processing industry remains highly dependent on CPO imports from both Indonesia and Malaysia, supporting the persistence of Malaysian market power.

In Pakistan, residual demand elasticity ranges from -0.30 to -0.26, which is slightly larger in absolute magnitude than the corresponding estimates for India (-0.29 to -0.25) reported in Tables 7 and 8. This implies that the residual demand faced by Malaysian exporters in Pakistan is marginally less elastic than in India, allowing for a somewhat stronger price markup. Statistical significance at the 5 percent level confirms Malaysia’s relatively strong bargaining position in this market. Pakistan’s reliance on CPO imports as a primary input for domestic cooking oil production further reinforces Malaysia’s capacity to influence export prices. Long-term bilateral supply arrangements also contribute to stabilizing Malaysian export performance in this market.

Table 7. RDE estimation results using Malaysia's 3SLS and SUR approach in the Indian market.

Parameters	With Export Restrictions				No Export Restrictions			
	3SLS		SUR		3SLS		SUR	
	Coef	t-stat	Coef	t-stat	Coef	t-stat	Coef	t-stat
η_{IND}^{MAL}	-0.2874**	-2.6385	-0.2796**	-2.4813	-0.2652**	-2.2281	-0.2517**	-2.0479
α_{IND}^{MAL}	0.3025**	3.6023	0.2879**	3.4037	0.2941**	3.4821	0.2795**	3.2847
σ_{IND}^{MAL}	-0.0458	-1.0834	-0.0432	-1.0112	-0.0387	-0.9425	-0.0361	-0.8573
δ_{IND}^{MAL}	0.0128	1.0842	0.0121	1.0234	0.0114	0.9582	0.0109	0.9104
β_{INR}^{MYR}	-0.0589*	-1.7547	-0.0537*	-1.6825	-0.0478	-1.4108	-0.0461	-1.3726
φ_{IND}^{MAL}	0.2050**	2.1542	0.1915**	2.0186	0.1820*	1.9044	0.1705*	1.8175
$\vartheta_{IND}^{MALE.T}$	-0.1350*	-1.8032	-0.1240*	-1.7195				
$\vartheta_{IND}^{INA.T}$	0.1120**	2.0521	0.1015**	1.9764				
$\vartheta_{IND.NTM}$	-0.0780	-1.1820	-0.0705	-1.1156				
$\vartheta_{IND.FTA}$	0.1480**	2.0542	0.1357**	1.9754				
γ_{IND}^{MAL}	0.5150**	3.7025	0.5008**	3.5619	0.4869**	3.4328	0.4681**	3.3081
R-square	0.6120		0.6280		0.5430		0.4970	
DW-stat	2.0140		2.0820		1.9540		1.9760	
Hansen-Sargan stat	3.9281		3.7452		2.8693		2.5914	

Captions: **, and * express significance at the 1%, 5%, and 10% levels

Other explanatory variables reinforce the interpretation of Malaysia’s market power. Importer GDP exerts a positive and statistically significant effect across markets, with coefficients ranging from approximately 0.24 to 0.33 in India, Pakistan, and China (Tables 7–9). Higher income levels in importing countries increase demand for vegetable oils and strengthen Malaysia’s export price performance. The consumer price index generally displays a negative coefficient, suggesting that domestic food inflation encourages substitution toward alternative vegetable oils. Producer prices in competing countries exhibit positive and statistically significant coefficients in most markets, confirming substitution effects between Malaysia and Indonesia. Exchange rate movements also matter; depreciation of competitor currencies reduces Malaysia’s relative competitiveness and exerts

downward pressure on its export prices. Trade policy variables further shape market outcomes. Malaysian export duties generate significant effects, reflecting supply-side adjustments that influence price formation. Non-tariff measures generally display negative but statistically insignificant coefficients, suggesting that quality standards and administrative compliance affect trade less directly than explicit export restrictions. Free trade agreement variables tend to have positive coefficients, particularly in Pakistan and China, indicating that trade cooperation enhances Malaysia’s market access and supports pricing outcomes.

Table 8. RDE estimation results using Malaysia's 3SLS and SUR approach in the Pakistani market.

Parameters	With Export Restrictions				No Export Restrictions			
	3SLS		SUR		3SLS		SUR	
	Coef	t-stat	Coef	t-stat	Coef	t-stat	Coef	t-stat
η_{PAK}^{MAL}	-0.2986**	-2.8714	-0.2912**	-2.6958	-0.2764**	-2.4139	-0.2648**	-2.2362
α_{PAK}^{MAL}	0.2768***	3.3520	0.2630***	3.1886	0.2514***	3.0621	0.2397***	2.9012
σ_{PAK}^{MAL}	-0.0587	-1.2941	-0.0553	-1.2024	-0.0496	-1.1286	-0.0468	-1.0637
δ_{PAK}^{MAL}	0.0206	1.2801	0.0191	1.1724	0.0178	1.0923	0.0169	1.0312
β_{INR}^{MYR}	-0.0681*	-1.8214	-0.0634*	-1.7423	-0.0572	-1.4841	-0.0540	-1.3752
φ_{PAK}^{MAL}	0.2206**	2.2832	0.2091**	2.1203	0.1974*	1.9624	0.1868*	1.8541
$\vartheta_{PAK}^{MAL.ET}$	-0.1200	-1.5804	-0.1106	-1.5251				
$\vartheta_{PAK}^{INA.ET}$	0.1260**	2.1035	0.1148**	2.0184				
$\vartheta_{IND.NTM}$	-0.0743	-1.1520	-0.0689	-1.1195				
$\vartheta_{IND.FTA}$	0.1620**	2.0231	0.1497**	1.9875				
γ_{PAK}^{MAL}	0.4850**	3.6012	0.4725**	3.4908	0.4518**	3.3821	0.4342**	3.2742
R-square	0.6680		0.6820		0.5970		0.5520	
DW-stat	2.0834		2.1279		1.9745		2.0258	
Hansen-Sargan stat	4.3981		4.1027		2.8961		2.6039	

Note: **, and * express significance at the 1%, 5%, and 10% levels

The observed variation in Malaysia’s market power across destination markets is consistent with previous empirical findings. Malaysia maintains a competitive position in India, Pakistan, and China, although Indonesia exhibits stronger export dynamics (Ramadhani 2019). This aligns with the moderate but statistically significant residual demand elasticities identified in this study. Malaysia’s palm oil exports to India benefit from long-term trade relations and sustained demand from refining and food industries (Ali 2019). These findings correspond with the significant RDE estimates for India. Importer income, world palm oil prices, substitute oil prices, and exchange rates are important in determining Malaysia’s export performance (Jazuli and Kamu 2019). These determinants are consistent with the significant GDP, competitor price, and exchange rate coefficients obtained in the present model. The relatively lower market power observed in China is supported by Zaidi et al. (2022), who demonstrate strong cross-price linkages between palm oil and substitute oils using a structural VAR approach. Substitution reduces Malaysia’s ability to influence export prices in the Chinese market. Gan (2014) emphasizes that Malaysia’s long-term competitiveness depends on downstream upgrading and coordinated policy support. This conclusion is consistent with the current findings, which highlight the importance of export duties, trade agreements, and strategic positioning in shaping Malaysia’s realized market power. Malaysia exhibits measurable and statistically significant market power in India and

Pakistan, with relatively weaker but still significant influence in China. Market power is shaped by structural import dependence, substitution possibilities, macroeconomic conditions, and trade policy instruments. Malaysia does not act purely as a price taker in international CPO markets; instead, it retains strategic pricing influence that varies systematically across destination countries.

Table 9. RDE estimation results using Malaysia's 3SLS and SUR approach in the Chinese market

Parameters	With Export Restrictions				No Export Restrictions			
	3SLS		SUR		3SLS		SUR	
	Coef	t-stat	Coef	t-stat	Coef	t-stat	Coef	t-stat
η_{CHI}^{MAL}	-0.2583**	-2.4125	-0.2469**	-2.2571	-0.2337**	-2.0664	-0.2215*	-1.9018
α_{CHI}^{MAL}	0.3268***	3.2412	0.3110***	3.0618	0.2987***	2.9721	0.2842***	2.8237
σ_{CHI}^{MAL}	-0.0852**	-1.9813	-0.0801*	-1.8710	-0.0743*	-1.7623	-0.0691*	-1.6721
δ_{CHI}^{MAL}	0.0182	1.2204	0.0175	1.1816	0.0168	1.1017	0.0159	1.0612
β_{INR}^{MYR}	-0.0517	-1.5132	-0.0478	-1.4315	-0.0442	-1.3324	-0.0420	-1.2213
φ_{CHI}^{MAL}	0.1964*	1.9245	0.1853*	1.8421	0.1789	1.7324	0.1695	1.6210
$\vartheta_{CHI}^{MAL.ET}$	-0.1100	-1.4532	-0.1010	-1.3914				
$\vartheta_{CHI}^{INA.ET}$	0.0850*	1.7031	0.0785*	1.6619				
$\vartheta_{CHI.NTM}$	-0.0702	-1.1824	-0.0648	-1.1542				
$\vartheta_{CHI.FTA}$	0.1351	1.6243	0.1243	1.5428				
γ_{CHI}^{MAL}	0.4320**	3.4521	0.4187**	3.3314	0.4049**	3.2135	0.3898**	3.1618
R-square	0.5820		0.5960		0.5210		0.4780	
DW-stat	1.9680		1.9820		1.9430		1.9630	
Hansen-Sargan stat	3.2174		2.9874		2.1075		1.9186	

Note: **, and * express significance at the 1%, 5%, and 10% levels

Export restrictions on the market power of Indonesia and Malaysia. Export restrictions play an important role in shaping the market power of Indonesia and Malaysia in the international crude palm oil (CPO) market. Estimation results from the residual demand elasticity (RDE) model using the 3SLS and SUR approaches (Tables 3–5 for Indonesia and Tables 7–9 for Malaysia) show that export restriction policies significantly influence exporter pricing behavior in India, Pakistan, and China. Across all model specifications, residual demand elasticity is negative and statistically significant, indicating that neither Indonesia nor Malaysia behaves as a pure price taker. Both exporters influence destination-market prices through adjustments in export quantities.

Clear differences emerge across destination markets. In India, Indonesia’s RDE values under export restrictions range from approximately -0.61 to -0.57 , substantially more inelastic than Malaysia’s values of -0.2874 to -0.2796 under the same specification (Table 7). When export restrictions are excluded from the model, Indonesia’s elasticity becomes less inelastic, shifting to a range of -0.54 to -0.49 . Malaysia’s elasticity remains relatively stable between -0.2652 and -0.2517 , indicating limited sensitivity to policy changes. This pattern suggests that Indonesia’s export restriction policies exert a stronger influence on its pricing power than Malaysia’s. India’s position as the world’s largest CPO importer and its strong dependence on Indonesian supply amplify the price effects of Indonesian export restrictions. A contraction in Indonesian export supply therefore generates upward pressure on international prices and strengthens Indonesia’s bargaining position.

A similar pattern appears in the Pakistani market. Indonesia's residual demand elasticity under export restrictions ranges between -0.69 and -0.65 , while Malaysia's elasticity remains around -0.2986 to -0.2912 (Table 8). When restrictions are excluded, Indonesia's elasticity becomes less inelastic, shifting to approximately -0.60 to -0.56 , whereas Malaysia's elasticity again changes only slightly, remaining between -0.2764 and -0.2648 . Pakistan's high structural dependence on Indonesian CPO imports explains the magnitude of this response. Supply tightening through Indonesian export controls increases export prices and reinforces Indonesia's market power. These results are consistent with residual demand theory, which predicts that exporter market power increases as residual demand becomes more inelastic (Pinelopi Koujianou Goldberg and Michael Knetter 1999; Colin Carter and Donald MacLaren 1997).

The effect of export restrictions is comparatively weaker in China. Indonesia's RDE under export restrictions is approximately -0.30 and becomes about -0.25 when restrictions are excluded. Malaysia's elasticity in China ranges from -0.2583 to -0.2469 with export restrictions and -0.2337 to -0.2215 without restrictions (Table 9). These values reflect the more diversified structure of China's vegetable oil market, where palm oil competes with soybean, rapeseed, and sunflower oils. Greater substitution possibilities increase residual demand elasticity and reduce the effectiveness of export restrictions in influencing prices compared with India and Pakistan.

Estimated coefficients of export duty variables further reinforce these findings. Indonesian export duties exert positive and statistically significant effects on export prices across the three markets, with coefficients of 0.1120 in India, 0.1260 in Pakistan, and 0.0850 in China (Tables 7–9). These results indicate that Indonesian export policies transmit supply restrictions into higher prices in destination markets. In contrast, Malaysia's export duty coefficients are negative and statistically weaker, with values of -0.1350 in India, -0.1200 in Pakistan, and -0.1100 in China, suggesting a more limited influence on price formation. The stronger response associated with Indonesia reflects its larger market share and dominant position in major importing countries.

These results are consistent with previous empirical studies showing that Indonesian export policies generate substantial pass-through effects on global palm oil prices. Export tax policies influence international palm oil prices through supply adjustments (Jamilah et al. 2022), while export restrictions can transmit domestic policy shocks to international markets (Nur'Aeni et al. 2024). Similarly, Indonesian export duties and export controls can raise world CPO prices, particularly when importing countries rely heavily on Indonesian supply (Pratama and Widodo 2020).

Overall, the empirical patterns align closely with the theoretical predictions of residual demand analysis. The price effects generated by export restrictions increase with the degree of destination-market dependence on the exporting country. India and Pakistan exhibit the strongest responses due to their structural reliance on Indonesian CPO, whereas China demonstrates more moderate effects owing to diversified consumption and greater substitution possibilities. Statistical significance across alternative model specifications confirms the robustness of these results.

Overall, Indonesian export restrictions exert a substantial influence on international CPO prices, particularly in India and Pakistan. The effect remains present but weaker in China due to greater substitution among vegetable oils. Malaysian export restrictions also affect market power, although their impact is smaller and more stable across markets. Differences in market share, competitive interaction, and policy design explain this divergence. Export restriction policies therefore emerge as an important determinant of exporter market power in the global palm oil market, operating through supply adjustments that alter residual demand elasticity and price formation across heterogeneous destination markets.

CONCLUSION AND RECOMMENDATIONS

Residual demand elasticity estimates indicate that both Indonesia and Malaysia possess measurable market power in major crude palm oil (CPO) importing markets and therefore do not behave as pure price takers. Indonesia exhibits stronger market power, particularly in India and Pakistan, while Malaysia's influence is more moderate. In China, market power is weaker for both exporters due to greater substitution among vegetable oils. Export restriction policies influence pricing behaviour, especially for Indonesia, where changes in export supply have a stronger impact on international prices. In contrast, Malaysia's pricing influence appears more stable and less dependent on export restrictions. Overall, differences in market power across destination markets are shaped by levels of import dependence and substitution possibilities. From a policy perspective, Indonesia should apply export restrictions selectively while strengthening downstream development to enhance value-added production. Malaysia should focus on improving supply reliability, logistics, and trade facilitation to sustain competitiveness. For both countries, export strategies should be adaptive to evolving global market conditions and aligned with sustainability standards.

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CACAO PRODUCTIVITY AND SOIL CARBON STORAGE IN TWO CROPPING SYSTEMS WITH SELECTED SOIL AMENDMENTS APPLIED IN KABACAN LOAM SOIL

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ABSTRACT

Rising demand for cacao requires nature-based solutions and improved cropping systems to enhance yields, improve soil health, and store carbon. This study assessed the influence of different cacao cropping systems and soil amendments on the yield of 14-year-old cacao (*Theobroma cacao* L.) trees and soil carbon storage, conducted at the University of Southern Mindanao in Kabacan, Cotabato, Philippines (2023-2024). Using a split-plot design and 2-way ANOVA, the trial evaluated two cacao cropping systems: cacao-rubber-coconut (CS 1) and cacao-rubber (CS 2); and soil amendments (control-C, inorganic fertilizer-RR, lime-L, organic fertilizer-OF, and lime + organic fertilizer-L+OF). Two seasons trials, wet (2023) and dry (2024) seasons, revealed that CS 2 significantly increased the yield of cacao (763.82 g/tree dried beans), elevated stored C in the soil, and maintained light intensity within the range limit for cacao. The application of lime and organic fertilizer further enhanced yield by 60%, improved soil organic carbon (SOC) levels, and stored soil C at 80.22 t/ha and 71.33 t/ha, respectively. The increased CN ratio observed in these plots indicated enhanced stabilized carbon. The study demonstrated that lime and organic fertilizer applications in a cacao-rubber system (CS 2) serve as an effective management strategy for improving both cacao productivity and soil health.

Key words: rubber, coconut, light intensity, organic fertilizer, lime

INTRODUCTION

Proper agricultural soil management could be the most effective strategy for reducing the sector's contribution to global carbon emissions. Soils, among other natural resources, sequester and store a significant amount of carbon (C), the primary agent of global warming, and transform it from one form to another, which benefits the ecosystem. C sequestration is the process of capturing CO₂, which can be stored in the soil as soil organic carbon (SOC) (Corning et al. 2016).

Agricultural soils containing around 5% organic matter (OM) or 3% organic carbon (OC) are considered healthy soils capable of sustaining food production, soil microflora, and fauna (Brady and Weil, 2008). However, the intensive and continuous practice of unsustainable farming decreases the

ability of the soil to store C and sustain life. Employing tillage in soil has a negative impact on its OC content (Szostek et al. 2022; Haddaway et al. 2017) as tillage hastens the decomposition process through soil aggregate disruption, increasing aeration, and accelerating the SOC oxidation, resulting in the loss of C in soil (Farahani et al. 2022; Lu et al. 2016; Toth et al. 2025). The rampant use of chemical fertilizers is one of the drivers of greenhouse gas emissions in the atmosphere (Wang et al. 2017). The synthetic nitrogen fertilizer supply chain alone is responsible for 2% of global heat-trapping gas emissions, which is greater than the emissions from all aviation (Heimsoth 2023). If left unattended and the land is degraded, it will impact food security, water availability, and ecosystem health, as well as the loss of ecosystem services that will directly affect humanity (United Nations n.d.). Thus, investment must be made to restore the health of the soil through sustainable land management practices, such as the use of organic inputs and other nature-based solutions for production and the practice of various cropping systems.

One of the strategies to improve soil fertility is through the continuous cycle of nutrients and C and C storage in the soil by effective cropping systems and soil management. All simplifications in tillage, reducing interference in the soil, and the use of organic fertilizers contribute to the improvement of soil properties (Szostek et al. 2022), which assists in the assimilation of carbon and nutrients from plants into the soil, affecting plant-soil interactions. Soil litter production is a major source of SOC and plant nutrient cycles (Novara et al. 2015). As a perennial crop, cacao naturally produces litter and stores C in the soil. Different soils grown with cacao in Davao City, Philippines, stored a considerable amount of SOC, ranging from 1.18 to 3.34% (Novara et al. 2015). Similarly, cacao agroforest cropping systems showed improved soil organic matter content (Monroe et al. 2016; Mustari et al. 2020; Schneidewind 2022; Silue et al. 2024), soil microbial activity (Schneidewind 2022), and soil carbon storage (Araujo et al. 2013; Asigbaase et al. 2021; Miharza et al. 2023; Monroe et al. 2016; Mustari et al. 2020; Schneidewind 2022; Silue et al. 2024; Somarriba et al. 2013), and improved soil quality compared to cacao monoculture. Furthermore, the utilization of soil for perennial crops, such as cacao, improves soil quality. The soil quality, SOC, and nutrient availability in the soil increased progressively with the age of cacao in Ghana (Arthur et al. 2022).

With the continuously increasing demand for cacao beans, information on the effectiveness of various cropping systems and nature-based solutions in improving the yield of cacao and its effect on soil health, as well as on storing carbon (C), is becoming important for sustainability. In Mindanao, Philippines, the productivity per hectare of cacao is declining at a fast rate of 5% from 0.4 to 0.2 tons/ha from 2010 to 2023, and so with the level of income of the smallholder cacao families. A similar trend was observed for the entire country based on cacao statistics (Sales 2025).

Cropping systems have a direct effect of the productivity of cacao where cacao yield under different cropping system is correlated to shade trees associated. In cacao-cropping systems, cacao yield is positively correlated to the amount of light received by the cacao trees (Asitoakor et al. 2022; Chowdary et al. 2024; Koko et al. 2013; Saj et al. 2025). This can be influenced by the crop species (Asitoakor et al. 2022; Jadán et al. 2015; Mattalia et al. 2022), its crop morphology (Ariza-Salamanca et al. 2024), crop density (Koko et al. 2013; Silue et al. 2024), and planting distance (Koko et al. 2013; Notaro et al. 2021). The legume tree *Albizia lebbek* is a compatible shade tree for cacao intercropping compared to *Acacia mangium* (Silue et al. 2024). There was an increase in cacao yield with *Cedrela odorata*, *Khaya ivorensis*, *Terminalia superba*, and *Millicia excelsa* tree shades as compared to the unshaded cacao plots (Asitoakor et al. 2022). The complementary effect of shade trees to cacao is a result of the tree structure of these species that allows light penetration to cacao trees. The four species mentioned in the study of Asitoakor et al. (2022) have morphological structures that allow higher light penetration. Cacao yield and incident light are logistic functions of the distance between fruit trees and cacao (Koko et al. 2013). Higher yield was observed in cacao cropping system with lower shade tree density and cacao crops in full sun produced higher yield as compared to agroforest cacao cropping systems (Chowdary et al. 2024; Jadán et al. 2015; Koko et al. 2013; Niether et al. 2017; Saj et al. 2025).

Other than the amount of light received, competition for water and soil nutrients, species compatibility (Ariza-Salamanca et al. 2024; Notaro et al. 2021; Silue et al. 2024) and the interaction of organism diversity have influenced the cacao productivity (Ntsoli et al. 2025). Due to this range of factors which vary across locations, assessment and management should be site specific (Mattalia et al. 2022). Given this, it is essential to evaluate the cacao productivity in different cacao cropping systems in a site-specific approach.

In the Philippines, cacao is the major crop planted under coconut trees, but some areas have already established cacao-rubber systems, especially in North Cotabato, Central Mindanao, Philippines (Mag-aso and Garcia, 2021). Given the rising trend of intercropping cacao to rubber and coconut, research into these cropping systems is critical. An earlier published study on cacao-rubber was conducted in Brazil, requiring validation to ensure the feasibility of cacao-rubber combinations (Alvim and Nair 1986). The influence of cacao-rubber cropping systems on cacao productivity and C stocks remains scarce. Also, no prior studies were conducted on the effect of soil amendment application in cacao-rubber cropping systems, specifically for Kabacan loam soil. Therefore, this study was conducted to assess and compare the effects of two cacao-cropping systems (cacao-coconut-rubber and cacao-rubber) and selected soil amendments (control, recommended rate of inorganic fertilizer RR, lime L, organic fertilizer OF and lime + organic fertilizer L + OF) applied within the cacao-cropping system on the productivity of cacao, SOC content and stored C in the soil.

MATERIALS AND METHODS

Experimental design. Experiments were conducted in two (2) different cropping systems of cacao planted in *Typic Hapludpts* (Carating et al. 2014) with the Kabacan loam type located in the experimental field of the Philippine Industrial Crops Research Institute (PICRI), University of Southern Mindanao Agricultural Research and Development Center (USMARDC), University of Southern Mindanao, Kabacan, Cotabato, Philippines, from January 2023 to May 2024. The experiment was done in a split-plot design having two (2) cacao-cropping systems: cacao-rubber-coconut (CS 1) and cacao-rubber (CS 2) as the mainplot factor, and five (5) soil amendments (control, inorganic fertilizer-RR, lime-L, organic fertilizer-OF, and lime + organic fertilizer-L + OF) as subplots. A two-way ANOVA was used to determine the significant difference between the two cacao-cropping systems and among different soil amendments applied within the cacao-cropping systems.

In CS 1, cacao plants were established as a rectangular double row, with distances within cacao rows were 3 m x 3 m and 15 m between double rows (559 trees/ha). Coconut was intercropped 7.5 m x 18 m in a rectangular design (74 trees/ha). While rubber is intercropped in a rectangular double row, the distance within cacao rows were 5 m x 2.5 m and 13 m in between double rows (444 trees/ha). Meanwhile, cacao plants in CS 2 were established in 3-row triangular design with 3 m distance between plants having a double row with 10 m distance in between (864 trees/ha). Similarly, rubber in CS 2 was intercropped in rectangular double row plants with 5 x 4 m distance and 10 m distance between double row (329 trees/ha) (Table 1, Fig. 1).

Table 1. Planting distance and layout design of the two cropping systems in PICRI Research Area, USMARDC, USM, Kabacan, Cotabato.

Cropping System	Crops	Age of the crops (years)	Planting Distance (m)	Planting Design	Planting density of crops (trees/hectare)	Planting Density of the cacao-cropping system (trees/hectare)
Cacao + Coconut + Rubber (CS 1)	Cacao	14	15 x 3 double row 3 x 3	Rectangular double rows	559	1, 077
	Coconut	14	7.5 x 18	Rectangular	74	
	Rubber	14	13 x 2.5, double row 5 x 2.5	Rectangular double rows	444	
Cacao + Rubber (CS 2)	Cacao	14	3 x 3 10	Triangular Double row	864	1, 193
	Rubber	14	10 x 4 double row 5 x 4	Rectangular double rows	329	

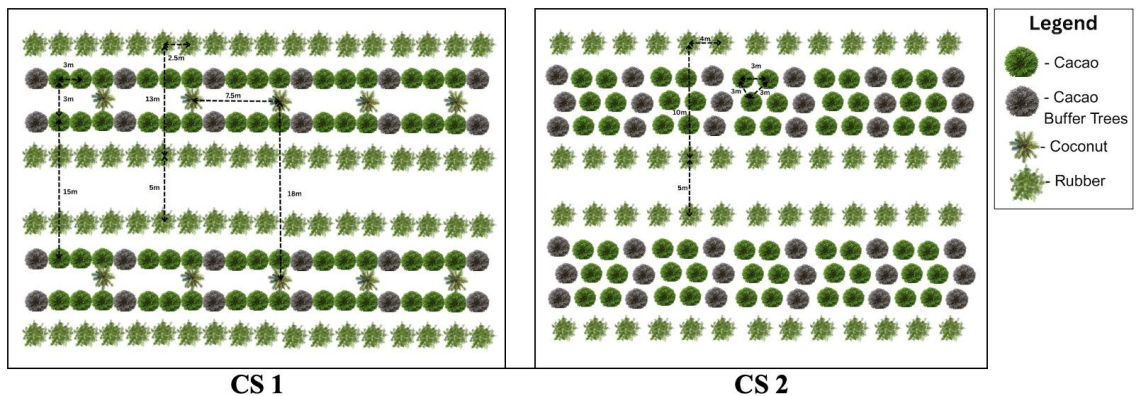


Figure 1. Planting design of the two cropping systems, cacao-coconut-rubber (CS 1) and cacao-rubber (CS 2) in PICRI Research Area, USMARDC, USM, Kabacan, Cotabato.

Liming and fertilization. Application of lime and soil amendments started in October 2022 and was done annually in the month of October for two (2) consecutive years (2022-2023). The lime (L) application rate was 1 kg/tree. Inorganic fertilizer (RR) rate applied was 160g N - 60g P₂O₅ - 120g K₂O/tree, and organic fertilizer application (OF) rate was 2,000 g/tree (Table 2).

Table 2. Treatments and the types of fertilizer applied in the different cacao (*Theobroma cacao* L.) cropping systems in PICRI Research Area, USMARDC, USM, Kabacan, Cotabato.

Treatments	Application Rate (kg/tree)	Time of Application
T1- Control	No fertilizer application	
T2- RR	160g N - 60g P ₂ O ₅ - 120g K ₂ O/tree	Fertilization was done annually starting October 2022.
T3- Lime (L)	1000 g/tree of lime	Liming was done annually starting October 2022.
T4- Organic Fertilizer (OF)	2000 g/tree of organic fertilizer	Fertilization was done annually starting October 2022.
T5- Lime + Organic Fertilizer (L + OF)	1000 g/tree lime + 2000 g/tree organic fertilizer	Liming and fertilization were done annually, starting in October 2022.

Soil analysis. Soil samples were collected from the experimental area before the application of each treatment. One (1) composite sample, composed of 15 subsamples, was collected at a depth of 20 cm. The samples were submitted to the USMARDC-Central Laboratory, where soil pH (1:2.5 soil: water), organic C% (Walkley-Black method), total N% (Kjeldahl method), available P (Bray P2 method), exchangeable K (Ammonium Acetate 7 method), cation exchange capacity (CEC Ammonium Acetate 7 method), and texture (Hydrometer method) were analyzed.

Chemical analysis of fertilizers. The organic fertilizer and lime used were also submitted to the USMARDC-Central Laboratory for analysis. Organic C content (Walkley-Black method), P₂O₅% (colorimetric method), and K₂O (AAS determination) were determined for the organic fertilizer. For the calcic lime, total Ca and CaCO₃ (acid digestion method) were determined.

Cacao yield. Data were collected at the onset of harvest from September 2023 to March 2024 (peak season of cacao). A sample of six cacao trees per plot were used to estimate the number of cacao pods, the bean weight per pod, and the bean weight (wet and dry) per tree. The number of pods per tree were counted, bean weight per pod was recorded and the total bean weight per tree was calculated by aggregating the bean weight in each sample tree. The beans were oven-dried at 70°C until a constant weight was achieved. Both fresh and dried weights of cacao beans per tree were expressed in grams.

Soil C storage assessment. The soil samples were collected and prepared for each experimental plot. Each soil sample was a composite of ten (10) subsampling points randomly selected within the experimental plots, and collected using an auger to a depth of 20 cm. These were analyzed for soil organic C (OC%) following the Walkley-Black chromic acid wet oxidation method (GLOSOLAN 2019) and bulk density using the core method (Jabro et al. 2020). Carbon stored in soil (t/ha) was estimated using the C storage formula (Araujo et al. 2013; Morgan and Ackerson 2022; Tadiello et al. 2022) as follows:

$$\text{Soil C storage} \left(\frac{\text{t}}{\text{ha}} \right) = \text{OC}\% \times \text{layer thickness} \times \text{bulk density} \times (1 - \text{RF}) \times 10^4$$

where OC is the organic carbon content and RF is the rock fragment content fraction.

Total N (%) in the soil was also determined using the Kjeldahl method (GLOSOLAN 2021) to determine the CN ratio.

Light intensity (lux). Light intensity was determined using the lux light meter, collected at 10:00 am and 2:00 pm on March 2024. The collection of light intensity using the light meter was done five times, at a height of 1.5 m from the ground, within the experimental plots.

Litterfall production (t/ha). Litterfall production was gathered following the modified procedure of Pitman et al. 2010. A litterfall trap was established by setting-up one (1) meter square mesh net with a distance of 10 cm from the ground for litterfall collection in the center of each experimental unit. The plant litterfall samples were collected monthly during the wet season 2023 (May to October 2023) and the dry season 2024 (November 2023 to April 2024). Dry weight of leaf litter was determined using a convection oven, and monthly data were consolidated for each season.

Statistical analysis. Two-way ANOVA was used to determine the differences between cropping systems and among soil amendments. The difference between the two cropping systems was tested using Least Significant Difference (LSD) at 5% level, and the differences among soil amendments were separated using Tukey's Honest Significant Difference (HSD). The Statistical Tool for Agricultural Research (STAR 2013) was used to analyze the data.

RESULTS AND DISCUSSION

Soil initial analysis. Soil pH, available P, and cation exchange capacity had sufficient levels for cacao production; however, soil OC, total N, and exchangeable K were deficient when compared to the cacao nutrient threshold established by Snoeck et al. (2016) (Table 3). The soil of the experimental area was moderately acidic (pH 5.62), which was within the optimal threshold of cacao. The available P content was higher than the cacao threshold level (6-15 ppm) with a value of 77.91 ppm. Cation exchange capacity (CEC) was slightly higher than the cacao threshold (12-30 cmol₊ kg⁻¹ soil), which was 30.43 cmol₊ kg⁻¹ soil. The soil organic C content, total N, and exchangeable K analysis were lower than the range for cacao threshold with values 1.24%, 0.17% and 0.09 cmol₊ kg⁻¹ soil, respectively. The soil texture was loam.

Table 3. Initial soil analysis of the experimental area, PICRI research area, USMARDC, USM Kabacan, Cotabato.

Soil analysis	Value
Soil pH	5.62 S
Soil organic carbon (%)	1.24 D
Total nitrogen (%)	0.17 D
Available phosphorus (ppm)	77.91 S
Exchangeable potassium (cmol ₊ kg ⁻¹ soil)	0.09 D
CEC (cmol ₊ kg ⁻¹ soil)	30.43 S
Soil texture	Loam (46.08% sand, 29.18% clay, and 24.75% silt)

S – sufficient and D-deficient for cacao based on Snoeck et al. 2016

Chemical analysis of organic fertilizer and calcic lime. The organic C and organic matter content of the organic fertilizer was 8.26 and 14.20%, respectively. The total N content was 1.69%, P₂O₅ and K₂O were 0.70 and 0.84%, respectively. The lime used in the experiment had 35.6% total Ca and the total CaCO₃ was 89.1% (Table 4).

Table 4. Chemical analysis of organic fertilizer and calcic lime used in the field trials experiment.

Chemical analysis	Organic Fertilizer	Calcic Lime
Organic carbon (%)	8.26	
Organic matter (%)	14.20	
N (%)	1.69	
P ₂ O ₅ (%)	0.70	
K ₂ O (%)	0.84	
Total Ca (%)		35.7%
Total CaCO ₃ (%)		89.1%

Yield of cacao

Cropping system. Significant interactions between the cropping system and soil amendment were recorded in cacao yield, where liming under CS 2 resulted in the highest yield. Moreover, it was observed that cropping system significantly increased the cacao yield which was notably higher in CS 2, having higher cacao plant density and a lower rubber population per unit area. Number of cacao pod, weight of beans per pod and weight of wet beans per tree were significantly higher in CS 2 than in CS 1 (Table 5). The fresh (Table 6) and dried weight (Fig. 2) of beans per tree were also higher in CS 2 as compared to CS 1.

Wider spacing between the cacao under CS 2 provided ideal conditions to produce higher fruit numbers and weights of wet and dried beans. CS 1 has a larger number of tall trees, such as rubber and coconut, which reduces the space for cacao and resulted in lower light received which is 9,510 lux as compared to CS 2 which have 31,636 lux light intensity (Fig. 2). Hence, pod production is lower in CS 1 with an average of 7 pods/tree (Table 5). This indicates that increasing the density and population of rubber and coconut trees and decreasing planting distance will result in lower pod development and reduced bean weight in pods.

Competition for light between tall trees and cacao might have affected cacao yield as light intensity penetrating the CS 1 was lower than CS 2. (Fig. 2). Excessive shade in CS 1 indicated by low light intensity (9,510 lux) is detrimental to the photosynthetic activities (Arévalo-Gardini et al. 2021), resulting in reduced cacao growth and productivity. Although cacao is a shade-tolerant crop, it requires a certain light limit ranging from 27,000 lux (De Santana et al. 2025; Lennon et al. 2021) to 81,000 lux (De Santana et al. 2025), reaching up to 97,200 lux (Galyoun et al. 1996) which may vary depending on the cacao genotype and season (Acheampong et al. 2013; Lahive et al. 2019). Several studies shows that cacao yield in the cacao-cropping system is influenced by the associated shade trees, affecting light inflexion and penetration to cacao. The amount of light received by the cacao trees in the cacao-cropping systems is positively correlated with the cacao tree vigor and yield (Chowdary et al. 2024). Light availability is the critical limiting factor for production in the cacao cropping system (Saj et al. 2025).

These results were consistent with an earlier study on a coconut-cacao system that revealed higher cumulative cacao yield in higher cacao plant density with fewer coconut trees as an intercrop (Osei-Bonsu et al. 2002). Similar findings were also shown by Silue et al. (2024), where cocoa productivity is lower in cacao-*Acacia mangium* agroforests with lower cacao density and reduced

distance between cacao trees and the shade tree *Acacia mangium*. Increasing the shade tree cover from about 20% to 80% in the cacao system resulted in about a 60% decrease in cacao yield (Blaser et al. 2017). Cacao yield is lower in a cropping system having high density shade trees as compared to monocrop cacao (Jadán et al. 2015) . Thus, shade management is key in balancing cocoa productivity and carbon sequestration (Somarriba et al. 2013).

Soil amendments. The application of soil amendments significantly increased the cacao yield which was found to be more effective in CS 2. Under CS 2, cacao trees treated with lime significantly increased the yield of cacao in terms of the number of pods per tree (51 pods/tree), followed by cacao trees treated with OF (37 pods/tree). The combination of L and OF application resulted in a yield output of 30 pods/tree, similar to that of cacao trees treated with RR of inorganic fertilizer (31 pods/tree) (Table 5). Soil amendment can improve the yield of cacao cropping systems by providing nutrients in optimum shade (Acheampong et al. 2015; Goudsmit et al. 2023) and full sunlight (Goudsmit et al. 2023).

Table 5. Number of pods/tree and weight of wet beans of cacao per pod (g/pod) under different cacao cropping systems applied with soil amendments, during the wet 2023 and dry 2024 season.

Soil Amendments	Number of pods/tree ^{1/}		Weight of wet beans per pod (g/pod) ^{1/}	
	CS 1	CS 2	CS 1	CS 2
T1- Control	0 ± 0.00 a	3 ± 1.22 c	0.00 ± 0.00 c	99.09 ± 8.23 c
T2- RR	7 ± 4.18 a	31 ± 4.33 b	112.10 ± 7.04 b	111.39 ± 13.38 bc
T3- Lime (L)	9 ± 3.93 a	51 ± 10.68 a	116.04 ± 1.00 b	124.73 ± 4.33 b
T4- Organic Fertilizer (OF)	13 ± 2.31 a	37 ± 9.24 ab	139.32 ± 4.68 a	151.09 ± 8.86 a
T5- Lime + Organic Fertilizer (L + OF)	5 ± 2.52 a	30 ± 4.37 b	109.76 ± 168.83 b	127.14 ± 0.06 b
Pr (>F) _a	0.0115		0.0159	
Pr (>F) _b			0.0004	0.0000
Pr (>F) _{axb}			0.0255	0.0000

^{1/}In a column, means followed by the same letter are not significantly different at the 5% level according to Tukey's HSD test.

Soil amendment applications significantly increased the weight of wet beans per pod in both CS employed (Table 5). The application of OF recorded the highest bean weight per pod in both CS 1 (139.32g) and CS 2 (151.09g). This was followed by the bean weight per pod applied with L (CS 1 - 116.04 g and CS 2 124.73 g) and L + OF (CS 1 - 109.76 and CS 2 – 124.14 g), which did not differ significantly from the results of RR (112.10g and 111.39g).

The wet bean yield of the cacao trees also increased significantly following the application of soil amendments. Under CS 1, the highest wet bean yield per tree was observed in cacao trees treated with OF (1,086.70 g/tree). The application of lime alone resulted in the wet bean weight increase of 36.72% relative to RR; however, the L + OF application resulted in a lower bean weight output of 331.37 g/tree as compared to L (653.02 g/tree) and OF (1,086.70 g/tree) application, which was not significantly different from bean weight output of cacao applied with RR inorganic fertilizer (413.20 g/tree) (Table 6).

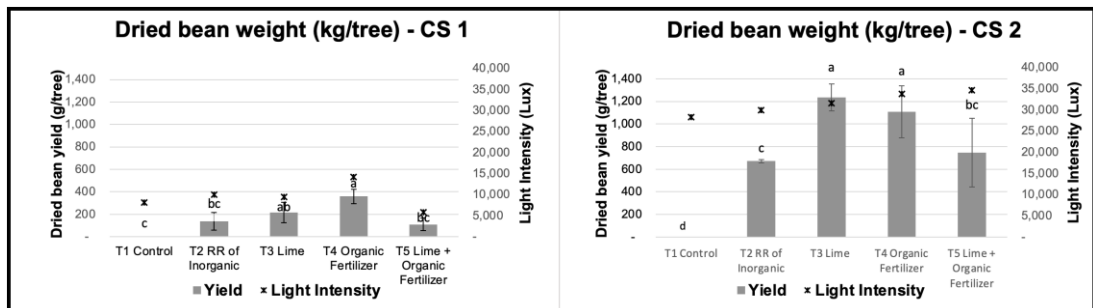
In CS 2, the wet bean weight output of cacao trees treated with L was significantly higher than those applied with RR. Wet bean weight of cacao applied with L was 3,743 g/tree, which was 84% higher than that of cacao trees subjected to RR (2,034 g/tree). The application of OF produced a bean weight yield output of 3,359.31 g/tree, which was at par with the output of cacao trees applied with L (3,743.36 g/tree). However, the combination of L and OF resulted in a significantly lower wet bean weight output of 2,263.28 g/tree compared to wet bean weight treated with L alone or OF alone (Table 6).

The dried bean yield per tree of cacao increased significantly when the soil amendments were applied. Under CS 1, the OF application resulted in the highest dried bean yield (355.61 g/tree), which was not significantly different from the dried bean yield obtained from cacao trees treated with L (215.50 g/tree). However, significantly lower dried bean yield was obtained when lime and organic fertilizer were combined (109.35 g/tree). Under CS 2, the application of lime resulted in a higher dried bean yield (1,235.31 g/tree), which was at par with those that were applied with OF (1,108.57 g/tree) (Fig. 2).

Table 6. Weight of wet beans (g/tree) under two cacao cropping systems applied with soil amendments, during the wet 2023 and dry 2024 seasons.

Soil Amendments	Weight of wet beans per tree (g/tree) ^{1/}	
	CS 1	CS 2
T1- Control	0.00 ± 0.00 a	172.91 ± 49.24 d
T2- RR	413.20 ± 235.40 a	2,034.09 ± 358.25 c
T3- Lime (L)	653.02 ± 277.61 a	3,743.36 ± 700.17 a
T4- Organic Fertilizer (OF)	1,086.70 ± 190.10 a	3,359.31 ± 918.60 ab
T5- Lime + Organic Fertilizer (L + OF)	331.37 ± 168.83 a	2,263.28 ± 334.10 bc
Pr (>F) _a	0.0132	
Pr (>F) _b		0.0003
Pr (>F) _{axb}		0.0276

^{1/}In a column, means followed by the same letter are not significantly different at 5% level Tukey's HSD test.



*Cropping system significantly different at p -value < 0.05 LSD

^{1/}Within the cropping systems, bars followed by the same letter are not significantly different at the 5% level according to Tukey's HSD test.

Figure 2. Dried bean weight of cacao (kg/tree) in different cropping systems* and soil amendments.

Both organic fertilizer application and liming significantly increased the wet and dry bean yield of cacao. OF application improved the cacao yield by providing nutrients to the plants and increasing nutrient uptake and efficiency (Muda et al. 2021; Mulia et al. 2019), contributed by the effect of organic fertilizer on enhancing soil microbial activity, improving soil structure, and increasing nutrient availability (Fungenzi et al. 2021). Furthermore, liming soil improves the pH of the soil and the availability of nutrients, which increases yield (Ejigu et al. 2023; Qaswar et al. 2020) and is necessary for application in acidic soils (Snoeck et al. 2016). Rosas-Patiño et al. (2019) showed that liming increases the yield of cacao. However, combining lime to organic fertilizer did not significantly increase the wet and dry bean yield of cacao. Similar results were found in the study of Islam et al. (2021) where the combination of lime and organic manure (cow dung) resulted to lower first crop (T. aman) yields compared to lime alone, with result comparable to control (no application). Ca in lime may form inner and outer sphere complexes with OC (Adusei-Gyamfi et al. 2019; Galicia-Andrés et al. 2021). These forms dense agglomerates which enhances OM stability and protect SOM from further degradation (Galicia-Andrés et al. 2021). Stable OM from agglomeration through Ca-SOM complexation might reduce the mineralization of nutrients making it temporarily unavailable for crop uptake, hence, reducing cacao yield.

Soil pH

Cropping system. Soil pH was not significantly influenced by the different cropping systems and soil amendments during wet season (2023), however, a significant difference was recorded during dry season (2024) (Table 7).

Soil amendments. Soil pH was increased significantly in soil applied with OF in CS 2 (pH 5.95) and L + OF in CS 1 (pH 5.90). However, liming soil in CS 1 (pH 5.40) and CS 2 (pH 5.55) did not significantly increase the soil pH, while L + OF applied in CS 2 resulted in a lower soil pH (pH 5.27). Soil applied with OF in CS 1 has a soil pH value (pH 5.59) similar to soil applied with RR under CS 1 (pH 5.56) and CS 2 (pH 5.58), and control in CS 2 (pH 5.65) (Table 7).

OF application in CS 2 and L + OF in CS 1 have shown to increase the soil pH attributed to the mechanism of organic matter decomposition that includes decarboxylation, where reaction products may consume proton (Yan et al. 1996) and the release of basic ions and salts which are products of mineralization. Similar results were also found in the study of Islam et al. (2021) and Regasa et al. (2025) where application of lime combined with organic amendment significantly increased the soil pH as compared to lime alone. Liming soil without OF application did not significantly increase the soil pH, as the amount of lime applied might be insufficient to increase the pH in soils. Factors affecting the change in pH with liming application rate, other than the type of liming material, timing, and method (Jouichat et al. 2024). A low application rate of lime below the buffering capacity of the soil will not effectively increase the soil pH (Fageria and Baligar 2008; Fageria and Nascente 2014). Similar results were also found in an earlier study wherein application of lime at a rate of 0.5 to 1 ton per hectare in wheat resulted in soil pH similar to control (without lime) (Ejigu et al. 2023).

It was also observed that soil pH in dry season (2024) was higher than the soil pH recorded during wet season 2023 noticeable in CS 2. Soil pH was recorded as higher during the dry season than in wet season based on the laboratory analysis of Solonchaks soil in Yinbei region, China (Jia et al. 2021). This difference is attributed to the intensified leaching of basic ions by rainfall during the wet season, which is reduced in the dry season, thereby maintaining a higher pH.

Table 7. Soil pH under two cacao cropping systems applied with soil amendments during the wet 2023 and dry 2024 seasons.

Treatments	Wet Season (2023) ^{ns}		Dry Season (2024) ^{1/}	
	CS 1	CS 2	CS 1	CS 2
T1- Control	5.38 ±0.08 a	5.07 ±0.03 a	5.31 ±0.03 b	5.65 ±0.08 ab
T2- RR	5.51 ±0.04 a	5.43 ±0.16 a	5.56 ±0.04 ab	5.58 ±0.16 ab
T3- Lime (L)	5.37 ±0.01 a	5.13 ±0.09 a	5.40 ±0.04 ab	5.55 ±0.09 ab
T4- Organic Fertilizer (OF)	5.55 ±0.13 a	5.47 ±0.09 a	5.59 ±0.03 ab	5.95 ±0.09 a
T5- Lime + Organic Fertilizer (L + OF)	5.37 ±0.19 a	5.37 ±0.13 a	5.90 ±0.14 a	5.27 ±0.13 b
Pr (>F) _a	0.1716		0.6943	
Pr (>F) _b			0.1005	0.0684
Pr (>F) _{axb}			0.6870	0.0013

Ranges of soil pH as follows: very strongly acid (4.5–5.0), strongly acidic (5.1–5.5), moderately acidic (5.6–6.0), slightly acidic (6.1–6.5) (Ditzler et al. 2017)

^{1/}In a column, means followed by the same letter are not significantly different at 5% level Tukey's HSD test.
^{ns} - Not significantly different

Soil organic C and litterfall

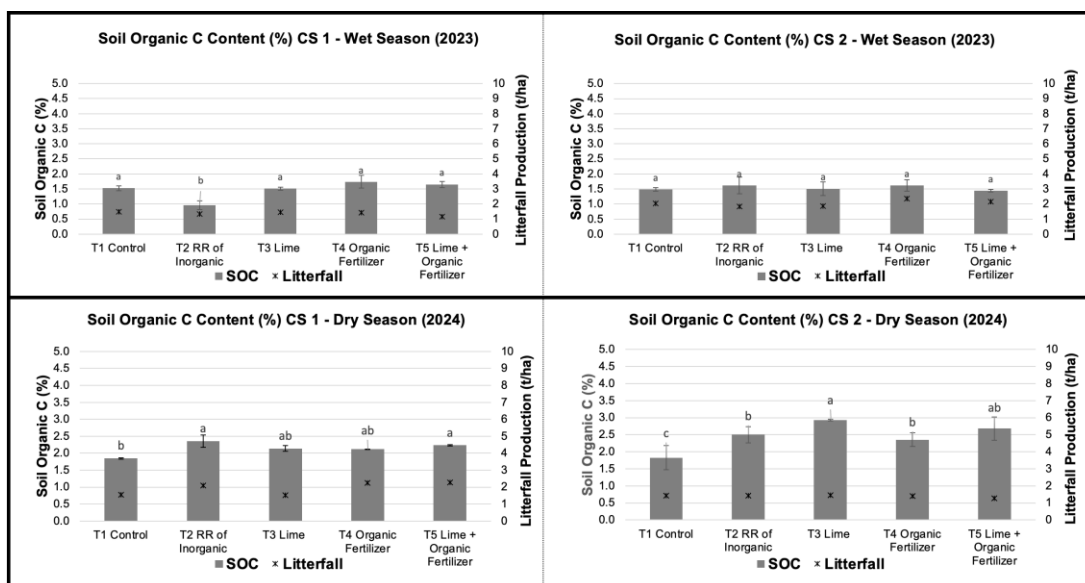
Cropping system. Significant interaction was recorded between the cropping system and soil amendments on their effect on the soil organic carbon content. The organic C (OC) content in the soil increased significantly with the application of soil amendment in both cropping systems - CS 1 and CS 2. Over time, a noticeable increase in OC was observed, indicating an accumulation of OC in the soil. The SOC content between cacao cropping systems tends to be higher under CS 2 compared to CS 1, specifically during DS 2024 (Fig. 3). The higher SOC accumulation observed in CS 2 might be attributed to the higher biomass from total litterfall production in the system, owing to its higher cacao plant density than CS1. The overall litterfall production tends to be higher in CS 2, where relatively higher litterfall accumulated in CS 2 during the wet season (2023) (Fig. 3). Higher litterfall production was observed in CS 2 in wet season (2023) brought about by cacao litter as CS 2 had higher cacao density. Whilst, during the dry season (2024), higher litterfall was observed in CS 1, as this period was wintering for rubber, where CS 1 had greater rubber density. Overall, CS 2 recorded relatively higher litterfall production.

In a cacao agroforest system, the biomass and density of cacao trees were the determinants of biomass production (Silue et al. 2024). The sources of this biomass in cacao were litterfall and litter from cacao management, such as pruning, and the abundance of roots and fine root biomass (Monroe et al. 2016).

Soil amendments. Soil organic C content is also significantly influenced by the application of soil amendments. The highest significant increase in soil organic C content was achieved in CS 2 with L and L + OF amendments (Fig. 3).

During the wet season of 2023, the application of soil amendments to CS 1 significantly influenced the soil organic matter content. The lowest SOC content (0.96 %) was recorded in soils treated with inorganic fertilizer. Statistically, the application of L, OF, and L + OF gained SOC content similar to the control. However, the application of OF recorded 14% higher SOC content (1.74%) relative to control (1.52%) and was 58% higher than the application of RR. Under CS 2, soil organic C content applied with soil amendment was not significantly different (Fig. 3).

During the dry season (2024), the addition of soil amendments increased soil organic C content. Under CS 1, the SOC content of the soil subjected to RR (2.36%) increased, which was not statistically different from the SOC content of the soil treated with L + OF (2.23%). An increase in SOC was also observed in soils treated with OF (2.12%) and L (2.14%) relative to the control. Similarly, a significant increase in SOC was also observed under CS 2. The highest SOC was observed in the soil treated with L (2.93%), which was similar to the SOC level of the soil treated with L + OF (2.68%). SOC content was also significantly higher in soil applied with OF (2.36%) as compared to control where SOC content applied with OF was statistically similar to SOC content applied with RR (2.50%) (Fig. 3).



^{1/}Within the cropping systems, bars followed by the same letter are not significantly different at the 5% level according to Tukey's HSD test.

Figure 3. Soil organic carbon (%) under two cacao cropping systems after application of selected soil amendments during the wet 2023 and dry 2024 seasons.

The increase in OC content in soil treated with OF is attributed to the OC content of the amendment, which might be stable (Yilmaz and Sönmez 2017). Furthermore, a noticeable decline in OC was observed in soil treated with RR, which might be attributed to the low C:N ratio (6.11) and faster rate of SOC oxidation (Fig. 4). The retention of C in soil with inorganic fertilizer is much lower (Ndung'u et al. 2021). Liming alone did not increase the amount of OC in the soil during the wet season of 2023, as liming delayed the effect of increased litter and other sources of C in increasing SOC levels. The effect of liming on SOC was observed in the succeeding season (dry season, 2024) (Fig. 3).

The addition of L + OF and OF to the soil effectively increases the SOC in soil, as these soil amendments might improve the conversion of litterfall to stable SOC, acted by decomposers (Paradelo

et al. 2015). Additionally, Ca from the applied lime formed complexes with OC, flocculated the soil, and stabilized SOC (Rowley et al. 2018).

Stored carbon (C) in soil

Cropping system. Cropping systems influenced the stored C in soil in two different seasons, wherein higher stored C was noted in CS 2, having a high cacao tree density that distributes more leaf litter in the soil (Fig. 4).

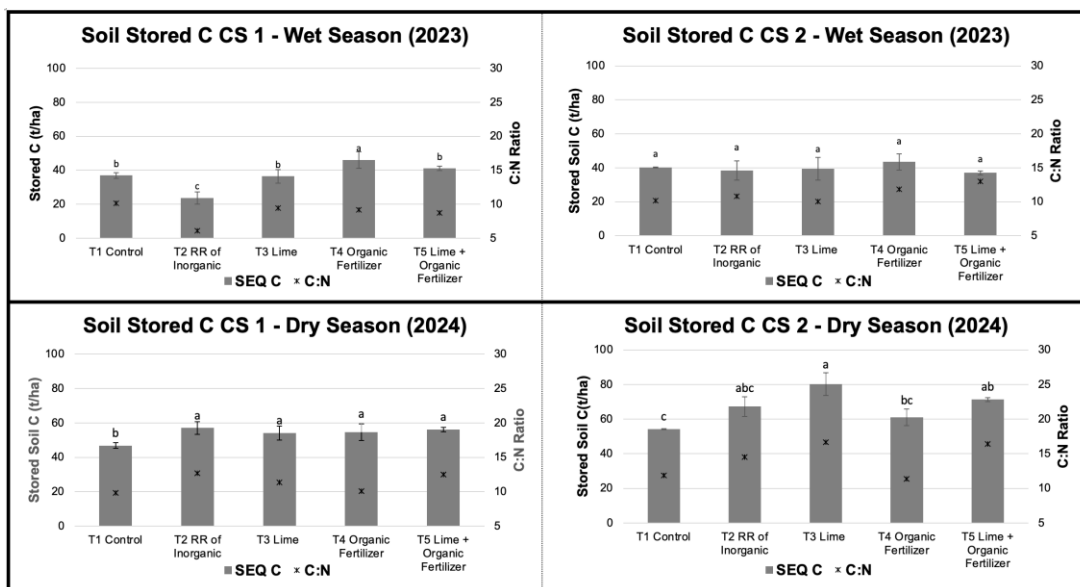
The density of cacao trees is a major determinant of the biomass in agroforest systems. This is attributed to the reduced competition for light among cacao trees, increased photosynthetic activity, and C assimilation, which results in higher biomass production (Silue et al. 2024). Furthermore, in the cacao-rubber system, soil C storage was greater in the cacao rows than in the rubber rows, which is attributed to the deposition of cacao litter and root biomass in the system (Monroe et al. 2016). In addition, the addition of coconut, in a dense rubber-cacao system in CS 1, resulted in low turnover, as coconut fronds are composed of a high percentage of lignin components (18-21%) and low N content (Mohamad Aziz et al. 2018), making it resistant to decomposition.

Soil amendments. The application of soil amendments increased the stored C within the different cropping seasons. The highest significant increase in stored C content was achieved in CS 2 with L amendments (Fig. 4).

During the wet season of 2023 under CS 1, the highest C stored was observed in soil applied with OF (46.10 tons/ha), which was not statistically different from soil applied with L + OF (41.04 t/ha), having a noticeable difference of 9.19 tons/ha of C stored in soil against the control (Fig. 4). The application of L alone did not significantly increase the stored carbon (36.42 tons/ha), while RR application decreased the stored C in soil by 13.19 tons/ha relative to the control. This implies that the addition of organic fertilizer in CS 1 provided additional C in the soil, which is more stable, while inorganic fertilizer resulted in greater OC release. This might be attributed to the faster rate of mineralization as reflected in the low C:N ratio of the soil treated with inorganic fertilizer. Furthermore, under CS 2, the level of stored C in the soil was not statistically different when soil amendments were applied. Stored C in soil ranged from 37.07 t/ha (L + OF) to 43.48 t/ha (OF).

During the dry season of 2024, adding soil amendments to CS 1 increased the amount of C stored in the soil compared to the control (46.81%). The increase was about 7.39 t/ha (L) to 10.27 t/ha (RR). Similarly, a significant increase in stored C with applied soil amendments was observed in CS 2. The highest stored C was recorded in soil treated with lime (80.22 t/ha), which was statistically similar to that in soil treated with L + OF (71.33t/ha). The stored C applied with OF (60.97 t/ha) was comparable to the stored C in soil applied with RR (67.29 t/ha), which increased stored C by 13 t/ha and 6.67 t/ha, respectively, relative to the control (54.30 t/ha).

The addition of fertilizers and soil amendments improves the growth of crops in the system, which effectively utilizes atmospheric CO₂, sequestering it in the crops, and a portion of the C is stored in the soil. L and L + OF applications resulted in a significant increase in stored C. Liming promotes microbial activity that decomposes organic materials; however, over time, the decomposition process provides more stable C, that is, humus, which is resistant to destruction and hence stored as stable carbon (Greff et al. 2022; Rowley et al. 2018).



^{1/}Within the cropping systems, bars with the same letter are not significantly different at the 5% level according to Tukey's HSD test.

*Significantly different at p -value < 0.05 LSD test.

Figure 4. Stored C in soil under the different cacao cropping systems* as influenced by the application of soil amendments^{1/} during wet season 2023 and dry season 2024.

CONCLUSION

Cacao-cropping systems and soil amendment application influenced significantly the yield of cacao, organic carbon content and the carbon storage of Kabacan loam soil. The cacao-rubber system increased significantly the yield of cacao, elevated stored carbon in the soil, and maintained light intensity within the acceptable light intensity limit. The application of lime, particularly in combination with organic fertilizers, increased yield by 60%. This amendment strategy specifically improved soil organic carbon (SOC) levels and elevated stored soil carbon. The improved C:N ratio observed in these plots indicated enhanced stabilized carbon. Consequently, the study highlighted that the cacao-rubber system, combined with lime and organic fertilizer applications, serves as an effective management strategy for improving both cacao productivity and soil health. Similar research in other cacao-producing areas in the Philippines would be worth considering for broader recommendations. Further studies are needed to determine the best planting densities for rubber, coconut, and cacao intercropping and to optimize the application rates of soil amendments to achieve maximum yield.

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TECHNICAL EFFICIENCY AND BANK CREDIT IN INDONESIAN RICE FARMING

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ABSTRACT

Rice farming in Indonesia faces high input costs and limited access to capital, increasing reliance on external financing. Despite the availability of bank credit, uptake among farmers remains low. This study assessed the impact of bank credit on the technical efficiency (TE) of rice farming, using 2024 survey data from 283 farmers across four provinces. Propensity Score Matching (PSM) and Stochastic Meta-Frontier (SC-SMF) models were employed to control for selection bias and technological differences. The Generalized Likelihood Ratio (GLR) test favored the *transcendental logarithmic* over the Cobb-Douglas production function, confirming heterogeneity in production technologies. Results showed that conventional models overestimated TE due to unobserved bias, while the SC-SMF model provided a more accurate benchmark. Using SC-SMF, credit users exhibited significantly higher TE (67.06%) than non-users (58.68%), indicating that credit access improved efficiency. However, both groups remained inefficient, with room for improvement of 32.94% and 41.32%, respectively. Findings suggest that expanding credit access can enhance productivity by optimizing input use.

Key words: formal credit, propensity score matching, stochastic meta-frontier, technical efficiency

INTRODUCTION

Rice is a strategic commodity in Indonesia, serving as the staple food for over 90% of the population, projected to exceed 280 million in 2024. Ensuring rice self-sufficiency is therefore central to national food security policy. Despite recent annual production surpluses, periodic monthly deficits continue to necessitate rice imports, highlighting ongoing challenges in achieving sustainable self-sufficiency. Fluctuations in deficits and surpluses were observed based on monthly rice consumption and production data from 2022 to 2024. However, on an annual average, surpluses of 0.11 million tons, 0.04 million tons, and 0.10 million tons were recorded in 2022, 2023, and 2024, respectively (Fig. 1).

inputs have driven up production costs, while labor shortages and generational renewal issues have further compounded the problem, with labor alone accounting for over 40% of total farming expenses (Suprehatin et al. 2024). Environmental challenges such as droughts, floods, shifting rainfall patterns, and pest outbreaks also continue to hinder productivity. These challenges emphasize the role of financial capital as a key enabling factor in achieving efficiency gains.

According to the Agricultural Household Model (Singh et al. 1986), farm households simultaneously make production, consumption, and labor allocation decisions subject to liquidity and credit constraints. Limited access to credit restricts their ability to purchase inputs or adopt new technologies, leading to suboptimal input combinations and lower productivity. Conversely, adequate access to credit relaxes these liquidity constraints, enabling farmers to move closer to the production frontier, thereby enhancing technical efficiency. This mechanism reflects the production approach to credit, where credit functions as a credit as funding or facilitating optimal use of production input that shifts the isocost line outward, allowing farmers to reach higher isoquants (Debertin 2012). Credit as a constraint-relaxing financial factor that eases liquidity limitations, shifts the isocost line outward, and expands the feasible input set.

Although the government has promoted agricultural credit programs such as KUR (Kredit Usaha Rakyat) and KPEN-RP, agricultural credit has remained below 8% of total national credit disbursement since 2000, despite exceeding IDR 400 trillion in nominal terms in 2022 (OJK 2025a). More broadly, credit access in Indonesia exhibits a dual structure in which informal sources, such as family networks, traders, and moneylenders, remain dominant, particularly in rural areas, while access to formal credit through commercial banks is still limited. Recent evidence shows that a significant proportion of borrowing still occurs outside the formal financial system: around 71% of borrowers rely on informal or semi-formal sources, with nearly 60% borrowing from family or friends, while only about 13% access credit through commercial banks. Similarly, informal and semi-formal providers account for roughly 60% of total loan access, highlighting the continued dominance of non-bank financing channels (OJK 2025b).

This study focuses on commercial bank credit because commercial banks are the primary providers of formal finance, the main channel for government lending programs, and operate under standardized regulatory and reporting frameworks that ensure data consistency. Moreover, commercial bank lending is central to monetary transmission and financial system stability, making it especially relevant for policy analysis. Other formal institutions, including rural banks, cooperatives, and microfinance institutions, play complementary roles but differ in scale, regulation, and clientele, and are therefore beyond the scope of this study. The imperfect credit market theory (Stiglitz and Weiss, 1981) suggests that asymmetric information leads to credit rationing, where even creditworthy farmers are excluded; this is reinforced by supply-side risks such as price volatility and climatic uncertainty, as well as demand-side constraints including low education, lack of collateral, and procedural complexity (Zeller 1994; Arshad et al. 2017a, b).

Empirical studies consistently show that access to credit improves farm performance by facilitating better input use, technology adoption, and risk management (Dong et al. 2010; Li et al. 2016; Amanullah et al. 2020). From the perspective of efficiency theory, technical efficiency (TE) represents the ability of a farm to produce the maximum possible output from a given set of inputs under existing technology (Farrell 1957; Battese and Coelli 1995). Credit enhances TE by enabling farmers to operate closer to the production frontier through optimal input allocation and adoption of improved technologies.

The Stochastic Frontier Approach (SFA) provides a framework to estimate TE by distinguishing between random shocks (e.g., weather) and inefficiency effects arising from managerial and financial constraints (Battese 1992). In this framework, credit acts as an efficiency-enhancing

variable that reduces the inefficiency component, enabling farmers to shift upward toward the production frontier. The theory of input complementarity also supports this relationship: access to capital increases the effective use of other inputs, particularly labor and fertilizers, leading to synergistic productivity gains (Feder et al. 1990; Carter and Olinto 2003).

Globally, evidence supports this linkage. Credit access has been shown to enhance farm productivity and efficiency in Pakistan (Chandio et al. 2017), Ghana (Abdallah 2016), Vietnam (Duy, 2015), and Bangladesh (Afrin et al. 2017). Studies in China (Dong and Featherstone 2006; Jia et al. 2010) and Latin America (Carter and Olinto 2003) highlight how credit constraints and informal lending limit production efficiency. Similarly, institutional economics posits that structural factors, such as property rights, extension systems, and social capital, mediate how credit affects farm outcomes (North 1990; Ostrom 2005).

Productivity in agricultural production can be measured using either partial or total factor approaches. Partial productivity refers to output per single input (e.g., yield per hectare or output per unit of labor), whereas total factor productivity (TFP) captures the efficiency with which all inputs are jointly transformed into output. TFP is commonly decomposed into several components, including technical efficiency (the extent to which producers operate close to the existing production frontier), technological change (shifts in the frontier due to innovation or improved production techniques), and, in some cases, scale efficiency. In this study, the focus is on technical efficiency, defined as farmers' ability to maximize output given a set of inputs and the prevailing technology. Accordingly, the analysis does not attempt to estimate technological change or other components of TFP, ensuring consistency with the stochastic frontier framework employed.

A clear distinction must be drawn between technical efficiency and technological change in the production process. Technical efficiency refers to the extent to which producers operate close to the existing production frontier, whereas technological change denotes an outward shift of the frontier resulting from innovation or improvements in production techniques. This study focuses exclusively on the technical efficiency channel. It hypothesizes that access to commercial bank credit relaxes liquidity constraints, enabling farmers to allocate inputs more efficiently and operate closer to the existing production frontier. While credit may, in principle, support technology adoption, this channel is not examined in the present study. Consistent with this focus, credit is incorporated as a determinant of the inefficiency term within a stochastic frontier framework, and no attempt is made to model shifts in the production frontier.

Building on this framework, the analysis examines whether access to commercial bank credit improves technical efficiency in Indonesian rice farming by enhancing farmers' ability to optimize input use within a given technological environment. Accordingly, the central research question is: Does access to commercial bank credit improve the technical efficiency of Indonesian rice farmers? The general objective of this study is to analyze the effect of access to commercial bank credit on the technical efficiency of Indonesian rice farmers. Accordingly, the specific objectives are to estimate the level of technical efficiency using a stochastic frontier approach and to examine the extent to which access to commercial bank credit influences farmers' technical efficiency by enabling more efficient input allocation within a given production technology. These objectives are strictly confined to technical efficiency and do not extend to technological change or technology adoption, ensuring full alignment between the conceptual framework, empirical specification, and research questions.

RESEARCH METHODOLOGY

Type and sources of data. The data utilized in this study were primary data, which were obtained from a survey conducted by the Micro Farming Study Team of the Department of Agribusiness, Faculty of Economics and Management, Bogor Agricultural University (IPB) in July to November 2024.

Data collection. The survey was conducted in four provinces (West Java, Central Java, East Java, and South Sulawesi) as the biggest rice production centers in Indonesia which contributes more than 50% of national rice availability. In each province, districts were selected purposively based on their status as major rice production centers in Indonesia, resulting in the selection of Karawang Regency, Grobogan Regency, Lamongan Regency, and Gowa Regency. Within each selected district, two sub-districts were purposively chosen using similar criteria as above. Subsequently, two villages in each sub-district were selected based on their designation as key rice production centers. The total number of respondents across the four provinces was 288 farmers, with 72 farmers from each province (Table 1).

The sampling frame consists of rice farming households engaged in on-farm production during the survey period. A stratified sampling approach was applied based on geographic regions and farm characteristics to ensure representativeness across major rice-producing areas. Farmers are classified into treatment and control groups based on access to commercial bank credit. The treatment group includes farmers who reported having access to or receiving credit from commercial banks during the production cycle, while the control group consists of farmers without access to commercial bank credit. This binary classification allows for the identification of the credit effect within the stochastic frontier framework.

Table 1. Number of farmer respondents by research location.

Province	District	Sub total (farmers)
West Java	Karawang	72
Center Java	Grobogan	72
East Java	Lamongan	72
South Sulawesi	Gowa	72
Total		288

The respondents in this study were rice farmers selected based on the following criteria: (1) rice farming constitutes the primary source of household income (>50%); (2) a minimum of four planting seasons of experience; (3) the most recent rice harvest occurred in 2024; (4) a monoculture cropping pattern; (5) irrigation-based water management; (6) non-organic cultivation techniques; and (7) total rice farming area of less than 10 hectares, (8) the last planting season is on 2024. To ensure data validity, observations identified as outliers were excluded from the data processing stage. The final sample consisted of 285 rice farmers, comprising 214 credit users and 71 non-credit users.

Based on the initial dataset of 285 farming households, a control group (non-credit users) with characteristics similar to the treatment group (credit users) was established using the PSMATCH2 command in STATA (15th version) (Leuven and Sianesi 2003). A probit binary choice model was employed to generate propensity scores (PS), followed by the application of the nearest neighbor matching method to identify a control group (non-credit users) that matched the treatment group (credit users). During this process, two farmers from the treatment group were excluded from the analysis because their PS values fell outside the common support range. Consequently, the final matched sample comprised 283 farmers, with 214 in the control group and 69 in the treatment group.

Analytical framework. Understanding the relationship between credit access and farm performance requires distinguishing between managerial efficiency and technological differences. Technical efficiency reflects the ability of a farmer to maximize output given available inputs and the existing production frontier. In contrast, technological change shifts the production frontier itself, representing innovations or improved production methods. In the context of smallholder rice farming in Indonesia, access to bank credit can relax liquidity constraints, enabling farmers to allocate inputs more effectively, purchase timely inputs, and operate closer to the prevailing production frontier. This study focuses

primarily on this efficiency channel, while acknowledging that credit may indirectly facilitate technology adoption.

The Stochastic Production Frontier (SPF) model provides a standard approach to estimating technical efficiency. By assuming a single production frontier for all farmers, SPF attributes deviations from the frontier to either random noise or inefficiency. However, smallholder farmers operate under heterogeneous technological environments due to variations in irrigation systems, mechanization levels, and agroecological conditions. In such cases, applying a single frontier risks confounding technological differences with inefficiency, as farmers using advanced technologies may appear more efficient while others are penalized simply for operating under less productive conditions.

To address technological heterogeneity, the Stochastic Meta-Frontier (SMF) framework is employed. The SMF distinguishes between group-specific frontiers, representing the technology available to each subset of farmers, and a common meta-frontier that envelops all group frontiers. This approach allows efficiency to be decomposed into two components: technical efficiency relative to the group frontier, capturing managerial performance, and the technology gap ratio, reflecting the distance between the group frontier and the meta-frontier. By combining SPF and SMF, it becomes possible to identify whether higher efficiency among credit users reflects true improvements in input allocation or merely differences in technological endowments.

Integrating credit into the meta-frontier framework highlights two mechanisms for improving farm performance. First, credit reduces inefficiency within a given technology group by enabling optimal input use, better timing of operations, and improved farm management practices. Second, credit may facilitate the adoption of improved technologies, reducing the technology gap between the group frontier and the meta-frontier. In this study, the primary focus is on the efficiency channel, ensuring that observed improvements among credit users represent real gains in technical efficiency rather than simply access to superior technologies.

Data analysis. This study evaluates the impact of bank credit on the technical efficiency (TE) of rice farming in Indonesia by comparing a treatment group (farmers who utilize bank credit) with a control group (farmers who do not utilize bank credit). Directly comparing TE values between these groups using the conventional Stochastic Production Frontier (SPF) method may produce biased estimates due to both observable and unobservable factors. To correct for selection bias arising from observed variables, the Propensity Score Matching (PSM) method is employed. The propensity scores are estimated using a logit model, which appropriately models the probability of credit adoption as a function of observable farm and household characteristics. One-to-one nearest-neighbor matching without replacement is applied to pair each credit-using farmer with the closest non-user in terms of propensity score. This approach ensures intuitive comparability between matched units while minimizing bias from dissimilar observations (Baglan et al. 2020a). Observations that do not satisfy the common support condition are excluded to maintain valid comparisons.

Bias arising from unobserved factors, such as managerial ability or risk preferences, is addressed using the Sample-Corrected Stochastic Production Frontier (SC-SPF) method, implemented in Limdep-11. Furthermore, when the production technologies employed by the two groups are heterogeneous, comparing TE values using separate frontiers may misrepresent efficiency differences. To account for technological heterogeneity, the Stochastic Meta-Frontier (SMF) approach is used, which constructs a common frontier enveloping all group-specific frontiers. When unobserved-variable bias is also present, the Sample-Corrected Stochastic Meta-Frontier (SC-SMF) model is employed, providing an efficiency benchmark that incorporates both selection bias and technological differences (Bravo-Ureta et al. 2020; Villano et al. 2015). This combined strategy ensures that the estimated effects of credit on TE are robust to both observed and unobserved confounding factors, as well as differences in production technologies across farmers.

Conventional-SPF Method (*Stochastic Production Function*)

Using the SPF model (Coelli et al. 1996), the technical efficiency (TE) value is estimated for each group (i.e., farmers using bank credit and those not using bank credit) and compared using an independent two-sample T-test. This SPF model (Coelli et al. 1996) can be estimated using the Corrected Ordinary Least Squares (COLS) method.

Model SPF (Coelli et al. 1998) :

$$y_i = \beta' x_i + (v_i - u_i)$$

Where ;

- v_i = Error component (beyond managerial control)
- u_i = Technical Inefficiency (IT) component
- $u_i = |\sigma_u U_i| = \sigma_u |U_i|, \quad U_i \sim N(0,1)$
- $y_i = \sigma_v V_i, \quad V_i \sim N(0,1)$
- x_i = Production Input Vector

Model SPF (Coelli et al. 1996) :

$$y_i = \beta' x_i + (v_i - u_i)$$

Where ;

- v_i = Error component (beyond managerial control)
- u_i = Technical Inefficiency (IT) component \cong Technical Inefficiency (TE)

The technical efficiency (TE) of farming is influenced not only by access to bank credit but also by other variables (e.g., gender, age, education, experience, number of dependents, and farmer group membership), represented as vector z. When using a t-test (two independent samples), there is a potential for Bias in Observed Variables. This bias must be corrected using Propensity Score Matching (PSM).

The application of PSM begins by constructing a control group (farmers who do not use bank credit) with characteristics as similar as possible (in terms of vector z) to those in the treatment group (farmers who use bank credit) (Khandker et al. 2010; Sianesi 2001). Individuals in the control group served as comparable matches (in terms of vector z) for those in the treatment group if their propensity scores (PS) are closely aligned. The propensity score represented the probability of an individual using bank credit, estimated using a probit or logit model with predictors from vector z. The number of observations in each matched pair depended on the technique used to construct a comparable control group.

Several matching techniques are available for Propensity Score Matching (PSM), including nearest-neighbor, caliper, kernel, stratification, and radius matching. This study employed the one-to-one nearest-neighbor matching without replacement method, primarily due to its intuitive interpretation and direct comparability between treated and control observations. Each treated unit was paired with the control unit having the closest propensity score, minimizing the risk of matching with dissimilar units. Observations that do not satisfy the common support condition, i.e., those without an adequate match, were excluded to ensure valid comparisons and reduce extrapolation beyond the observed data.

While alternative methods, such as kernel or radius matching use weighted averages of multiple control units, they may include matches that are farther from the treated observation, potentially introducing bias if distant units are not truly comparable. Caliper matching can restrict matches within a specified distance to reduce bias but may result in fewer matches and reduced sample size, affecting efficiency. Stratification divides the sample into propensity score blocks, which smooths over local differences but may obscure fine-grained variation at the individual observation level. In contrast, nearest-neighbor matching strikes a practical balance: it minimizes bias by selecting the

closest match while retaining a sufficient number of observations for robust estimation. Although this method may have slightly higher variance compared with kernel or radius techniques, the clarity of interpretation and ease of implementation make it particularly suitable for assessing the impact of credit access on technical efficiency in the current study (Baglan et al. 2020b).

The comparison of the outcome variable, namely Technical Efficiency (TE), was conducted only between matched individuals. The output of the PSM procedure is a matched dataset for both groups, estimated using the PSMATCH2 Stata package. Based on this matched dataset, TE is estimated using LIMDEP-11 software through models such as Conventional-SPF, SC-SPF (Sample Correction – Stochastic Production Frontier), and SC-SMF (Sample Correction – Stochastic Meta Frontier Production Function). The impact of bank credit on TE can be directly measured through the Average Treatment Effect on the Treated (ATET) using the PSMATCH2 module in Stata 15.

$$ATET = E(Y_1|D = 1) - E(Y_0|D = 0)$$

Where :

- Y_1 and Y_0 represent the TE (outcome) values for the groups of farmers who use bank credit and those who do not use bank credit, respectively.
- D is a dummy variable, where $D=1$ if the farmer belongs to the group that uses bank credit, and $D=0$ otherwise;

If there is a potential bias due to Unobserved Variables, it can be corrected using the sample correction-stochastic production frontier (SC-SPF) method (Greene, 2010). The SC-SPF model is specified as follows.

$$d_i = 1[\alpha' z_i + w_i > 0], w_i \sim N[0,1] \Rightarrow \text{Logit Model}$$

$$y_i = \beta' x_i + \varepsilon_i; \varepsilon_i \sim N[0, \sigma_\varepsilon^2]$$

(y_i, x_i) It is only observed when $d_i=1$, with the following error structure:

$$\varepsilon_i = v_i - u_i$$

$$u_i = \sigma_u |U_i| \text{ with } U_i \sim N[0,1]$$

$$v_i = \sigma_v V_i \text{ with } V_i \sim N[0,1]$$

$$(w_i, v_i) \sim \text{normal bivariate } [(0,0), (1, \rho\sigma_v, \sigma_v^2)]$$

This condition allowed for the potential correlation between w_i and noise term v_i (i.e., $= \rho$). If the correlation coefficient (ρ) is ignored in the estimation of Technical Efficiency (TE), it may lead to bias due to unobserved variables. To address this issue, the sample correction-stochastic production frontier (SC-SPF) model must be applied to estimate TE using the matched dataset, which is obtained through LIMDEP-11.

Following this correction, a comparative analysis of the TE between the two groups was conducted using the Average Treatment Effect on the Treated (ATET). The final outcome ensures that the bias from both observed and unobserved variables in measuring the impact of bank credit access on rice farming TE is effectively corrected.

Stochastic Meta Frontier Production Function (SMF) approach

The comparison of technical efficiency (TE) scores between the two groups should be based on a common benchmark technology, following the Stochastic Meta-Frontier (SMF) Production Function Approach (Villano et al. 2015; Bravo-Ureta et al. 2020). The SMF procedure consists of the following steps.

1. The meta-frontier output obtained ($Y^* = e^{x_i\beta^*}$), through a two-step process:
 - First, we estimated the predicted output for each group (\hat{y}), using the Conventional-SPF or SC-SPF (Sample Correction – Stochastic Production Frontier) model.
 - Then, pool the predicted output values (\hat{y}) from both groups and estimate them using the SPF-Pooled model, yielding the meta-frontier function:

$$y^* = f(x_i, \beta^*) = e^{x_i\beta^*}$$

2. The Meta-Technology Gap Ratio (MTGR), which represents the ratio between the highest achievable output within a group and the maximum possible output under the meta-frontier, is calculated (Villano et al. 2015).

$$MTGR = \frac{e^{x_i\beta_j}}{e^{x_i\beta^*}}$$

where, $x_i\beta^*$ = Meta-frontier output

β^* = Vector of parameters SMF so that $x_i\beta^* \geq x_i\beta_j$

The TE score (with respect to the meta-frontier) is calculated as (Villano et al. 2015):

$$TE_M = TE_j \times MTGR_j$$

where TE_j = TE score obtained from the Conventional-SPF or SC-SPF model (whichever is the best-fitting model).

Generalized Log Likelihood Ratio Test (LR-Test)

To test whether the treatment and control groups rely on the same production technology, a generalized log-likelihood ratio test (LR test) was conducted based on the matched samples (Greene 2016; Chen et al. 2022).

Statistical Hypothesis:

H_0 : The production technology of both groups is the same.

H_1 : The production technologies of the two groups are different.

- Statistical tests:

$$LR_Stat = 2[\ln\{L(t)\} + \ln\{L(c)\} - \ln\{L(p)\}]$$

The log-likelihood value of the Cobb-Douglas model was obtained through Maximum Likelihood Estimation (MLE) based on sequential datasets: pooled group (p), treatment group (t), and control group (c).

where,

$\ln\{L(p)\}$ = Log-likelihood of the production function estimated through Maximum Likelihood

Estimation (MLE) for pooled data (restricted model).

$\ln\{L(t)\}$ = Log-likelihood for the treatment group (farmers using bank credit).

$\ln\{L(c)\}$ = log-likelihood for the control group (farmers not using bank credit).

- Testing:

If H_0 is true (fail to reject H_0), the LR statistic follows a chi-square distribution, with degrees of freedom equal to the difference between the restricted and unrestricted models (Greene 2016).

Estimation strategy of observed and unobserved bias correction. To formulate an estimation strategy for correcting observed and unobserved variable biases, the following steps should be undertaken.

1. Prepare the Matched Dataset using the PSM (Propensity Score Matching) technique based on Unmatched Data and Vector z (PSMATCH2 Stata Package).
2. We check for technology differences between the two groups using the Likelihood Ratio Test (LR Test) in Limdep-11 to determine whether the production functions differ.
3. The production function is estimated using three alternative models:
 - Conv-SPF (Conventional - Stochastic Production Frontier),
 - SC-SPF (Sample Correction – Stochastic Production Frontier),
 - SC-SMF (Sample Correction – Stochastic Meta Frontier Production Function), with the assistance of the Limdep-11 software.

Several previous studies, including those of Bravo-Ureta et al. (2012, 2020), Baglan et al. (2020a), and Chen et al. (2022), Lawin and Tamini (2018), and Villano et al. (2015) estimated bias correction using the following three-stage approach, which is also applied in this study:

- First, the PSM approach was used to correct the observed variable bias. If ρ the correlation between w_i and v_i is not significant and the two groups use the same production technology (single production function), then only observed variable bias needs correction. Technical Efficiency (TE) is estimated using Conventional - Stochastic Production Frontier in Limdep-11, and the impact of bank credit on TE is estimated using PSM (ATET - PSMATCH2).
- Second, the unobserved variable bias was corrected. The selectivity-corrected stochastic frontier production function (SC-SPF) model is applied to correct for unobserved variable bias. If ρ The correlation between w_i and v_i is significant, but the two groups still use the same production technology (single production function); then, both observed and unobserved variable biases must be corrected. TE is estimated using the sample correction-stochastic production frontier (SC-SPF) in Limdep-11, and the impact of bank credit on TE is estimated using PSM (ATET - PSMATCH2).
- Third, the meta-frontier production function (MFPPF) approach is applied. If the credit-user and non-credit-user groups are found to use different production technologies (Bravo-Ureta et al. 2020; Lawin and Tamini, 2018; Villano et al. 2015), the meta frontier production function (MFPPF) approach is applied. If ρ the correlation between w_i and v_i is significant and the two groups use different technologies (separate production functions), then both observed and unobserved variable biases must be corrected. TE is estimated using SC-SMF (Sample Correction – Stochastic Meta Frontier Production Function) in Limdep-11, and the impact of bank credit on TE is estimated using PSM (ATET - PSMATCH2). Table 2 presents the definitions of variables used in this study (PSM and SPF models).

Table 2. Definitions of research variables used in PSM and SPF models

Variables	Definition and Unit
Input and Output {y,x} :	
y Output	Total Rice Production (GKP) per Planting Season (kilograms). Planting season in this research is the last planting season in 2024.
x Input	(Vector of Classical Production Inputs)
X ₁ Land	Total Rice Planting Area (Owned and Non-Owned) (hectares)
X ₂ Seed	Total Rice Seed Input (kilograms per planting season)
X ₃ Fertilizer	Total Chemical Fertilizer Input (Urea, ZA, TSP19, NPK, KCL) (kilograms per planting season)
X ₄ Pesticides	Total Pesticide Input (Herbicides, Insecticides, Fungicides, Other Pesticides) (liters per planting season)
X ₅ Labor	Total Labor Input (Nursery, Land Preparation, Planting, Replanting, Weeding, Fertilization, Spraying, Harvesting) (HOK=working day per planting season)

Variables	Definition and Unit
Probit models {d,z} :	
d Credit	d = 1 ; if farmers access to commercial Bank Credit, and d=0, if farmers don't access to commercial Bank Credit.
z (vector from explanatory variables):	
Z ₁ Sex	Sex of farmer respondent (1 = Male, 0 = Female)
Z ₂ Age	Age of farmer respondent (years)
Z ₃ Education	Education of farmer respondent (years)
Z ₄ Training	Total Duration of Training (Rice Farming and/or AUTP) Received by Farmers (days per year)
Z ₅ Family_burden	Number of Household Dependents (persons)
Z ₆ Experience	Rice Farming Experience (years)
Z ₇ Cropping index	Rice Planting Frequency (times per year)
Z ₈ Farmer_group	Membership in Farmer Group (1 = Yes, 0 = No)
Z ₉ Farmer_cooperative	Membership in Cooperative (1 = Yes, 0 = No)
Z ₁₀ Plant_pests	Dummy for Pest and Disease Attack (OPT) (1 = If affected, 0 = If not)
Z ₁₁ Off-farm_Income	Net family income outside farming (trade, services, or employee in non-farm) (Rp/year)

RESULTS AND DISCUSSION

Respondents profile. Table 3 presents the descriptive statistics of the research variables based on matched samples. The table presents the output produced, inputs used, and characteristics of the farmers and their farming enterprises. The average rice productivity of credit-user farmers (69 individuals) was not significantly different from that of non-credit-user farmers, with 4.9 tons/ha for credit users and 5.2 tons/ha for non-credit-user farmers (214 individuals).

The average cultivated land area used for rice farming by credit-user farmers is 1.4 hectares, while that of non-credit-user farmers is 0.74 hectares. It can be concluded that the cultivated land area of credit-user farmers was larger and significantly different from that of non-credit-user farmers. This served as evidence of the allocation of credit received by farmers.

Similarly, pesticide usage during the research period, when pest infestations occurred, was higher among credit-user farmers (59.49 l/ha/season), indicating their ability to anticipate pest attacks, and this usage was significantly different from that of non-credit-user farmers (46.33 l/ha/season).

In contrast, credit-user farmers used seeds, fertilizers, and labor inputs more efficiently. Seed usage by credit-user farmers aligned more closely with the recommendations of agricultural extension officers (PPL), which is 25–30 kg/ha/season for irrigated land. Seed usage was significantly different, with credit-user farmers using seeds more efficiently (34.92 kg/ha/season) than non-credit-user farmers (45.10 kg/ha/season). Similarly, labor usage was more efficient among credit-user farmers (107.17 labor-days/ha/season) and significantly different from non-credit-user farmers (122.79 labor-days/ha/season).

Meanwhile, fertilizer usage by credit-user farmers was 529.12 kg/ha/season, and by non-credit-user farmers, it was 564.71 kg/ha/season, but this difference was not statistically significant. Thus, farming performance, as indicated by productivity, shows that credit-user farmers achieve their output by using inputs more optimally.

When examining the characteristics of the farmers and their farming enterprises in Table 3, it can be seen that gender, age, number of dependents, and farming experience did not differ significantly between credit-user and non-credit-user farmers. The majority of respondents (both credit users and

non-credit users) were male, aged 54 years, with 3–4 dependents, and had 27–30 years of farming experience. Almost all respondents were involved in farmer groups, and nearly all respondents experienced pest infestations during the research period.

Table 3. Descriptive statistics of research variables for production output, input, and the probit model based on matched samples.

Variables	Mean		Difference mean ^{a)}	
	Farmers who had access to credit	Farmers who did not have access to credit		
Output and input production {y, x}:				
y	Paddy production (kg) per hectare	4897.276 (283.981)	5185.795 (161.283)	-288.519
X ₁	Land (hectare)	1.439 (0.152)	0.746 (0.054)	0.693***
X ₂	Seed (kg) per hectare	34.921 (5.424)	45.100 (1.800)	-10.179**
X ₃	Fertilizer (kg) per hectare	528.126 (37.922)	564.714 (21.897)	-36.589
X ₄	Pesticides (liter) per hectare	59.490 (9.573)	46.326 (4.277)	13.164*
X ₅	Labor (HOK) per hectare	107.174 (7.299)	122.388 (4.266)	-15.214**
Socio-demographic {d, z}:				
Z ₁	Gender	0.884 (0.0389)	0.897 (0.020)	-0.013
Z ₂	Age	53.986 (1.296)	54.014 (0.779)	-0.029
Z ₃	Education	8.797 (0.3668)	8.089 (0.255)	0.708*
Z ₄	Training	3.449 (1.407)	1.486 (0.598)	1.963*
Z ₅	Family_burden	3.464 (0.159)	3.332 (0.100)	0.132
Z ₆	Experience	27.783 (1.647)	30.168 (1.040)	-2.386
Z ₇	Cropping index	2.0290 (0.0290)	2.313 (0.034)	-0.284***
Z ₈	Farmer_group	0.971 (0.020)	0.958 (0.014)	0.013
Z ₉	Farmer_cooperative	0.101 (0.037)	0.037 (0.013)	0.064**
Z ₁₀	Plant_pests	0.942 (0.028)	0.967 (0.012)	-0.025
Z ₁₁	Off-farm_income	18 800 000 (2985152)	12 100 000 (1107844)	6660393***
Observations		69	214	

Note: ^{a)} Mean difference using two-sample t-test between the group of farmers participating in bank credit and the group of farmers not participating in bank credit.

The parentheses indicate the standard errors.

*** Significant at 1 %, ** Significant at 5 %, * Significant at 10 % (one side test).

The characteristics that showed significant differences between the two groups were formal and non-formal education. Credit-user farmers have a higher level of formal education (8.8 years) than non-credit-user farmers (8.1 years). In terms of non-formal education or training experience, credit-user farmers participated in training sessions 3.4 times per year, whereas non-credit-user farmers participated 1.5 times per year. Membership in cooperatives also differed significantly, with a higher proportion of credit-user farmers involved in cooperatives. Off-farm income also showed a significant difference, with credit-user farmers earning higher off-farm income (IDR 18,800,000 per year) than non-credit-user farmers (IDR 12,100,000 per year). This served as evidence that farmers who have access to bank credit are those with higher off-farm income or those who are relatively wealthy. Off-farm income can act as a safety net in the case of credit default due to rice crop failure.

Another interesting finding is that the Planting Intensity Index (PII) or cropping index of credit-user farmers was significantly different from that of non-credit-user farmers. The IP of credit-user farmers was lower (two times per year) than that of non-credit-user farmers (2.3 times per year). This can be explained by the fact that credit-user farmers did not prioritize the frequency of planting per year but instead focused on expanding the cultivated land area and optimizing input usage.

Table 4 presents the results of the balance test for matching covariates obtained through propensity score matching (PSM) analysis, which was conducted using a probit approach and the nearest neighbor matching method. Based on the test results displayed in Table 4, no significant differences in means were found between the groups of farmers using commercial bank credit and non-credit-user farmers for all explanatory variables in the matched sample. These results provide empirical evidence that the matching quality achieved by the PSM method is excellent (Garcia-Iglesias 2022).

Table 4. Balance of matching covariates for farmer households for the matched sample

Matching covariates	Mean		% Bias	t-test	
	Farmers who access to credit (Treated)	Farmers who don't access to credit (Control)		<i>t</i> _{statistic}	P-value
Z ₁ Gender	0.884	0.913	-9.300	-0.560	0.576
Z ₂ Age	53.986	53.928	0.500	0.030	0.976
Z ₃ Education	8.797	8.797	0.000	0.000	1.000
Z ₄ Training	3.449	4.536	-10.500	-0.410	0.679
Z ₅ Family burden	3.464	3.362	7.300	0.470	0.643
Z ₆ Experience	27.783	26.478	9.000	0.510	0.610
Z ₇ Cropping Index	2.029	2.058	-7.200	-0.580	0.563
Z ₈ Farmer_group	0.971	0.942	15.700	0.830	0.407
Z ₉ Farmer_cooperative	0.102	0.130	-11.100	-0.530	0.598
Z ₁₀ Plant_pests	0.942	0.913	14.000	0.650	0.515
Z ₁₁ Off-farm income	19 000 000	17 000 000	9.100	0.550	0.584
Observations	69	214			

Note: *** Significant at 1 %, ** Significant at 5 %, * Significant at 10 %.

Selection of production function and technological differences. To determine the appropriate functional form for the stochastic frontier production function, both the Cobb–Douglas and the Translog specifications are estimated and compared using a generalized log-likelihood ratio (LR) test.

The Cobb–Douglas stochastic frontier model is specified as:

$$\ln Y_i = \beta_0 + \sum_{k=1}^K \beta_k \ln X_{ki} + (V_i - U_i)$$

where Y_i denotes output, X_{ki} represents input variables, V_i is the random error term, and U_i captures technical inefficiency.

The Translog stochastic frontier model is specified as:

$$\ln Y_i = \beta_0 + \sum_{k=1}^K \beta_k \ln X_{ki} + \frac{1}{2} \sum_{k=1}^K \sum_{j=1}^K \beta_{kj} \ln X_{ki} \ln X_{ji} + (V_i - U_i)$$

where the additional interaction terms $\beta_{kj} \ln X_{ki} \ln X_{ji}$ allow for variable elasticities of substitution between inputs.

The selection of the optimal stochastic production frontier (SPF) function for the research sample data was conducted using the generalized log-likelihood ratio (LR) test based on an analysis of the matched sample. The test statistic is formulated as follows.

$$LR_Stat = 2[\ln\{L(t)\} + \ln\{L(c)\} - \ln\{L(p)\}].$$

The results of the test, presented in Table 5, indicate that the transcendental logarithmic model is the most appropriate stochastic frontier production function (SPF) approach for examining the impact of credit on the technical efficiency (TE) of rice farming in this study.

Table 5. Generalized likelihood ratio test of the hypothesis for choosing of SPF model based on matched sample

Null hypothesis	LR statistic	Critical value ^{a)}	Decision
The Correct Cobb-Douglas SPF Model.	35.0258063	24.9957901	Reject H_0 . The Appropriate Transcendental logarithmic SPF Model for This Research Sample Data

Note: ^{a)} Critical value based on chi-square table with 15 degrees of freedom at 5% significance level (Greene, 2016).

To ensure homogeneity of production technology between farmers who accessed credit (treatment group) and those who did not (control group), a generalized log-likelihood ratio (LR) test was conducted based on matched samples. The test statistic is defined as follows.

$$LR_Stat = 2[\ln\{L(t)\} + \ln\{L(c)\} - \ln\{L(p)\}].$$

The test results presented in Table 6 indicate that the null hypothesis is rejected, suggesting that credit and non-credit farmers utilize different production technologies. This finding underscores the necessity of estimating technical efficiency (TE) scores for both groups using the stochastic meta-

frontier production function (SMF) model. In this approach, the TE scores are estimated based on a higher common benchmark technology.

Table 6. Generalized likelihood ratio test of hypothesis based on matched sample

Null hypothesis	LR statistic	Critical value^{a)}	Decision
Both groups adhere to the same production technology.	44.0913479	31.4104329	Reject H_0 . The two groups adhere to different production technologies..

Note: ^{a)} Critical value based on chi-square table with 20 degrees of freedom at 5% significance level (Greene, 2016).

Estimation of parameter for Conventional-SPF Models, Selectivity-Corrected Stochastic Production Frontier (SC-SPF) Models, and Stochastic Meta-Frontier (SMF) models

The Conventional Stochastic Production Frontier (Conventional-SPF) model presents separate estimations for rice farmers who use credit and those who do not. The results reveal that the land variable has a positive and significant coefficient in both groups (+4.5 for credit-user farmers and +10.79 for non-credit-user farmers), meaning that an increase in cultivated area can significantly increase production. This occurs because the land managed is still on a small scale (1.4 ha for credit-user farmers and 0.7 ha for non-credit-user farmers). This condition is reasonable since it is difficult for farmers to purchase or rent fertile land suitable for rice cultivation due to its scarcity and high price.

The seed variable has a negative coefficient in both groups (credit-user farmers and non-credit-user farmers), indicating that seed use is already excessive. For non-credit-user farmers, this happens because the seed requirement per hectare is relatively low (25 kg/ha) and easily available, making its cost relatively cheap (1.9% of total cost). In addition, farmers often receive subsidies or assistance, which leads to uncontrolled use of seeds. There is also a perception that the more seeds are sown, the higher the yield, whereas seed use should actually be reduced. For credit-user farmers, the seed coefficient is negative but not significant, meaning that increasing or decreasing seed use does not affect production. This indicates that seed use among credit-user farmers is already optimal. This indicates that what is needed is not an increase in the quantity of seeds used, but an improvement in seed quality.

The fertilizer variable has a negative and significant coefficient in both groups (credit-user farmers and non-credit-user farmers), indicating that fertilizer use is already excessive. An increase in fertilizer use can actually reduce production significantly. This occurs because the amount of fertilizer applied has exceeded the recommended rate (377 kg/ha for credit-user farmers and 806 kg/ha for non-credit-user farmers, while the recommendation is 300 kg/ha). Over-fertilization may be driven by rice farmers' belief that more chemical fertilizer is needed on nutrient-depleted soils to boost production, particularly among farmers with credit access who have greater financial flexibility.

The pesticide variable has a negative and significant coefficient among non-credit-user farmers, indicating that pesticide use is already excessive. This happens because of the perception that spraying more pesticides will be more effective in killing pests and preventing crop failure. However, crop failure still occurs because the rice plants become poisoned, implying that farmers should start reducing pesticide use. For credit-user farmers, the pesticide coefficient is positive but not significant, meaning that increasing or decreasing pesticide use does not affect production. This suggests that pesticide use among credit-user farmers is already optimal.

The labor variable has a negative and significant coefficient in both groups (credit-user farmers and non-credit-user farmers), meaning that labor use is already excessive. This may occur due

to the low level of mechanization, causing farmers to rely heavily on manual labor, particularly family labor. Increased use of labor can, in fact, significantly decrease production.

Based on the above explanation, it can be concluded that production can be increased through land expansion or technological improvement. However, since these factors are relatively expensive, farmers with access to credit tend to allocate their funds toward purchasing other inputs (fertilizers, seeds, pesticides), which are already being used excessively. This serves as a warning for farmers to avoid credit misallocation. In this regard, the role of agricultural extension officers (PPL) is crucial in advising farmers on which inputs still need to be increased. In addition to PPL, the roles of farmer groups (POKTAN) and farmer group associations (GAPOKTAN) are also essential in facilitating access to land, mechanization, and seed technology to improve production.

Table 7. Parameter estimates for conventional-SPF separated models, SC-SPF models, and SC-SMF models based on matched sample.

Variables		Conventional-SPF		SC-SPF		SC-SMF
		Farmers with access to credit	Farmers without access to credit	Farmers with access to credit	Farmers without access to credit	
Constant		32.0749*** (7.97222)	39.2866*** (6.93405)	11.3573*** (0.38462)	28.4217*** (8.09064)	17.9241*** (4.55302)
LnX1	Land	4.50208** (1.78063)	10.7943*** (1.94241)	1.7851*** (0.08328)	6.7214*** (2.22876)	3.29739*** (.44536)
LnX2	Seed	-0.06833 (1.62439)	-6.3853*** (1.54687)	2.7909*** (0.04922)	-3.6783** (1.44165)	-1.17797*** (.30831)
LnX3	Fertilizer	-4.03314** (2.01875)	-2.35722** (1.18127)	1.2568*** (0.06557)	-1.1583 (1.85337)	-.47315 (.29520)
LnX4	Pesticides	0.13366 (.52069)	-1.3401*** (0.39991)	0.8451*** (0.02113)	-0.1491 (0.61385)	.00835 (.11746)
LnX5	Labor	-5.82276*** (1.37163)	-5.5666*** (1.52411)	-5.9946*** (0.07236)	-4.9234** (1.9708)	-3.17110*** (.43019)
LnX11	Land*	-0.10536 (0.12805)	0.72417*** (0.11551)	-0.0255*** (0.00353)	0.3153** (0.14197)	.04904 (.03655)
	Land					
LnX22	Seed *Seed	0.20193** (0.08488)	0.27691** (0.11805)	0.00578 (0.00407)	-0.0029 (0.14416)	-.02898 (.02638)
LnX33	Fertilizer*Fertilizer	-0.09253** (0.04659)	-0.02529 (0.07078)	-0.01697*** (0.00244)	-0.0581 (0.15591)	.06091*** (.01585)
LnX44	Pesticides*Pesticides	0.03484 (0.02567)	-0.00845*** (0.00301)	0.0059*** (0.00151)	-0.0055 (0.01276)	-.00267*** (.00085)
LnX55	Labor* Labor	0.18370 (0.27061)	0.07228 (0.19158)	0.7046*** (0.00679)	0.2011 (0.25101)	.24108*** (.04450)
LnX12	Land* Seed	0.04887	-0.84469***	0.2728***	-0.3732	-.08582**

Variables		Conventional-SPF		SC-SPF		SC-SMF
		Farmers with access to credit	Farmers without access to credit	Farmers with access to credit	Farmers without access to credit	
		(0.19842)	(0.24719)	(0.00489)	(0.24046)	(.04192)
LnX13	Land* Fertilizer	-0.53040 (0.34195)	-0.56958*** (0.20164)	0.0404*** (0.01085)	-0.28597 (0.2913)	-.12616** (.05158)
LnX14	Land* Pesticides	0.19451** (0.08687)	-0.26339*** (0.06574)	0.3476*** (0.00334)	0.0103 (0.10427)	.02132 (.02019)
LnX15	Land* Labor	-0.45475* (0.25313)	-0.79000*** (0.25804)	-0.8808*** (0.00874)	-0.7689*** (0.29335)	-.45561*** (.06545)
LnX23	Seed * Fertilizer	0.06623 (0.26199)	0.25852 (0.18489)	-0.4926*** (0.00812)	0.2836 (0.2127)	.00370 (.05037)
LnX24	Seed * Pesticides	0.05658 (0.06065)	0.05233 (0.05018)	0.0241*** (0.00261)	-0.0725 (0.07876)	.00123 (.01649)
LnX25	Seed * Labor	-0.30447 (0.22727)	0.66214*** (0.17474)	0.0945*** (0.00623)	0.5054** (0.2491)	.33633*** (.05008)
LnX34	Fertilizer* Pesticides	0.08524* (0.04952)	0.04133* (0.0217)	0.0016 (0.00275)	-0.0072 (0.0738)	-.06223*** (.01808)
LnX35	Fertilizer* Labor	1.03722** (0.44284)	0.42610* (0.23366)	0.0874*** (0.01383)	0.2424 (0.3162)	.00105 (.05946)
LnX45	Pesticides * Labor	-0.21740*** (0.06192)	0.19539** (0.08389)	-0.2097*** (0.00305)	0.1031 (0.13398)	.08762*** (.02428)
Log Likelihood		-6.96728	-121.96826	-66.8036	-202.67596	78.95562
	σ	0.53575	0.85545	0.61078	0.85767	.18306
	σ_u	0.53575	0.85545	0.61067	0.81711	.00000
	σ_v	0.00017	0.00015	0.01162	0.26062	.18306
	Rho(v, w)	-	-	-0.9991*** (0.0061)	0.11393 (0.8994)	-
Observations		69	214	69	214	283

Notes: Parentheses indicate standard errors.

*** Significant at 1%, ** significant at 5%, * significant at 10%.

Interaction terms in this model also highlight notable input dynamics. For instance, the *Land*Seed* and *Land*Fertilizer* interactions are negative and significant in the non-credit group, indicating diminishing marginal returns or input mismatches when land is used jointly with these inputs. The *Land*Labor* interaction is significantly negative in both groups, further reinforcing concerns around inefficient labor usage. These patterns, combined with the relatively higher log-likelihood for the non-credit group, suggest that the Conventional-SPF may capture some relationships but fails to fully account for unobserved heterogeneity between the groups.

Moving to the Stochastic Correction Stochastic Production Frontier (SC-SPF) model, the estimates are adjusted to account for unobserved variables that could bias technical efficiency (TE) estimation. After this correction, the key input variables (land, seed, fertilizer, and pesticides) for credit users become positive and highly significant, which contrasts with the negative or insignificant signs in the conventional model. This finding indicates that, once hidden biases are addressed, the use of credit is clearly associated with more productive use of inputs. For example, seed, which previously had no significant effect, now shows a strong positive impact (2.79) on output. Fertilizer and pesticides also switch to positive and significant, suggesting improved input effectiveness when unobserved factors are controlled.

Notably, the Rho value for credit users ($\rho = -0.9991^{***}$) is statistically significant, indicating strong correlation between inefficiency and the composite error term. This confirms the presence of substantial bias in the Conventional-SPF estimates and validates the superiority of the SC-SPF model for a more reliable efficiency analysis. However, labor input remains significantly negative even in the SC-SPF, underscoring persistent inefficiencies in how labor is deployed in rice production, possibly linked to high labor costs, aging workforce, or low mechanization.

The Stochastic Correction Stochastic Meta-Frontier (SC-SMF) model allows both groups to be compared under a common benchmark technology, providing a broader perspective on efficiency gaps. In this model, land continues to be a dominant positive factor (coefficient = 3.30), highlighting its consistent importance across technologies. However, seed and fertilizer inputs become negative and significant, implying that even with credit, these inputs are not always used optimally relative to the benchmark. Labor input also remains significantly negative, confirming a widespread inefficiency that transcends credit access and technological boundaries.

Interactions between inputs provide further insight. The *Seed*Fertilizer* interaction becomes insignificant, while the *Pesticides*Labor* interaction is positive and significant. This suggests potential synergies in using labor to apply pesticides more effectively. However, other interactions, such as *Land*Labor* and *Fertilizer*Pesticide*, remain negative, indicating persistent inefficiencies in combining these inputs. Importantly, squared terms like *Fertilizer²* and *Labor²* also show statistical significance, pointing to nonlinear effects and possible overuse beyond optimal levels.

The SC-SMF model's log-likelihood is the highest among the three, reinforcing its statistical superiority. This model confirms that both credit and non-credit users are operating below the potential frontier, but credit users are relatively closer to full efficiency. The ability of the SC-SMF model to compare farmers under a common technological framework reveals deeper inefficiencies masked by technology-specific frontiers and highlights the importance of improving input effectiveness, beyond merely increasing access.

In summary, the progression from Conventional-SPF to SC-SPF and finally to SC-SMF models reveals three critical findings. First, the conventional model underestimates the benefits of credit due to unobserved heterogeneity. Second, after correcting for these biases, credit usage is shown to significantly improve input effectiveness, especially in land, seed, and fertilizer utilization. Third, the meta-frontier model illustrates that, although credit helps close the efficiency gap, rice farmers in general, regardless of credit use, still operate below the optimal frontier, mainly due to labor inefficiencies and input mismanagement. These insights underscore the need for targeted credit policies, better input allocation, and technological upgrading to enhance rice farm productivity in Indonesia.

Impact of credit on technical efficiency in Indonesian rice farming. The results from Table 8 show significant differences in technical efficiency (TE) scores between rice farmers who access credit and those who do not, depending on the estimation model used. Under the Conventional Stochastic Production Frontier (Conventional-SPF) model, the mean TE scores for both credit users and non-users

are exceptionally high 99.903% and 99.914% respectively, with a negligible difference of -0.011%. (Table 8). Although the t-statistic (-4.060) is statistically significant, the extremely high TE values suggest a misleading impression that all farmers are operating near perfect efficiency. These results do not account for unobserved factors such as differences in farmer characteristics, local farming environments, or access to technology, rendering the Conventional-SPF model insufficient for drawing accurate conclusions about the role of credit.

Table 8. Predicted mean frontier TE score (%) calculated from the Conventional-SPF, SC-SPF and the SC-SMF models based on matched samples.

ATET	Conventional-SPF	SC-SPF	SC-SMF	Observation
Credit Users (Treated)	99.903	65.499	67.057	69
Non-Credit User (Control)	99.914	58.653	58.681	214
Difference	-0.011	6.846	8.375	
Standard error	0.003	3.798	3.980	
t-statistic^{a)}	-4.060	1.800	2.100	

Note: ^{a)} The t-statistic is used to test the null hypothesis that there is no difference between the mean of the outcome variables for the Credit and non-Credit groups. This is a test of the average treatment effect on the treated (ATET). The critical value based on the t-test table with 69 degrees of freedom at a 5% significance level one tail ≈ 1.67 , and for two tails ≈ 2 . Critical value based on T-test table with 69 degree of freedom at 1% significant level for one tail ≈ 2.38 , and for two tail ≈ 2.66 .

In contrast, when using the Stochastic Correction Stochastic Production Frontier (SC-SPF) model, which controls for unobserved heterogeneity, a more realistic picture emerges. The TE score for credit users drops to 65.499%, while that for non-credit users is 58.653%. This indicates a notable and economically meaningful difference of 6.846 percentage points, with a t-statistic of 1.80. Although this is only weakly significant at the 10% level, it highlights the positive influence of credit in improving farm performance. The results suggest that farmers who access credit are better able to allocate inputs more efficiently and adopt improved farming practices, likely because they can afford higher-quality seeds, fertilizers, or timely labor, thereby reducing production inefficiencies.

The most comprehensive model, the Stochastic Correction Stochastic Meta-Frontier (SC-SMF), takes the analysis one step further by comparing both groups against a common benchmark technology. This model shows that the TE of credit users is 67.057%, while non-credit users have a TE of 58.681%. The difference of 8.375 percentage points is statistically significant at the 5% level (t-statistic = 2.10), providing the strongest evidence that credit access enhances technical efficiency. This finding underscores that credit users are not only more efficient within their group but also operate closer to the ideal production frontier, benefiting from broader technological advantages or more optimal input combinations enabled by credit.

In summary, the progression from the Conventional-SPF to the SC-SPF and finally the SC-SMF model reveals that the true impact of credit on rice farming efficiency was previously underestimated. Once statistical biases and technology gaps are accounted for, credit emerges as a critical factor in boosting technical efficiency. These results advocate for targeted policies that improve smallholder farmers' access to credit, alongside efforts to strengthen financial literacy and simplify lending procedures. Expanding credit access would allow more farmers to adopt timely and efficient input use, thus contributing significantly to productivity growth and food security in Indonesia's rice sector.

CONCLUSIONS AND POLICY RECOMMENDATIONS

The PSM method produced high-quality matching, with no significant differences between credit users and non-users across explanatory variables. The Generalized Likelihood Ratio Test showed that the transcendental logarithmic model better fits the Stochastic Frontier Production Function (SPF) than the Cobb-Douglas, indicating different technologies between groups and justifying the use of the Stochastic Meta-Frontier Production Function (SMPF). The SC-SPF model revealed significant unobserved variable bias in the conventional SPF model, making SC-SPF a more accurate alternative. Further, the SC-SMPF model proved superior, offering a common and representative technology benchmark for both groups.

Credit access is found to significantly improve technical efficiency in rice farming, although the magnitude of its impact varies depending on the estimation approach used. More robust modeling indicates that farmers with access to credit consistently achieve higher efficiency levels than those without, despite overall efficiency remaining below optimal levels. These findings underscore the important role of credit access in enhancing farm performance and supporting improvements in agricultural productivity.

Improving the performance of Indonesia's rice farming sector requires not only expanding farmers' demand for credit but also addressing structural constraints on the supply side of formal agricultural lending. Access to commercial bank credit significantly enhances technical efficiency in rice farming. However, limited access is not solely attributable to farmer-level barriers; it also reflects risk perceptions, regulatory constraints, and low profitability associated with agricultural lending from the perspective of commercial banks. Therefore, policy interventions must simultaneously target both demand- and supply-side bottlenecks within the rural credit market.

On the demand side, simplifying administrative requirements and developing loan products tailored to agricultural production cycles remain essential. Flexible repayment schedules aligned with harvest periods and seasonal cash flows would reduce default risk and improve loan uptake among smallholders. Strengthening rural financial institutions and expanding branchless banking infrastructure would further enhance outreach in underserved areas.

On the supply side, commercial banks often perceive agricultural lending as high risk due to weather variability, price volatility, and limited collateral among smallholders. To mitigate these concerns, the feasibility of expanding credit guarantee schemes warrants careful evaluation. Partial credit guarantee mechanisms, whereby the government absorbs a predefined share of default risk, can incentivize banks to increase agricultural loan portfolios without fully socializing credit risk. The design of such schemes must ensure appropriate risk-sharing ratios to avoid moral hazard while maintaining fiscal sustainability.

The introduction or reinforcement of mandatory agricultural lending quotas is worth considering. The experience of the Philippines under the Agri-Agra Reform Credit Act provides a relevant case, where commercial banks are required to allocate a minimum percentage of their loanable funds to agriculture and agrarian reform beneficiaries. While such mandates can increase formal credit flows to agriculture, their effectiveness depends on enforcement capacity, penalty structures, and the availability of viable agricultural investment opportunities. In the Indonesian context, careful assessment is required to determine whether setting a required proportion of commercial bank lending to agriculture would improve credit access or instead lead to compliance substitution, such as indirect or low-risk agricultural investments that do not reach smallholders.

Risk mitigation mechanisms should complement these structural reforms. Expanding agricultural insurance programs can reduce exposure to weather-related shocks for both farmers and

lenders. Integrating insurance with credit contracts, through bundled loan-insurance products, may further reduce default risk. Additionally, the development of agricultural credit scoring systems incorporating agronomic, climatic, and behavioral data could improve risk assessment and reduce information asymmetry between farmers and banks. Digital financial platforms may enhance transparency, lower transaction costs, and facilitate monitoring.

Beyond financial instruments, improving technical efficiency also requires coordinated institutional support. Credit provision should be integrated with extension services, input access, and managerial training. Bundled service delivery through cooperatives or farmer organizations can reduce transaction costs and enhance monitoring while supporting technology adoption. Given the heterogeneity observed across production frontiers, differentiated credit products and technical assistance packages are necessary to address varying technological capacities among farmers.

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PROFILE OF FARMERS' PRACTICES AND MAPPING OF TRADITIONAL RICE VARIETIES IN NUEVA VIZCAYA, PHILIPPINES

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ABSTRACT

The stewardship of traditional rice varieties (TRVs) predominantly rests with upland farmers. These varieties exhibit a rich source of genetic diversity and possess outstanding characteristics, including improved grain quality, health and nutritional values, and resistance to climate-related stress, pests, and diseases. However, limited information is available on their cultivation methods, geographic locations, and documented growers. This research examined farmers and their agricultural practices and created geographical distribution maps of traditional rice growers using a geographic information system. The research was carried out across nine municipalities in Nueva Vizcaya, Philippines, from September to December 2018. On-site interviews with 19 farmers and geotagging activities were carried out. Most farmers were members of indigenous peoples and resided in the province's undulating hills and steep mountains, specifically in the towns of Diadi, Bagabag, Villaverde, Solano, Ambaguio, Kayapa, Kasibu, Santa Fe, and Alfonso Castañeda. The *Kaingin* remained the locally utilized agricultural practice, with local farmers relying on traditional slash-and-burn techniques as their primary means of cultivating crops. There was little to no use of inorganic inputs in the rice ecosystems. Family labor was utilized for harvesting on small farms, employing manual techniques with tools such as *gapas* and *rakem*. Farmers continued to cultivate rice mainly to sustain their livelihoods. The applications Pic2map and Google Earth facilitated the online viewing of geotagged photographs. The study mapped the geographic coordinates of 30 TRVs currently cultivated by farmers in Nueva Vizcaya. The profiling of farmers and their agricultural practices, combined with geotagging, has improved access to the locations of existing TRVs in the province, paving the way for future research initiatives.

Key words: geotagging activities, *kaingin* system, EXIF data, GIS app, indigenous peoples

INTRODUCTION

The on-farm conservation of rice genetic resources involves the ongoing cultivation and management of diverse rice populations by farmers within the agroecosystems where these crops have evolved (Ocampo and Ocampo 2016). The development of improved rice varieties relies on the availability of genetic resources, including thousands of locally adapted varieties. These varieties face the risk of extinction in farming systems as farmers adopt new, improved varieties (Zhu et al. 2009). Also, farmers replace traditional cultivars with new ones because the new cultivars offer additional benefits (Laborte et al. 2015). Certain TRVs continue to be preserved and cultivated by farmers, potentially serving as valuable sources of germplasm for rice improvement, given their traits that are well-suited to adaptation to various abiotic and biotic stresses (Rabara et al. 2014).

Since TRVs are often grown in isolated, mountainous, or significantly fragmented areas, GIS helps identify the precise ecological location (e.g., geographic coordinate) where a particular rice variety thrives. This aids in mapping suitable areas for conservation and restoring lost varieties (Mosleh et al. 2015). In mapping, understanding spatial variation in crop responses to environmental and management factors is an essential component of agronomic research (White et al. 2002). Identifying the biophysical and socioeconomic characteristics of rice-producing regions is essential for formulating effective targeting strategies for disseminating new technologies and sustainable crop management and diversification options (IRRI 2018). Rabara et al (2015) used geotagging technology to locate and map TRVs in Aurora, Philippines, for genetic resources conservation. Similar studies have been carried out on rice geomapping: geographic information was gathered and analyzed through GIS technology to illustrate rice farming patterns and their correlation with environmental factors in West Java, Indonesia (Sondari et al 2024); utilizing remote-sensing and supplementary data sets developed for a geospatial database concerning the spatial distribution of rice cultivation areas and rice cultural varieties of major rice-producing countries of South and Southeast Asia (Manjunath et al. 2015); and the application of Satellite Remote Sensing improves the precision of paddy rice mapping, thus providing essential information for the government, planners, and decision makers to formulate policies (Zhao, Li, and Ma 2020).

Family farming is the typical operational farming model in the Philippines. It is a major contributor to socio-economic life in most rural areas (Ramos 2020). Rice is considered a staple food, and its production is an important source of employment and livelihood in the countryside (Laborte et al. 2015). Rice is still the main food crop grown by farmers in the province of Nueva Vizcaya. In irrigated lowlands, high-yielding varieties (HYVs) and hybrids dominate production. According to Andal and Sana (2008), in the highlands of Nueva Vizcaya, especially the rainfed areas, some farmers still cultivate TRVs. Still, production is considered marginalized even though traits dictate a premium price.

Because rice farmers contributed to rice diversity as they nurtured and selected rice cultivars throughout time, information about them, their geographic locations related to rice cultivation, and spatial distributions of traditional rice cultivars or landraces in the province are necessary for future crop improvement and conservation programs. Consequently, this research was conducted to document the current agricultural practices and to develop a geographical distribution map using geotagging technology through GIS for the TRVs in Nueva Vizcaya, Philippines.

MATERIALS AND METHODS

The research was conducted during the wet season months, September to December 2018. In the province of Nueva Vizcaya, there are a total of fifteen (15) municipalities; however, only nine (9) municipalities were considered in this study, namely Diadi, Bagabag, Villaverde, Solano, Ambaguio, Kayapa, Kasibu, Santa Fe, and Alfonso Castañeda (Fig. 1). These towns are recognized for their cultivation of traditional rice varieties within the province. Details regarding the production locations of TRVs and farmers were derived from the information provided by the concerned Municipal Agriculture Offices (MAGROs). Also, a Certificate of Precondition was secured from the office of the Regional Director of the National Commission on Indigenous Peoples (NCIP) Region 02. Its purpose was to allow the researcher to collect various seeds and to promote, protect, and recognize the rights of Indigenous Cultural Communities/Indigenous Peoples (ICCs/IPs) living within the collection sites. In accordance with the protocol for obtaining consent or approval, the researcher presented the proposed study to concerned farmers and farmer/tribal leaders. During the on-site visits, geotagging of TRVs was done for the GIS-based mapping activity.

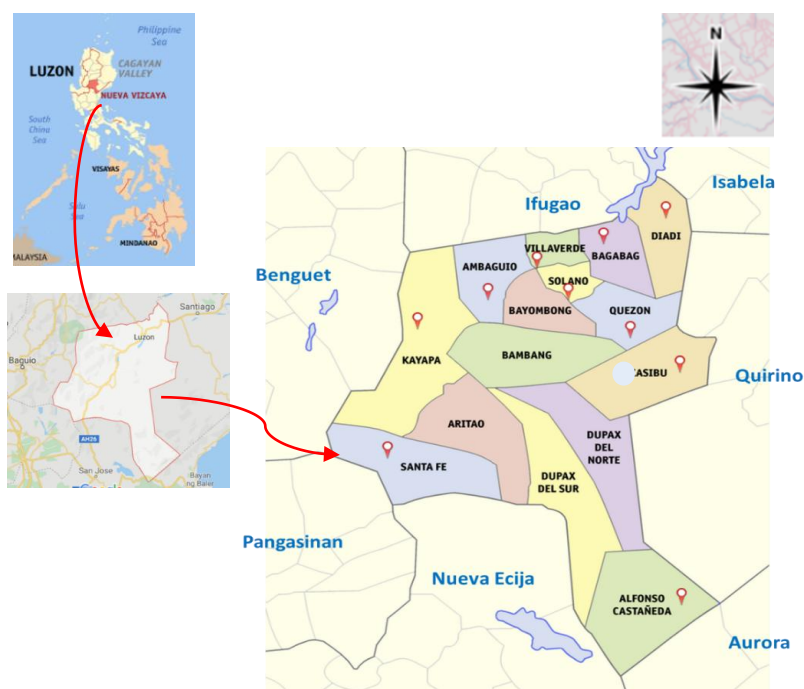


Figure 1. The production sites of TRVs in Nueva Vizcaya, Philippines.

Profile of selected TRV growers. Only farmers who planted TRVs for two cropping seasons were included in the survey. Nineteen (19) TRV growers were interviewed on-site using the prepared survey questionnaires and other documents for traditional rice. Farmers were asked open-ended questions to capture potential insights about the cultivation of TRVs. Documentation was centered on the different production techniques of farmers in the community. Location information, size of farms, yield, growing period, ethnicity, years in farming, reasons for planting, farmer’s description, special traits or uses, and cultural practices are recorded to understand the present farming scenario and the level of commitment to continue on-farm production of TRVs in the locality.

The geotagging activity. The geotagging processes of the study adapted the concept of the National Greening Program (NGP) Geo-Tagging Manual of the Department of Environment and Natural Resources (DENR, 2013) and the procedures listed on the <https://www.pic2map.com/> website. The Pic2Map was an online Exchangeable image file format (EXIF) data viewer with global positioning system (GPS) support, which allowed one to locate and view photos on Google Maps™. It analyzed EXIF data embedded in the image to find the GPS coordinates and location. The system used EXIF data available in all photos taken with the smartphone used during documentation activities. Hence, the Pic2Map photo mapper extracted the coordinates where all photos were taken in the study.

Geotagged photos from mobile phones were consolidated and saved on a laptop computer. A new folder was created in the desktop directory, and all pictures inside the geotagging device were copied and pasted into the created folder. The pic2map website was opened, and a selected photo was uploaded into the “Select Photo Files” icon for online viewing. The application automatically displayed the embedded data from a geotagged photo, like the location coordinates and elevation (Fig. 2).

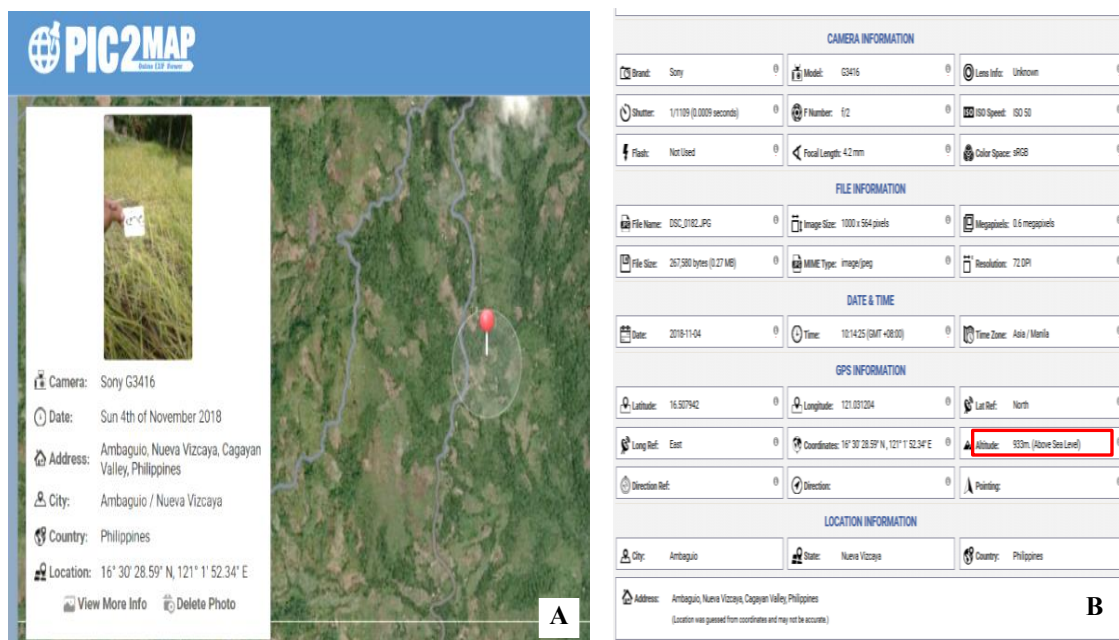


Figure 2. Example of a geotagged photo using a Pic2Map application: A) Photo EXIF data and B) Detailed file information.

RESULTS AND DISCUSSION

GIS-based maps of TRVs. Traditional rice varieties of the province are produced in different topographic locations, from plain level to mountainous. The geographic elevations were established on actual coordinates during the geotagging activity and not on estimated values. TRVs grown in upland rice land ecosystems are mostly located in the mountainous areas of Nueva Vizcaya and commonly under rainfed environments. These are found in the towns of Villaverde, Santa Fe, Kasibu, Solano, Alfonso Castañeda, and Diadi. There are some areas considered mountainous yet irrigated and terraced, like the production sites in Kayapa and Ambaguio, Nueva Vizcaya. Rice crop is cultivated under diverse environmental conditions and crop management regimes (Muralikrishnan et al. 2021). Particularly, traditional rice is primarily cultivated seasonally in marginal upland areas with highly degraded, infertile, and acidic soils (IRRI 2018).

Figure 3 shows geotagged photos plotted on a map, generated by geotagging production sites using Google imagery and a geographic information system. The thematic map of TRVs in Nueva Vizcaya showed the municipalities and names of TRVs where the photographs were captured. The procedure for creating a geographical distribution map through GIS involves utilizing spatial data, such as global positioning system (GPS) coordinates, to examine and visualize the production areas of TRVs.

Also, another example of a geotagged photo taken in the town of Diadi, Nueva Vizcaya, Philippines, showing the picture of panicles of the cultivated TRV (Milagrosa-Red), date/time taken (10-26-2018/11:26 AM), the model and brand of cell phone used (G3416, Sony), and the altitude of the area at 817.0 m (Fig. 4). The use of GIS and geotagging technology in agriculture allows farmers to update real-time field data, systematically organize and analyze it, and remotely monitor their crops, thereby connecting mapped information with agricultural communities (Yusopova 2024). Specifically, geotagged images of TRVs are essential for the *in-situ* conservation of genetic diversity, ensuring food security, and facilitating sustainable agricultural planning and policymaking (Mathenge et al. 2022).

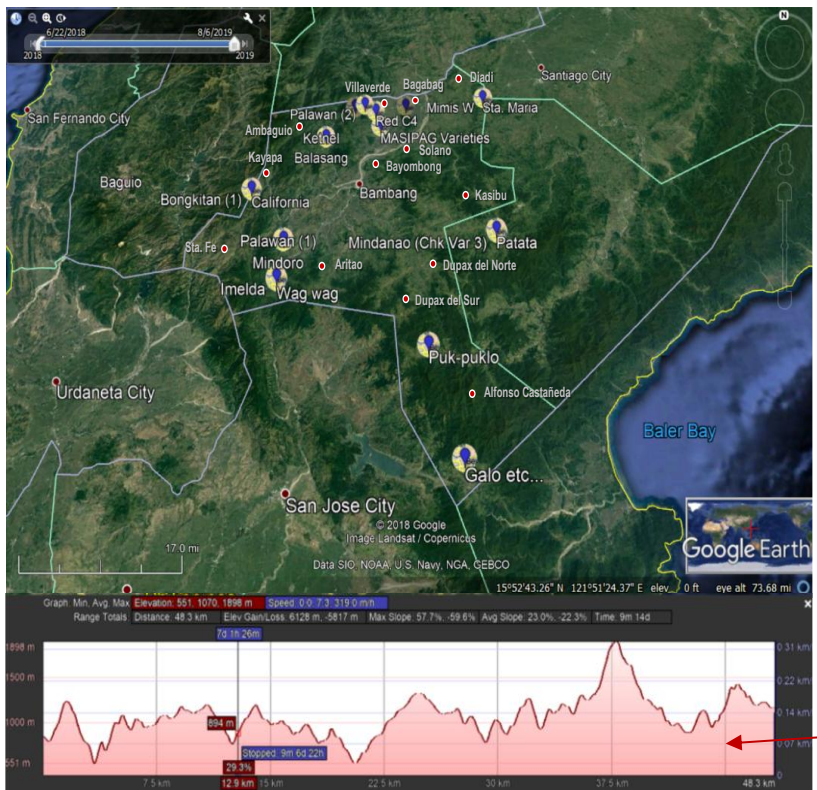


Figure 3. A geotagged map showing the sites of traditional rice varieties grown in Nueva Vizcaya, Philippines.

Legend:

- = Municipality
- 📍 = Location of TRVs

The pink graph is an elevation profile. Every peak and valley of the pink shape corresponds to an actual mountain, ridge, or lowland on the Google Earth map.

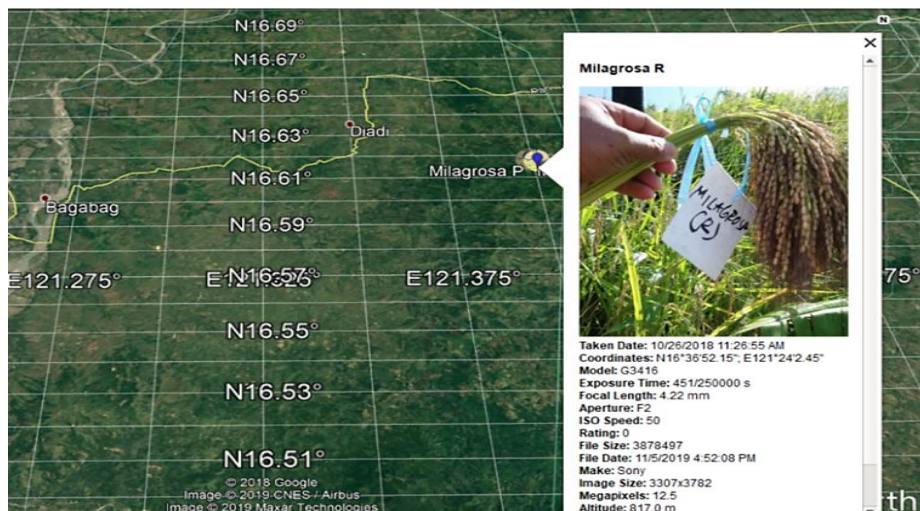


Figure 4. A geotagged photo of collected TRV (Milagrosa Red) panicles captured in Diadi, Nueva Vizcaya, viewed in Google Earth.

Farmers' profile growing TRVs. The interviewed farmers varied in ethnicity. A total of nineteen profiled farmers who belonged to the indigenous peoples (IPs) predominated in the cultivation of TRVs in Nueva Vizcaya (Table 1). The Ifugao, Ilocano, Kalanguya, and Iwak tribes comprised 7, 5, 4, and 2 farmers, respectively, and one farmer represents the Bugkalot group. These farmers largely owned undulating mountainous production sites of TRVs. The Ilocanos, the largest cultural group in Nueva Vizcaya, comprised 5 farmers who possessed most of the irrigated and plain-level traditional rice ecosystems in the community. Furthermore, the average age of all TRV growers documented in the study was 52 years. Also, farmers have been growing TRVs for a minimum of 2 to 42 years. Bolla and Galduen (2018) revealed that the wide age range and years in farming explained the involvement of younger and aging generations in the same farming practices for TRVs in Nueva Vizcaya. These findings show a mixture of young and old, new and seasoned TRV farmers in the area.

Seventeen farmers acknowledged that the sources of their TRV seeds were held by other TRV growers within the locality. Ten farmers practiced preserving and storing their seeds for future planting within their households and for the benefit of their neighbors. Other seeds were brought by other farmers and their ancestors from nearby provinces of Ifugao, Quirino, Nueva Ecija, and Tarlac when they migrated to Nueva Vizcaya. Traditional crop biodiversity has, for centuries, been selected by farmers for the seeds' unique suitability to local growing conditions, making scientists claim they are more likely to adapt to changing climatic conditions (Singh 2018). Thousands of local and heirloom food-crop varieties are in farmers' hands, mostly treasured through home and community seed banks. Traditional crop varieties are preserved by local farmers, especially IPs living in the mountains (Camacho et al. 2015). Likewise, TRVs are preserved along with the terraces where they are grown and the culture and traditions of the IPs growing them (Cuevas et al. 2021).

All farmers agreed that they grew TRVs primarily for family food, valuing the good eating quality, health benefits, and aroma of the traditional variety. Muralikrishnan et al. (2021) reported that several traits, including stickiness, high starch content, waxy and aromatic qualities of TRVs, lead farmers to conserve these genotypes for future cropping seasons. Also, the consumption of unpolished traditional rice is rich in bioactive components like phytochemicals, antioxidants, vitamins, and minerals, helping regulate various diseases such as cancer, cardiovascular disease, and diabetes (Kowsalya, Sharanyakanth, and Mahendran 2022). Moreover, fourteen farmers described TRVs that exhibit pest resistance across production sites, enabling them to reduce pesticide usage and apply little to no fertilizers. Traditional rice possesses desirable traits such as resistance to insect pests and diseases, tolerance to abiotic stress, aromatic, pleasant taste, and excellent palatability, which are usually transferred to modern cultivated varieties to enhance rice crop improvement (Rogeno and Seville 2018).

Production practices of TRVs. For primary farm operations like land preparation, planting, and weeding, all farmers agreed they practiced the *bayanihan* scheme to expedite the work (Table 1). The strategy works when fellow farmers in the community come together and help one another to achieve a common purpose as a team. Ealdama (2012) described *bayanihan* as a Filipino tradition in which people go out of their way to help those in need without expecting a reward; and a representation of the Filipino approach to collaborative efforts and communal support, which has become fundamental to the fabric of family and community life in the Philippines (Melendres et al. 2022). However, other farmers mentioned that *arawan/purdiya* and *pakyawan* are also practiced on their farms. In the *arawan* scheme, the owner pays workers daily or weekly according to the number of days they worked (<https://laborlaw.ph/wages-salaries-remuneration/>), and meals are provided by the owner. The *pakyawan* basis of payment is determined by the completion of the work rather than the duration taken to complete it. Once the work is completed, the worker receives a fixed amount as a wage, without regard to the standard measurements of time generally used in pay computation (<https://laborlaw.ph/workers-paid-by-results>). The population of other pests, like birds and weeds, was managed manually by the farmers. The presence of birds was minimized by setting up a series of plastic bags and cassette films in the field as scarecrows. A scarecrow serves as a component of the agricultural landscape designed to repel animals, particularly birds, from damaging crops on the farm (Król et al. 2019).

Table 1. Information on ethnicity and production practices of nineteen TRV growers in Nueva Vizcaya, Philippines.

Farm Site	Ethnic group	No. of farmers	Age	Years of planting TRV	Reasons for planting TRV	Source/ Origin of TRV	Farmer's description of the cultivar	Special traits preferred by farmers	Cultural methods
Villaverde	Ifugao	2			Source of food & income, and variety conservation	Owned seeds in the community and MASIPAG varieties from Nueva Ecija	Difficult in panicle threshability (awned), pest & disease resistance, good taste (soft & tender)	Aroma, water, and fertilizer efficiency, high spikelet fertility, and high cooked kernel (linear) elongation	Direct seeded (<i>Kaingin</i>), transplanted, <i>bayanihan</i> , <i>arawan/purdiya</i>
	Ilocano	2							
<i>Mean</i>			49	13					
<i>Range</i>			32-69	10-22					
Santa Fe	Iwak	1			Source of food & variety conservation	Owned seeds in the community	Good taste (soft & tender), pest & disease resistance, & high yielding	Aroma & nutrient efficiency	Direct seeded (<i>Kaingin</i>), transplanted, <i>bayanihan</i> , <i>arawan</i>
	Kalanguya	2							
<i>Mean</i>			51	21					
<i>Range</i>			31-72	17-25					
Solano	Ifugao	2			Source of food, variety conservation, and for breeding purposes (parent material)	Quirino province and MASIPAG varieties from Nueva Ecija	Good taste (soft & tender), pest & disease resistance	Aroma & drought stress tolerance	Direct seeded (<i>Kaingin</i>), transplanted, <i>bayanihan</i> , <i>arawan/purdiya</i>
	Ilocano	1							
<i>Mean</i>			58	10					
<i>Range</i>			54-65	3-19					
Bagabag	Ilocano	1			Source of food & income	Tarlac province	Hard grains, when cooked, non-seasonal variety	Aroma & high amylopectin content in the preparation of rice dishes (<i>kakanin</i> , <i>bibingka</i> , and <i>biko</i>)	Transplanted, <i>bayanihan</i> , <i>pakyawan</i>
<i>Mean</i>			45	2					
<i>Range</i>			-	-					

Profile of farmers' practices.....

Farm Site	Ethnic group	No. of farmers	Age	Years of planting TRV	Reasons for planting TRV	Source/ Origin of TRV	Farmer's description of the cultivar	Special traits preferred by farmers	Cultural methods
Diadi	Ilocano	1			Source of food, high price of commercial rice, and absence of commercial fertilizers	Quirino province, Ifugao province, and owned seeds in the community	Good taste (soft & tender), big grains, awned varieties minimize bird scaring, tall plant height, easy panicle threshability (awn less)	Aroma, pest & disease resistance, and nutrient efficiency	Direct-seeded (<i>Kaingin</i>), <i>bayanihan</i> , <i>arawan/purdiya</i>
	Ifugao	1	64	23					
<i>Mean</i>			59-70	22-24					
<i>Range</i>									
Kayapa	Kalanguya	1			Source of food & income	Owned seeds in the community	Good taste (soft & tender), long growing cycle, resistance to pests, tall plant height	Aroma & nutrient efficiency	Transplanted, <i>bayanihan</i> , <i>arawan/purdiya</i>
	Iwak	1	56	8					
<i>Mean</i>			45-65	5-10					
<i>Range</i>									
Ambaguio	Kalanguya	1			Source of food	Owned seeds in the community	Long growing cycle, mixed with other rice grains for food	Aroma & high amylopectin content in the preparation of rice dishes (<i>kakanin</i> , <i>bibingka</i> , and <i>biko</i>)	Transplanted, <i>bayanihan</i> , <i>pakyawan</i>
<i>Mean</i>			41	13					
<i>Range</i>			-	-					
Kasibu	Ifugao	2			Source of food	Ifugao province and owned seeds in the community	Soft & high fiber content for long satiety	Aroma, pest & disease resistance, and nutrient efficiency	Direct-seeded (<i>Kaingin</i>), transplanted, <i>bayanihan</i> , <i>arawan</i>
<i>Mean</i>			46	25					
<i>Range</i>			30-62	8-42					
Alfonso Castañeda	Bugkalot	1			Source of food	Owned seeds in the community	Hard grains, when cooked	Aroma, pest & disease resistance, and nutrient efficiency	Direct-seeded (<i>Kaingin</i>), <i>bayanihan</i>
<i>Mean</i>			40	20					
<i>Range</i>			-	-					

The *Kaingin* or the swidden type (slash-and-burn) of farming was still practiced for growing TRVs in the upland rainfed areas of Diadi, Sta. Fe and Kasibu, Nueva Vizcaya. Farmers grew TRVs annually, commencing in June or at the beginning of the rainy season, as the growth of TRVs relies on rainfall for irrigation. Palay (rice) seeds were dibbled in the soil using a wooden stick or *asad* in Diadi and Kasibu, while bolo (*sinanggap*) was used in Sta. Fe (Fig. 5).



Figure 5. The dibbling method of planting TRVs using *Sinanggap* by farmers in Santa Fe, Nueva Vizcaya, Philippines.

The swidden type is practiced by upland farmers in the Philippines, which involves cleaning an area to be farmed by slashing or removing all types of plants and trees, and burning the uprooted plants (Pollini 2014). The system is believed to rid the soil of pests' damage and make it fertile through nutrient-rich ash (Zapico et al. 2020). Additionally, rice seeds are established by dibbling in dry soil before the onset of the rainy season (Rao et al. 2017).

Concerning the management of nutrients and pests, eighteen farmers did not utilize inorganic inputs in the cultivation of TRVs. Farms in Diadi, Kasibu, and Sta. Fe are considered “organic by default,” or no agrochemicals have been used for many years of production. Farmers who practiced ‘organic-by-default’ (Dankers and Liu 2003) are those who refrain from using chemical inputs either because they do not require them or cannot afford them (Seufert et al. 2023). During harvesting, both *rakem* and *gapas* were utilized to gather panicles of TRVs under the *Bayanihan* scheme. Sun drying of palay was commonly practiced in the community. Some farmers in Kayapa put harvested palay inside rain-sheltered gardens for temporary drying and protection from birds. However, on rainy days, harvested palay was dried at home using the kitchen fire, especially for the immediate food of the family. Dried palay for food was pounded using a mortar and pestle or *alsong* to separate the husk and produce rice grains for food. The village-type rice mills can be found in rural communities and are used for service milling paddy of farmers for home consumption. The conventional method of milling for TRVs involves hand pounding paddy using a mortar and pestle (IRRI 2019).

In irrigated areas, TRVs were transplanted when seedlings reached 25-30 days after sowing (DAS), with 5-10 seedlings per hill, at 20 cm and 30 cm for small rice cultivars; tall TRVs were usually transplanted 30-35 DAS. A similar study on traditional rice was conducted using a row-to-row distance of 30 cm and a plant-to-plant distance of 25 cm, with 5 seeds per hill (Lumba and Posadas 2018). Wider row spacing is recommended for traditional rice cultivars. Wider spacing lessens mutual shading, making plants sturdier, encourages higher tiller production, and makes plants less prone to lodge (http://www.knowledgebank.irri.org/ericeproduction/bodydefault.htm#pop_up_spacing.htm), and quantity of tillers per stand and number of panicles per square meter were both significantly reduced under closer spacing (20 cm x 20 cm) compared to wider spacing (20 cm x 25 cm) in a rain-fed lowland rice ecosystem (Moro et al. 2016). Furthermore, traditional rice varieties are transplanted 40 to 80 days after seeding (IRRI 2007). During the harvest, the manual method was employed in which family members or hired workers, referred to as *pakyawan*, cut individual hills using a sickle (*gapas*). Other farmers opted to use a finger knife (*rakem*) to harvest tall TRVs in the towns of Kayapa, Diadi, and Solano. The finger knife is used to harvest individual panicles in an area where the rice has ripened unevenly (Murphy 2017). Traditional taller varieties, commonly located in the upland areas, are more effectively harvested using small hand-held knives.

Farm descriptions of TRVs. A brief profile of TRVs and their production sites is presented in Table 2. Thirty (30) distinct rice cultivars were profiled in their growing areas. Five TRVs were considered early maturing varieties (≤ 110 days) from seeding to harvest. Ten TRVs were under medium-maturing varieties (113-125 days), six TRVs were late-maturing varieties (126-136 days), and nine varieties were beyond 136-day maturity. TRVs under the early-maturing varieties were planted twice a year, while the rest of the cultivars were grown once a year due to photoperiod sensitivity, with a range of maturity of 120-170 days. Traditional rice varieties are mostly photoperiod-sensitive, which influences their flowering time, which ranges from 65 to 124 days and can therefore be categorized, based on duration, as short, medium, and long duration varieties (Dwiningsih 2023; Susmitha and Divya 2020).

The largest areas planted with TRVs were in barangays (the smallest administrative divisions and local government units or villages) of Ibung and Careb, found in the municipalities of Villaverde and Bagabag, Nueva Vizcaya, Philippines. Each production area of 1.5 ha was planted with Wag-wag and R5 cultivars, respectively. Farms of 200 m² each in Labang, Ambaguio, planted with Balasang and Ketnel cultivars, and in Wacal, Solano, planted with MASIPAG varieties (Elmer, PBB 410, Pilit, AG5, & Batangas), respectively, were considered the smallest production areas of TRVs. The recorded yield average of TRVs is 2.90 tons/ha. MASIPAG (*Magsasaka at Siyentipiko para sa Pag-Unlad ng Agrikultura*) is a farmer-led network of people's organizations, non-government organizations (NGOs), and scientists working towards the sustainable use and management of biodiversity through farmers' control of genetic and biological resources, agricultural production, and associated knowledge (FAO 2022). The Raminad in Villaverde and Palawan in Kayapa varieties had the highest 4.5 tons/ha yield. The lowest yielder of all TRVs was the Batangas cultivar in Solano with a total production of 1.2 tons/ha. Traditional rice varieties in the Philippines are rarely grown for commercial production due to their generally low yield characteristics (Rogeno and Seville 2018).

Table 2. Profile of TRVs and their production sites in the study.*

Genotype (Local name)	Maturity (days)	Land area planted (m ²)	Yield (t/ha)	Location			Rice Land Ecosystem
				Geographic Coordinate	Municipality	Topography	
Red C4	110	3500	2.9	16°34'50.16"N; 121°8' 38.69"E; 425 masl	Villaverde	Undulating	Irrigated
Palawan	143	5000	2.5	16°36'4.33"N; 121°7' 5.99"E; 742 masl	Villaverde	Mountainous	Upland
Bongkitan	135	17000	2.9	16°37'30.98"N; 121°10' 48.9E"; 244 masl	Villaverde	Plain level	Irrigated
Raminad	135	3900	4.5	16°37'31.36"N; 121° 10'25.56"E; 248 masl	Villaverde	Plain level	Irrigated
Wag-wag	125	15000	4.0	16°36'31.0"N; 121°10' 58.8"E; 240 masl	Villaverde	Plain level	Irrigated
Mindoro	134	1000	2.5	16°14' 0.61"N; 120° '22.15"E; 994 masl	Santa Fe	Mountainous	Upland
Palawan	143	1000	2.5	16°14'50.18"N; 120° 57'23.7"E; 996 masl	Santa Fe	Mountainous	Upland
Imelda	120	3000	3.3	16°9'49.73"N; 120° 57'0.79"E; 525 masl	Santa Fe	Undulating	Irrigated
Wag-wag	150	5000	4.0	16°9'35.46"N; 120° 57'1.44"E; 583 masl	Santa Fe	Undulating	Irrigated
Mindanao (W)	127	7500	1.7	16°15'15.11"N, 121° 23'47.2"E; 694masl	Kasibu	Mountainous	Upland
Patata	122	3000	4.2	16°15'33.52"N, 121° 23'42.0"E; 604masl	Kasibu	Undulating	Irrigated

Profile of farmers' practices.....

Genotype (Local name)	Maturity (days)	Land area planted (m ²)	Yield (t/ha)	Location			Rice Land Ecosystem
				Geographic Coordinate	Municipality	Topography	
Elmer, PBB 410, Pilit, AG5,	100	200 (each)	4.0 (each)	16° 32'8.99"N; 121° 9'19.5"E; 307 masl	Solano	Plain level	Irrigated
Batangas	150	5000	1.2	16°35'43.76"N; 121°5' 43.9" E; 878 masl	Solano	Mountainous	Upland
Mindanao (R)	127	1500	1.3	16°35'40.12"N; 121° 5'45.88"E; 741 masl	Solano	Mountainous	Upland
Kotse	170	1000	2.5	16°22'15.76"N; 120° 52'47.8"E; 1229 masl	Kayapa	Mountainous	Irrigated
California	154	2500	2.0	16°22'16.22"N; 120° 52'38.4"E; 1211 masl	Kayapa	Mountainous	Irrigated
Bongkitan	161	1000	2.5	16°22'20.24"N, 120° 52'37.0"E; 1187 masl	Kayapa	Mountainous	Irrigated
Tuddoy	159	1000	2.5	16°22'19.87"N, 120° 52'41.6"E; 1165 masl	Kayapa	Mountainous	Irrigated
Palawan	145	4000	4.5	16°17'45.2"N; 120° 54'04.3"E; 1487 masl	Kayapa	Mountainous	Irrigated
R5	125	15000	4.0	16°35'39.3"N; 121° 12'52.5"E; 272 masl	Bagabag	Plain level	Irrigated
Milagrosa (R)	125	1000	3.0	16°36'52.15"N; 121° 24'2.45"E; 817 masl	Diadi	Mountainous	Upland
Milagrosa (P)	123	1000	3.0	16°36'52.19"N; 121° 24'2.42"E; 818 masl	Diadi	Mountainous	Upland

Genotype (Local name)	Maturity (days)	Land area planted (m ²)	Yield (t/ha)	Location			Rice Land Ecosystem
				Geographic Coordinate	Municipality	Topography	
Mimis	120	3000	3.3	16°36'52.17"N; 121° 24'2.72"E; 803 masl	Diadi	Mountainous	Upland
Sta. Maria	121	2000	1.75	16°36'54.32"N; 121° 23'54.3"E; 732 masl	Diadi	Mountainous	Upland
Balasang	135	200	2.5	16°30'29.28"E; 121° 1'51.81"E; 886 masl	Ambaguio	Mountainous	Irrigated
Ketnel	125	200	2.0	16°30'28.21"N; 121° 1'51.59"E; 934 masl	Ambaguio	Mountainous	Irrigated
Puk-puklo	125	3500	1.4	16°1'15.83"N; 121° 14'40.8"E; 725 masl	Alfonso Castañeda	Mountainous	Upland

* Adopted from the Philippine Specialty Rice: Understanding Production, Culture, Quality, and Market (Beltran et al. 2020).
W = White, **R** = Red, **P** = Purple.

CONCLUSIONS AND RECOMMENDATIONS

The cultivation of TRVs in Nueva Vizcaya, Philippines, is primarily a food security product for individual households rather than a market-oriented commodity. TRV-growers are part of the indigenous peoples and actively engaged in preserving the rich biodiversity of traditional rice varieties within the community. Characteristics such as aroma, pest and disease resistance, and nutrient efficiency have become important indicators of the conservation of TRVs. Documenting farmers' practices and traditional rice varieties is necessary to conserve agrobiodiversity and ensure food security. Furthermore, the Geographic Information System technology effectively maps the different locations of TRVs cultivated in the province, which enhances decision-making and efficiency.

Additional collection is suggested for various TRVs grown by other farmers, which were not part of the profiling study, for conservation purposes. Considering the significance of analyzing genetic diversity, it is essential to conduct studies that emphasize the morphological and molecular characterization of both the collected and the existing traditional rice varieties, aiming for possible enhancements in crop yield in the future.

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RICE MECHANIZATION LEVEL IN THE PHILIPPINES

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ABSTRACT

With the significant contribution of mechanization in modernizing the agriculture sector, an appropriate mechanization strategy is imperative. This paper assessed the status of rice mechanization across major rice-producing areas in the Philippines to support evidence-based decision-making. The study employed complete enumeration, analysis of secondary data, and key informant interviews to estimate the level of rice mechanization using different indices. Conducted in 2021-2022, the study covered 58 rice-producing provinces nationwide. Results revealed notable regional disparities in the concentration of rice machinery. Four-wheel tractors are increasingly used for land preparation in several regions, particularly Region I, although two-wheel tractors are still widely utilized as primary and secondary tillage machines in all areas. Meanwhile, there was high machine intensity for rice combine harvesters recorded in Regions III, II, and XI. The level of rice mechanization based on power available was estimated at 2.68 hp/ha in 2022 and improved to 2.81 hp/ha in 2025. Six provinces recorded high levels of mechanization, exceeding 4.0 hp/ha, while most provinces exhibited mechanization indices ranging from 2.0 to 3.0 hp/ha. In terms of power ratio, the level of rice mechanization was 84.25%, with four regions surpassing 90%. In terms of mechanization degree per operation, 77.59% of the total area was already mechanized using either two-wheel or four-wheel tractors, while harvesting-threshing was 53.66% mechanized using rice combine harvesters. The findings provide a comprehensive benchmark of rice mechanization levels in the Philippines and serve as an important reference for setting mechanization directions, identifying targeted interventions, and strengthening the monitoring and evaluation of various mechanization programs in the country.

Key words: level of mechanization, power available

INTRODUCTION

While rice remains as the most important crop in the Philippines, the local rice value chain has been constrained by low productivity, huge postproduction losses and high costs of production that contribute to low competitiveness. Postproduction losses still persist at 16.5 percent of potential output, with milling, drying and harvesting-threshing accounting for 95 percent of total losses (Salvador et al. 2012). Meanwhile, the unit cost of production is 49% and 104% percent higher than Thailand and Vietnam, respectively (Bordey et al. 2016). Among the costs of production, labor costs have been 6 to 7 times higher than the two countries. This was explained by the predominant use of mechanization technologies such as combine harvesters, four-wheel tractors, and labor-saving direct-seeding techniques as exhibited by the higher mechanization level of major rice-exporting countries. This

highlights the significance of labor-saving technologies in improving competitiveness. This is consistent with empirical studies indicating the strong relationship between the level of agricultural mechanization and the productivity/yield of certain crops, and also the country's level of economic development.

With its strategic importance in improving productivity, efficiency, income, and attaining agricultural modernization (Kishida 2006; Clarke 2000; Lu 2009; Emami et al. 2018; Vortia et al. 2019; Shi et al. 2021; Liu and Li 2023; Takeshima and Mano 2023), mechanization was given an increasing role in the government's development agenda with the enactment of AFMA, AfMech Law, and the Rice Tariffication Law. As the country is steadfast in its efforts to accelerate mechanization, formulation of an appropriate mechanization program is imperative, and this requires a benchmark study on the level of mechanization to know the current status, set mechanization directions, and guide monitoring and evaluation. This is especially called for since the most recent studies conducted in 2011 and 2012 are no longer relevant. With the implementation of major government mechanization programs such as the Rice Competitiveness Enhancement Fund and DA-National Rice Program, there is an urgent need to formulate mechanization plans and establish the bases in monitoring the progress of government and private initiatives in advancing rice modernization through agricultural mechanization.

While there are several indicators being adapted in assessing the status of agricultural mechanization (Bermudez et al. 2004; Dela Cruz and Bobier 2013; Malanon et al. 2014; Firouzi 2015 (rice cultivation machinery); Nath et al. 2017 (harvesting); Amongo et al. 2018; Hassan et al. 2021 (percent area mechanized)), a more comprehensive and practical approach to data collection and analysis is needed to support evidence-based decision making. This requires a combination of nationwide coverage, international comparability, real-time updating, and granular data visualization that create a novel data ecosystem that integrates local, national and international dimensions. This is to ensure representative coverage across different geographic and socio-demographic environments and cultural contexts for more location and technology-specific and tailored policy recommendations. Moreover, the application of a simplified index also facilitates direct comparison with data from other countries. This adds global relevance, enabling cross-country analysis, performance evaluation, monitoring and identification of best practices in the area of mechanization. Furthermore, the system developed through this research is also designed to follow near real-time updating, a significant advancement over traditional periodic or partial static reporting approaches. This allows policymakers, program implementers, and researchers to respond quickly to emerging trends and monitor the immediate impact of mechanization-related interventions. Thus, the study sought to assess the rice mechanization level in the Philippines using relevant indicators to serve as policy inputs in the formulation and implementation of rice mechanization programs in the country.

METHODOLOGY

Conceptual/analytical framework. The conceptual framework depicts the pathway in attaining the goal of mechanization in improving rice competitiveness. Through an appropriate and effective mechanization program, problems on low productivity, high production cost, and high postharvest losses will be addressed. This can be realized by promoting both public and private investments in mechanization and enhancing the adoption and sustained utilization of the technologies.

Updating the current state of mechanization will provide insight on the magnitude of intervention needed to fill the mechanization gap to achieve the desired state of agricultural development. In addition, there is a pressing need to have an accurate assessment of the mechanization requirements of rice farmers based on the available number of rice mechanization facilities and equipment and the practices of farmers particularly on the use of farm power. This will ensure resource allocation efficiency and realize the goal of mechanization program (Fig.1).

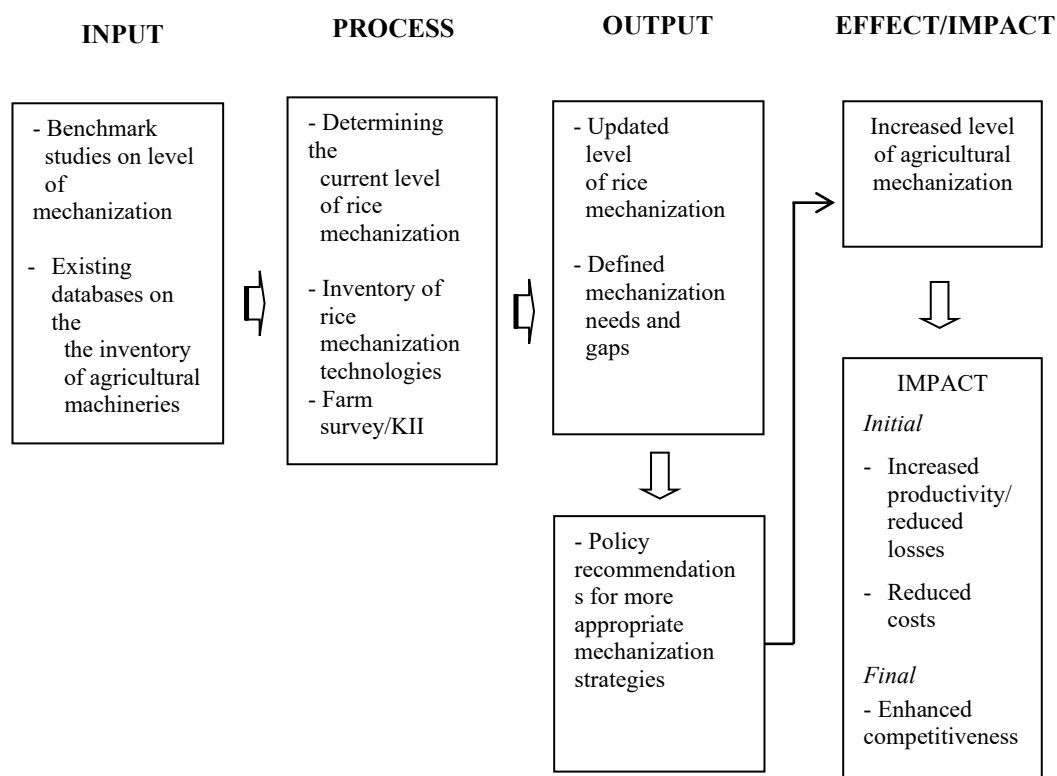


Figure 1. Conceptual framework of the study

Data needs and sources. In updating the level of rice mechanization, the study used countrywide data. Primary and secondary data were gathered from the following:

Table 1. Data needs and sources

Data Needs	Source
1. Inventory of rice mechanization technologies	Complete enumeration of rice mechanization technology owners/operators
2. Total area planted to rice	PSA; MLGU
3. Census of farm laborers employed in rice farming	PSA; MLGU
4. Census of draft animals engaged in rice farming	PCC, PSA; Office of the Provincial Veterinarian
5. Efficiency factors of different power sources	AMTEC, PCC

An inventory of available mechanization technologies was conducted in 58 rice-producing provinces identified by the Department of Agriculture as the focus of interventions based on their potential to enhance competitiveness. The criteria in selecting these provinces include area harvested, yield, percent irrigated area and unit cost of production.

Table 2. Areas of the study

Region	Province
CAR	Apayao; Ifugao; Kalinga
Region I-Ilocos Region	Ilocos Sur; Ilocos Norte; La Union; Pangasinan
Region II-Cagayan Valley	Cagayan; Isabela; Nueva Vizcaya; Quirino
Region III-Central Luzon	Aurora; Bataan; Bulacan; Nueva Ecija; Pampanga; Tarlac; Zambales
Region IV-A-CALABARZON	Cavite; Laguna; Quezon
Region IV-B-MIMAROPA	Occidental Mindoro; Oriental Mindoro; Palawan
Region V-Bicol Region	Albay; Camarines Sur; Masbate; Sorsogon
Region VI-Western Visayas	Aklan; Antique; Capiz; Iloilo; Negros Occidental
Region VII-Central Visayas	Bohol; Negros Oriental
Region VIII-Eastern Visayas	Biliran; Leyte; Samar; Southern Leyte
Region IX-Zamboanga Peninsula	Zamboanga del Sur; Zamboanga Sibugay
Region X-Northern Mindanao	Bukidnon; Lanao del Norte; Misamis Occidental; Misamis Oriental
Region XI-Davao Region	Davao de Oro; Davao del Norte; Davao del Sur; Davao Oriental
Region XII-SOCCSKSARGEN	North Cotabato; Sarangani; South Cotabato; Sultan Kudarat
CARAGA	Agusan del Norte; Agusan del Sur; Surigao del Sur
BARMM	Lanao del Sur; Maguindanao

Complete enumeration of rice mechanization technologies covering land preparation to milling equipment and facilities was gathered from barangay, municipal and provincial levels. All operational or functional facilities as of 2020 were included although old equipment (beyond economic life) still utilized were noted. Validations were done through complete enumeration of farmers or machinery operators in selected barangays and municipalities.

Municipal data from the PHilMech database or municipal data were used as a guide in validating/updating the list of machinery owners by filtering out the non-functional/non-operational units and adding up new facility acquisitions or appending other technology owners not included during the last inventory. To determine the rice cropping/farming systems and use of farm power, information was abstracted from the baseline study of SEPRD in support to RCEF-Mechanization Component program. These were supplemented by key informant interviews from the Provincial Agriculture Offices, Municipal Agriculture Offices, and other entities involved in rice mechanization.

Data encoding, processing, and analysis. Data were encoded using Microsoft Excel to facilitate consolidation, processing, and tabulation. Inventory data were exported to the PHilMech database for data storage, security, updating, access, and data processing for other applications.

The following indices were estimated:

$$\text{Machinery intensity} = \text{Total no. of machines} / \text{Total production area} \times 50 \text{ has} \dots\dots\dots (1)$$

The rice mechanization level followed the methodology adopted by Dela Cruz and Bobier (2013), Panagsagan (2011), and other countries (Almasi et al. 2000; Ereno, 2008; Magalhaes et al. 2013; Paman, 2020; Islam, 2018; Maheshwari and Tripathi, 2019; Singh, 2006; Singh and Kumar, 2017; Singh and Singh, 2021). This indicator draws on the assumption that the power being utilized by farmers is based on the existing or available power. This approach is the most practical to use considering the following: a) The index primarily uses inventory of machines which also needed updating; b) A baseline was already established in 2011 so the change in the level of mechanization over time can be estimated by applying the same formula; c) Ease of updating with the institutionalization of machinery registration by LGUs; and d) Estimation of index could be even at provincial and municipal levels. This is essential for the preparation of local master plans with the full devolution of functions to LGUs with the implementation of the Mandanas-Garcia Ruling. With simple calculations and readily available data, LGUs can do their own updating.

The study determined the contribution of the three main sources of power: human, draft animals and engine to the total available power per unit area of rice crop, in hp/ha.

$$\text{Available Power (hp/ha)} = \frac{\text{Human Power} + \text{Animal Power} + \text{Mech'l Power}}{\text{Total Physical Area}} \dots\dots\dots(2)$$

Where:

$$\text{Human Power} = \text{Total no. of rice farm laborers} \times \text{Power factor (0.10 hp)}$$

$$\text{Animal Power} = \text{Total no. of draft animals} \times \text{Power factor} \\ \text{(0.67 hp for carabao, 0.45 for cattle and 1.0 hp for horse)}$$

$$\text{Mech'l Power} = \text{Total no. of machines} \times \text{Power rating of machine} \times \\ \text{Efficiency factor (80\% for motors and engines, 85\% for} \\ \text{tractors and 80\% for other machines, AMTEC)}$$

While this index has limitations as it does not account how power is being utilized, it has been widely used by other countries; hence, it is relevant for benchmarking, setting mechanization target and for monitoring and evaluation purposes. For more specific policy prescriptions, other indicators were estimated such as Power Ratio and Degree of Mechanization or Percent Area Mechanized.

Using the same data in determining the Mechanization Index, the power ratio was computed using the formula

$$\text{Power Ratio (\%)} = \frac{\text{Mechanical Power}}{\text{Total Power}} \times 100 \dots\dots\dots(3)$$

Where:

Total Power is the sum of human power, animal power and mechanical power

Mechanization Degree expressed as percent area mechanized, as adopted from Malanon and Dela Cruz. 2018:

$$\text{Mechanization Degree (\%)} = \frac{\text{Area Mechanized (ha)}}{\text{Total Area (ha)}} \times 100 \dots\dots\dots(4)$$

RESULTS AND DISCUSSION

Intensity of rice mechanization technologies. The distribution of rice mechanization technologies is presented in terms of machine intensity per unit of land. Since the Rice Competitiveness Enhancement Fund - Mechanization Component requires FCA/LGU applicants to have at least 50 hectares aggregate area as one of the technical requirements, this was used in determining the number of existing machineries in a certain area.

Land preparation technologies. The regional data on intensity of four-wheel tractors indicates that larger tractors were widely used in Region I, with 1.59 units per 50 hectares (Fig. 2). This was followed by Region III, Region IV-B, and Region II with 0.78, 0.48, and 0.45 unit/50 ha, respectively. On the other hand, low tractor intensities were recorded in Region IV-A, Region V, Region VI, Region VII, Region VIII, Region IX, CARAGA, and BARMM. The concentration of four-wheel tractors in these regions ranges from 0.08 to 0.32 unit per 50 hectares. The average four-wheel tractor intensity in the 16 regions was 0.51 units per 50 hectares. In the Visayas and Mindanao islands, the distribution of four-wheel tractors was more sparse compared to Luzon. The majority (57%) of the provinces reported machine intensity of less than or equal to 0.20 units per 50 hectares, nine provinces recorded 0.21 to 0.30 units per 50 hectares, while only four provinces recorded higher than 0.30 unit per 50 hectares

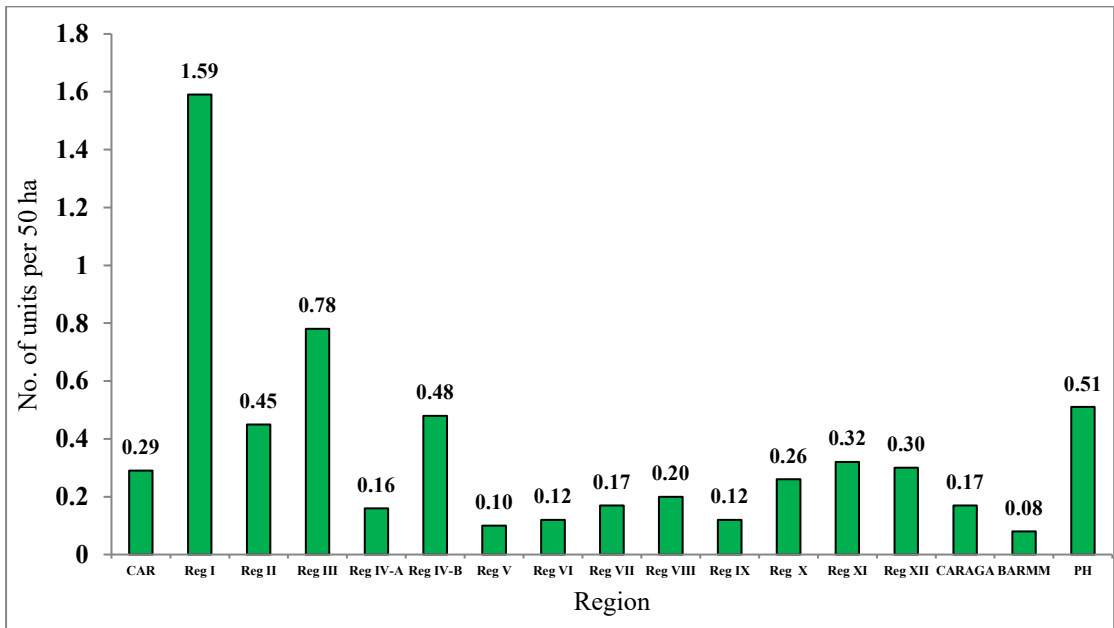


Figure 2. Number of four-wheel tractors per 50 hectares, Philippines, 2021-2022

While four-wheel tractors were already used as primary land preparation machinery in some areas, two-wheel tractors were still used in most areas for land preparation activities that include plowing, harrowing, and leveling. The regional average on intensity of two-wheel tractors shows that hand tractors were predominantly used in Region II and Region IV-A, with tractor intensities higher than 8.0 units per 50 hectares (Fig. 3). This was followed by Region I, Region VI, and Region VII, recording at least 7.0 to 8.0 units per 50 hectares. These indicate that high percentages of rice farmers own hand tractors and do not depend on custom service providers. Meanwhile, Region IX, Region XII, Region XI and BARMM recorded less than 3.0 units per 50 hectares. It should be noted that standard hand

tractors were predominantly used in Luzon provinces, with minimal numbers of floating tillers recorded in CAR, Region I, Region III, and Region II. Small numbers of floating tillers were noted in Region V, Region IV-A and Region IV-B, registering 0.26, 0.33 and 0.46 unit per 50 hectare, respectively. All the regions in Mindanao (Regions IX, X, XI, XII, CARAGA and BARMM) and Central Visayas (Region VII) have higher proportion of floating tillers compared to standard hand tractors popularly utilized in Luzon.

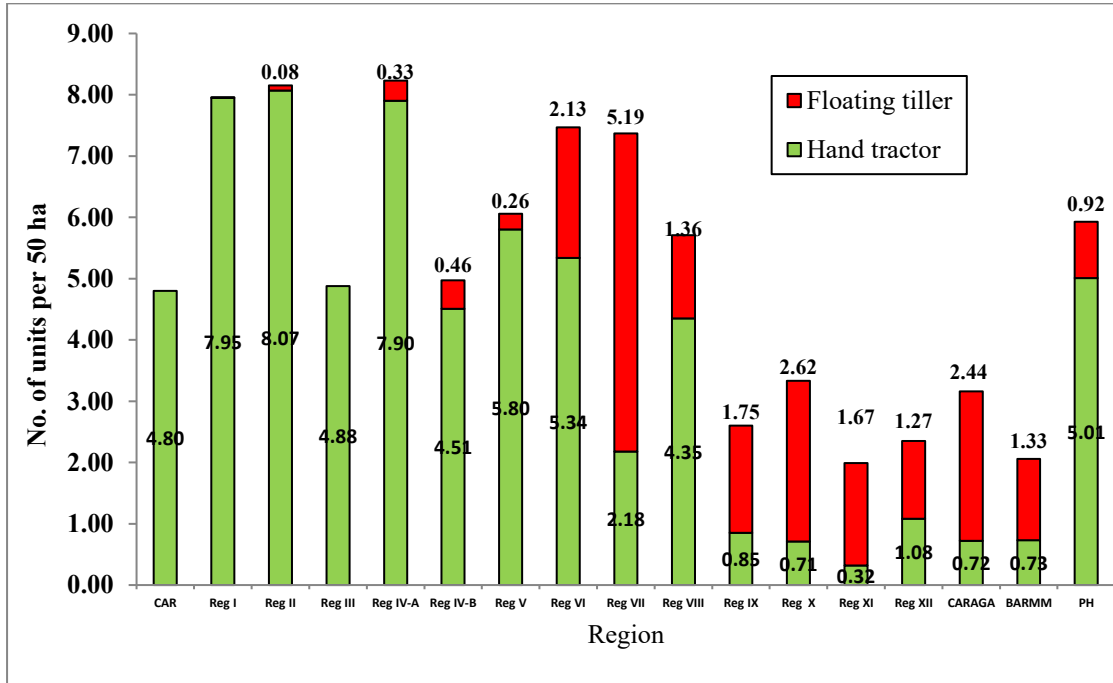


Figure 3. Number of power tillers per 50 hectares, Philippines, 2021-2022

Harvesting and threshing technologies. While threshing operation had long been mechanized with the development of rice threshers, harvesting was only mechanized in the early part of the 2010s with the introduction of rice combine harvesters. The increasing cost of labor driven by dwindling labor supply and the design of machines suitable to the agro-physical condition of rice farms in the country influenced the wide adoption of the technology. As of 2022, the regional distribution of RCH exhibited that there were high concentrations of the technology in Region III, Region II, and Region XI while RCH intensities were still very low in Region V, the entire Visayas, Region IX, and BARMM (Fig. 4).

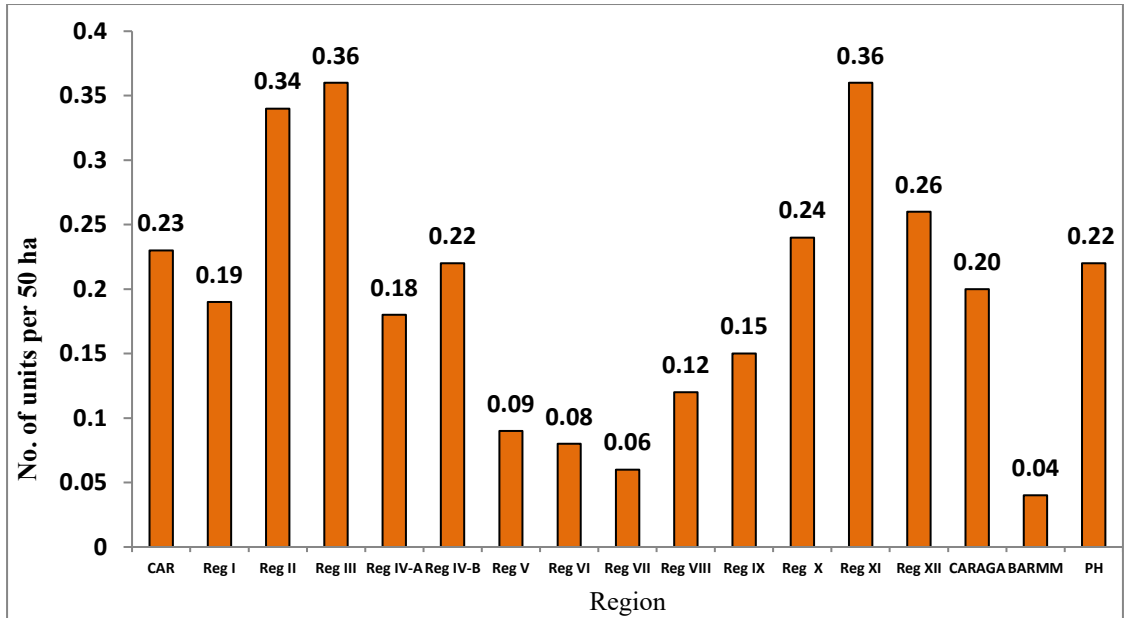


Figure 4. Number of rice combine harvesters per 50 hectares, Philippines, 2022

Rice mechanization level based on the power available. This section presents the updated level of rice mechanization in the country based on the power available. Using the inventory of rice mechanization technologies, census of available workforce and draft animals employed in rice production and postproduction activities, the provincial, regional and national levels of rice mechanization were estimated.

In terms of the regional data on mechanical power available for rice farm operations, Region II (Cagayan Valley) recorded the highest mechanization index at 3.30 hp/ha, while the Bangsamoro Autonomous Region of Muslim Mindanao (BARMM) registered the lowest mechanization level at 0.57 hp/ha (Table 3). Other regions that have relatively high levels of mechanical power available include Region I (Ilocos Region), Region IV-A (CALABARZON), Region VI (Western Visayas), Region III (Central Luzon), Region V (Bicol Region), and Region VII (Central Visayas), with a 2.00 – 3.00 hp/ha index. Meanwhile, the Cordillera Administrative Region (CAR), Region VII (Eastern Visayas), Region X (Northern Mindanao), Region IX (Zamboanga Peninsula), Region XI (Davao Region), Region XII (SOCCSKSARGEN), CARAGA, and BARMM recorded less than 2.0 hp/ha available mechanical power.

For mechanical power available, land preparation accounted for 1.41 hp/ha, comprising about 63% of the total mechanical power (Fig. 5). This was followed by harvesting-threshing at 0.59 hp/ha, irrigation at 0.16 hp/ha, and milling at 0.08 hp/ha. It should be noted that postharvest facilities such as mechanical dryers and rice mills operated by commercial millers were not included in the inventory because of the difficulty in gathering information from these sources.

Table 3. Mechanical power available per operation, per region, Philippines, 2022

Region	Land Prep	Crop Est.	Irrigation	Harvesting-Threshing	Drying	Milling	Total
CAR	1.09	<0.01	-	0.55	<0.01	0.11	1.76
Ilocos Region	2.16	<0.01	0.19	0.44	<0.01	0.06	2.86
Cagayan Valley	1.90	<0.01	0.61	0.77	<0.01	0.02	3.30
Central Luzon	1.41	<0.01	0.31	0.64	0.01	0.03	2.39
CALABARZON	1.43	0.01	-	0.91	0.02	0.24	2.61
MIMAROPA	1.26	<0.01	-	0.48	0.04	0.22	2.01
Bicol Region	1.18	<0.01	-	0.79	0.01	0.33	2.32
Western Visayas	1.60	0.01	0.02	0.70	0.01	0.09	2.43
Central Visayas	1.58	0.01	0.02	0.49	0.01	0.15	2.27
Eastern Visayas	1.17	0.01	0.05	0.54	0.03	0.10	1.90
Zamboanga Peninsula	0.56	0.01	0.04	0.41	0.03	0.06	1.10
Northern Mindanao	0.80	0.03	0.02	0.71	0.02	0.08	1.65
Davao Region	0.94	0.01	-	0.75	<0.01	<0.01	1.70
SOCCSKSARGEN	0.63	0.01	0.03	0.47	<0.01	<0.01	1.14
CARAGA	0.75	0.01	0.04	0.46	0.04	0.03	1.33
BARMM	0.38	<0.01	-	0.12	0.01	0.06	0.57

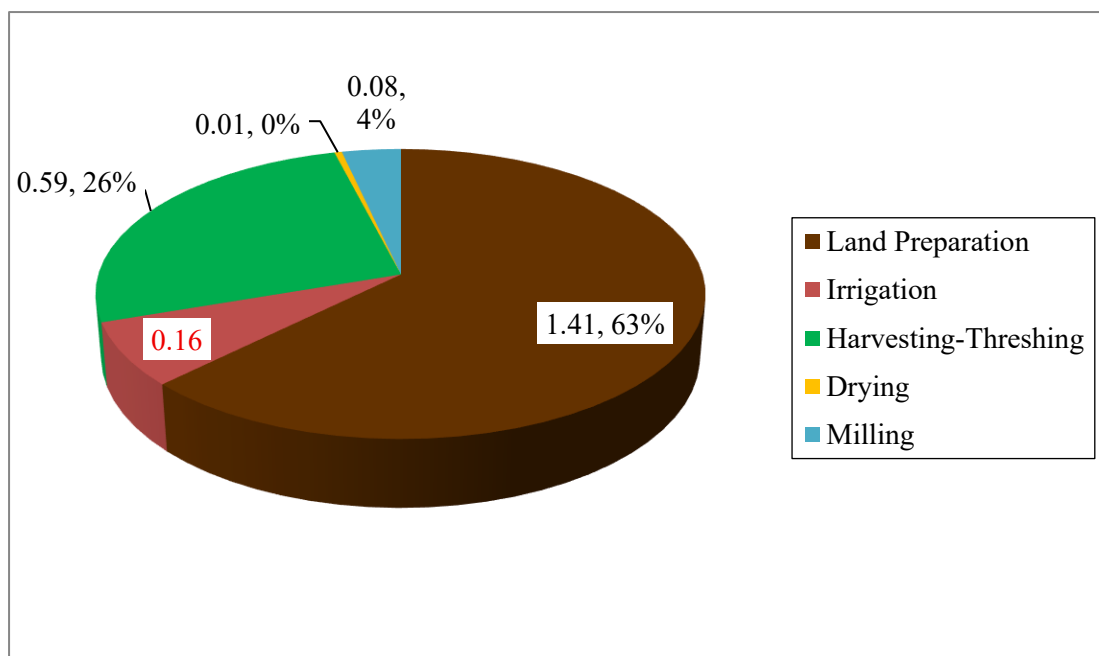


Figure 5. Distribution of mechanical power available per operation, Philippines, 2022

Rice mechanization level in the Philippines.....

The provinces with the highest levels of rice mechanization include Ilocos Sur, Ilocos Norte, La Union, Quezon, Aklan and Capiz (Fig. 6). These provinces have a mechanization level higher than 4.0 hp/ha. Other provinces that recorded high levels, with rice mechanization index of 3.0 to 4.0 hp/ha, were Cagayan, Isabela, Quirino, Tarlac, Cavite, Albay, Sorsogon, Bohol, Misamis Occidental, Misamis Oriental, Davao del Sur, Davao de Oro and Davao Oriental. Majority of the provinces (41%) have mechanization index ranging from 2.0 to 3.0 hp/ha. Meanwhile, 15 provinces (26%) have less than 2.0 hp/ha mechanization level. These provinces were Aurora, Palawan, Antique, Southern Leyte, Zamboanga del Sur, Zamboanga Sibugay, Davao del Norte, North Cotabato, Sultan Kudarat, South Cotabato, Agusan del Norte, Agusan del Sur, Surigao del Sur, Maguindanao and Lanao del Sur.

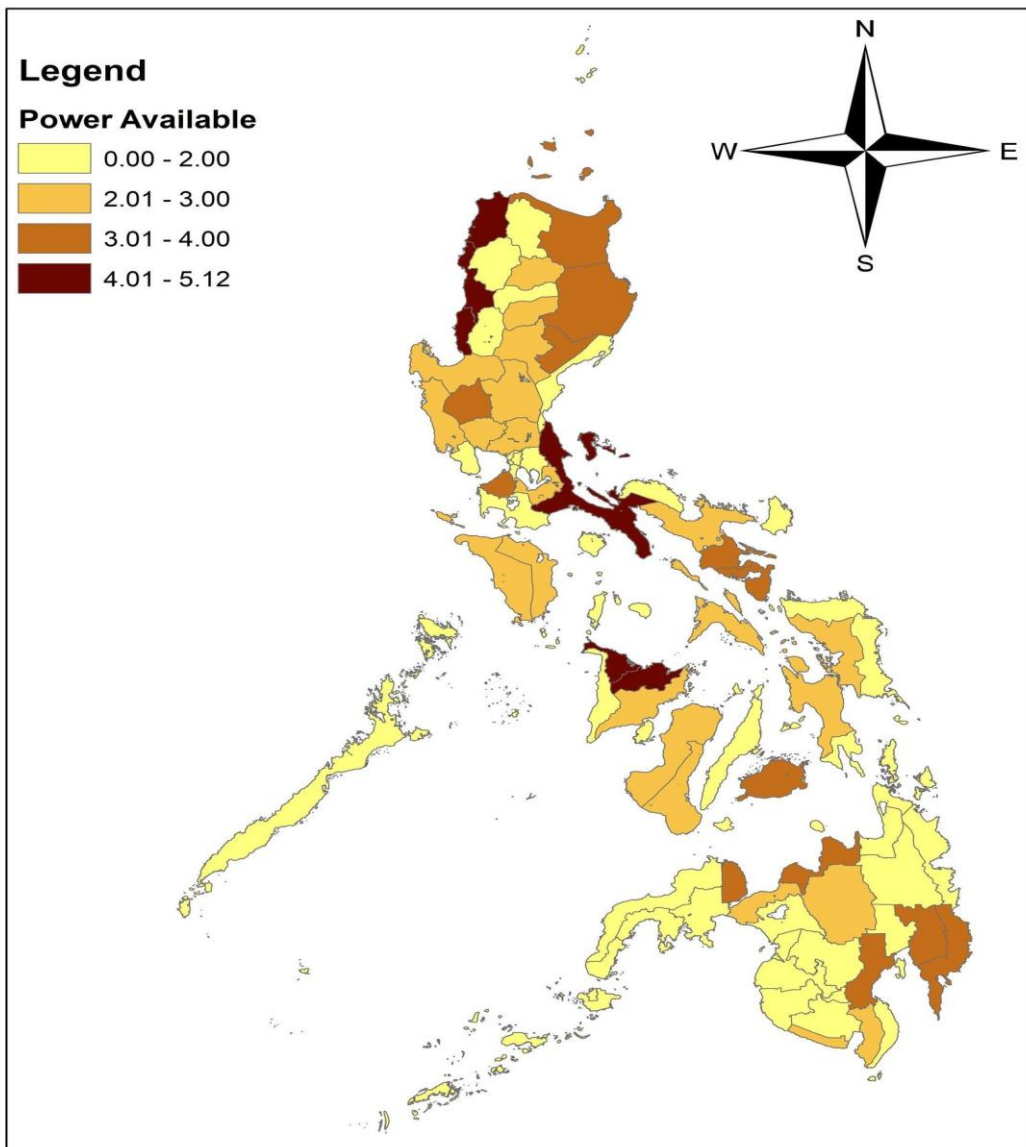


Figure 6. Level of rice mechanization per province based on power available, Philippines.

In terms of regional data on the level of rice mechanization, Region II (Cagayan Valley) recorded the highest level of mechanization based on power available while the Bangsamoro Autonomous Region of Muslim Mindanao (BARMM) registered the lowest mechanization level (Fig. 7). Other regions that have relatively high levels of mechanization includes Region IV-(CALABARZON), Region I (Ilocos Region), Region VII (Central Visayas) and Region V (Bicol Region). The regions that approximate the national average were Region III (Central Luzon), Region XI (Davao Region), and Region VI (Western Visayas). Meanwhile, the Cordillera Administrative Region (CAR), Region IV-B (MIMAROPA), Region VIII (Eastern Visayas), Region X (Northern Mindanao), Region IX (Zamboanga Peninsula), Region XII (SOCCSKSARGEN), CARAGA, and BARMM recorded mechanization indices lower than the national average. Moreover, four regions in Mindanao – Region IX (Zamboanga Peninsula), Region XII (SOCCSKSARGEN), CARAGA, and BARMM all recorded less than 2.00 hp/ha mechanization index.

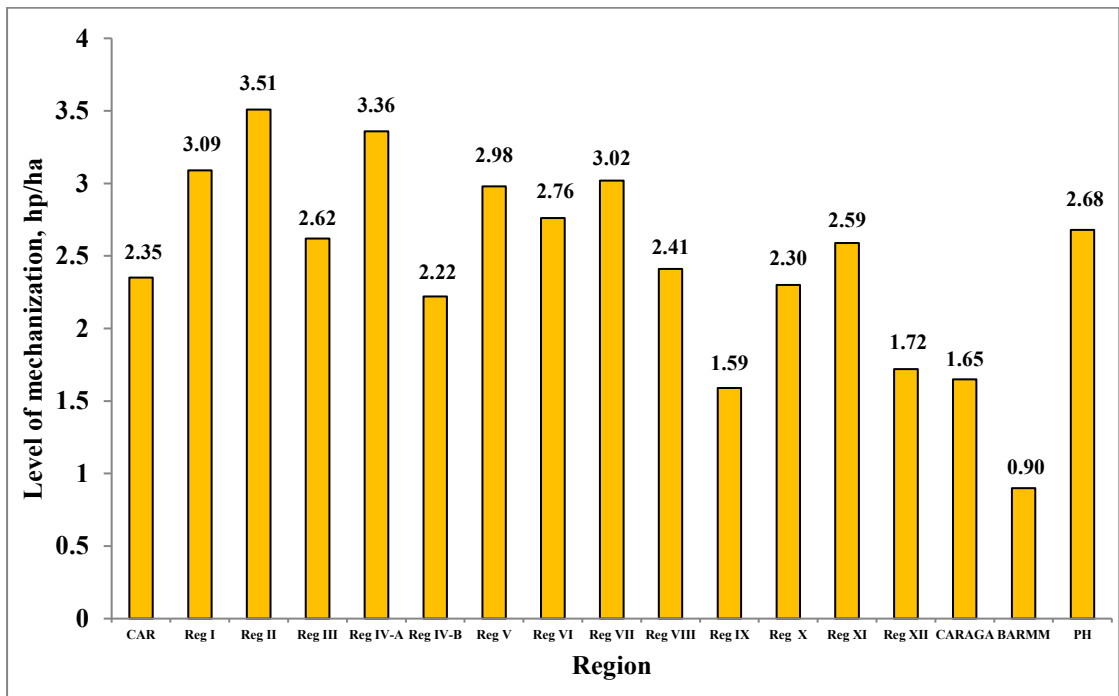


Figure 7. Level of mechanization per region based on power available, Philippines, hp ha^{-1}

Among the sources of power, mechanical power accounts for 84% of the total power available, 11% from animal power and 5% from human power (Fig. 8).

Comparing the national rice mechanization level for 2011 and 2022, mechanical power increased by 0.49 hp/ha while the two other sources of power slightly decreased by 0.02 hp/ha and 0.10 hp/ha , for human and animal power, respectively (Fig. 9). Since 2011, mechanical power increased by 28% while human power declined by 13% and animal power also decreased by 26%. The intensification of mechanical power could be attributed to the growing popularity of larger machinery, such as the use of rice combine harvesters and four-wheel tractors as promoted by the DA rice banner program and RCEF mechanization component. The adoption of machines in rice farm operations as influenced by increasing wage rates, also provides an incentive to enterprising individuals to acquire machines for a custom service provision business. Because of the increase in mechanical power, the other sources of power decreases as a consequence of using labor and draft animal-replacing technologies.

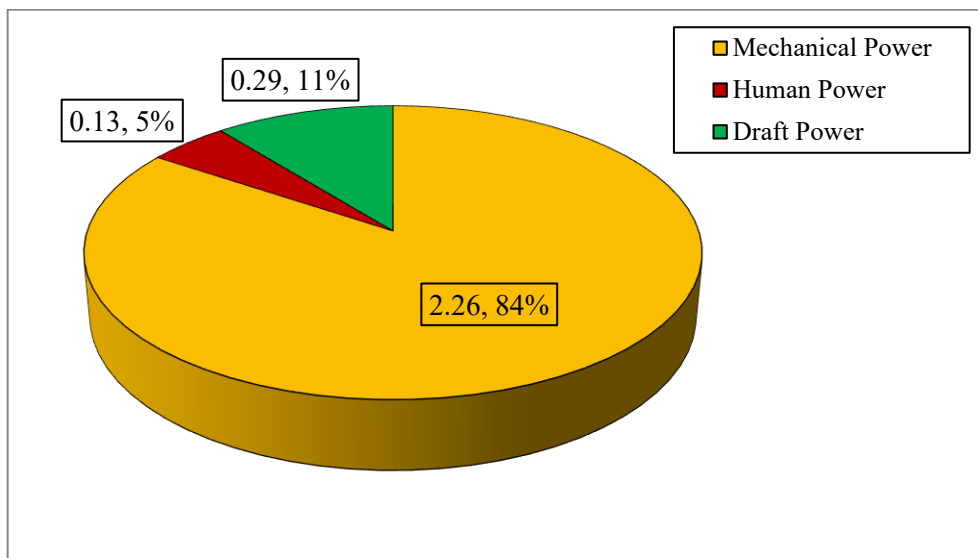


Figure 8. Contribution of mechanical, draft and human power to total power available for rice farm operations, Philippines, 2022

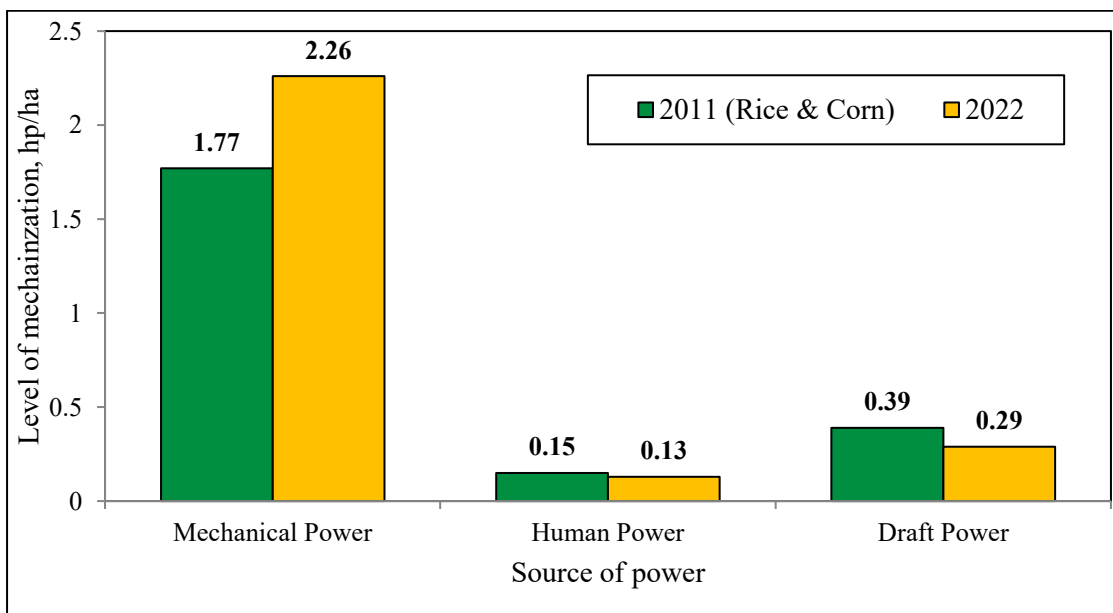


Figure 9. Change in rice level of mechanization based on power sources, 2011 and 2022

Overall, the rice mechanization level in the country improves from 2.31 hp/ha in 2011 to 2.68 hp/ha in 2022, exhibiting a 16% growth rate for the period (Fig. 10). As of October, 2025, the level of rice mechanization was estimated at 2.81 hp/ha.

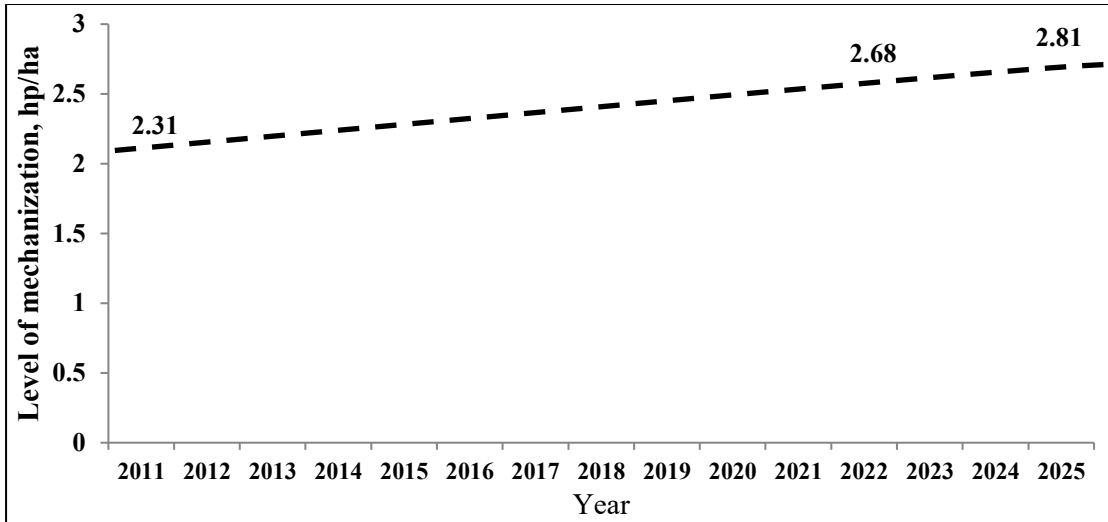


Figure 10. Overall increase in the rice level of mechanization, 2011, 2022, and 2025

Mechanization based on power ratio. Using the power ratio as an indicator of mechanization level, four regions recorded higher than 90% power ratio. These regions include Region II (Cagayan Valley), Region I (Ilocos Region), Region III (Central Luzon) and Region IV-A (CALABARZON) (Fig.11). Meanwhile, Region VI (Western Visayas) and CARAGA regions registered 80% to 90% power ratio. Other regions that had above 70% to 80% power ratio were CAR, Region IV-A, Region V, Region VII, Region VIII, and Region X. Four regions in Mindanao that include Region IX, Region XI, Region XII and BARMM had less than 70% power ratio. This indicates the relatively high application of draft and manual power in these areas.

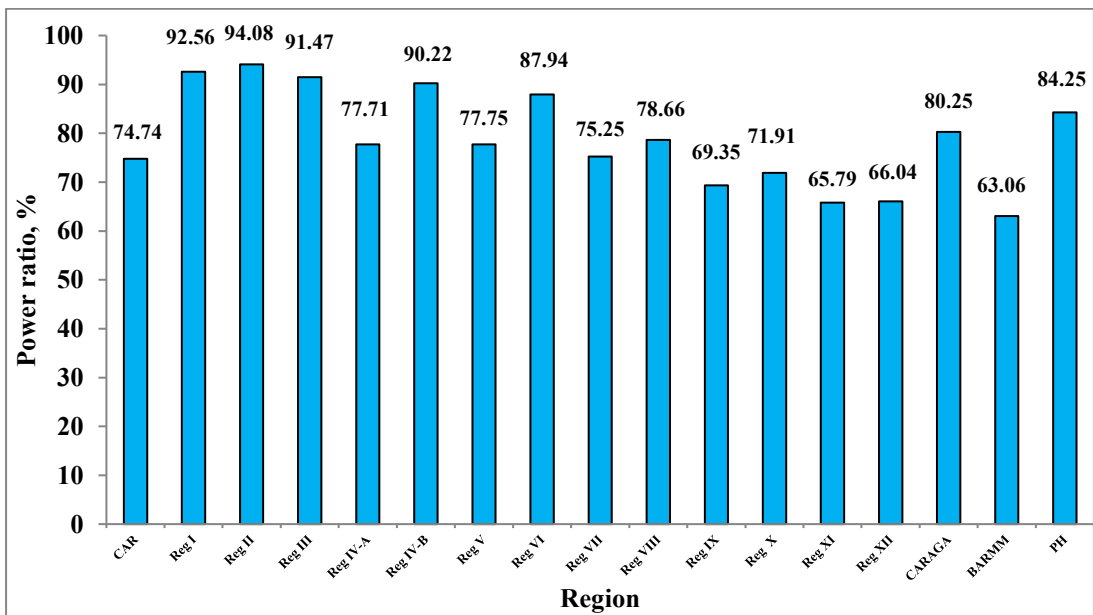


Figure 11. Level of mechanization per region based on power ratio, Philippines, 2022

Mechanization based on the percent of rice farm area mechanized. The percentage of rice farmers mechanizing farm operations was highest in land preparation (77.59%) (Table 4). This is consistent with other research findings indicating that the most difficult farm operations are mechanized first. The development and local fabrication of affordable two-wheel tractors enable farmers to acquire machines, hence, the fast uptake of technology adoption. In terms of land preparation, all regions have more than 50% mechanization degree but relatively high rates of adoption for hand tractor and four-wheel tractors were noted in Region III (Central Luzon), Region II (Cagayan Valley), Region XI (Davao Region), Region I (Ilocos Region), Region VI (Western Visayas), Region IV-B (MIMAROPA) and Region IV-A (CALABARZON). The lowest mechanization degrees were observed in CAR and Region VII (Central Visayas) regions, with less than 60% of farmers using machines in land preparation.

While mechanization of harvesting operations had just started several years ago, the rate of technology diffusion has been dramatic since the introduction of rice combine harvesters in the country. PhilMech study revealed that in 2013, only 3% of rice farmers were using RCH and this figure ballooned to 53.66% in 2022. High rates of technology adoption were noted in Region III (Central Luzon), Region II (Cagayan Valley), Region IV-B (MIMAROPA) and CARAGA. The percentages of farms utilizing engine-powered machines in crop establishment were still very low in all regions.

This situation reflects a common pattern in some Asian countries such as China, Pakistan, India and Bangladesh, where rice mechanization tends to progress unevenly among different farm operations. Land preparation and harvesting are typically mechanized earlier, while planting and crop care continue to lag behind (Khan and Rehman 2019; Shi et al. 2021).

The uneven pace of mechanization can be attributed to several factors, including the nature and complexity of specific tasks, as well as the availability and cost of manual labor, draft animals, and farm machinery. Although the cost of mechanized transplanting or seeding is often lower than that of traditional manual methods, adoption remains constrained by technological and practical challenges. These include the intricacies of seedling preparation, the need for thorough land preparation and effective maintenance of irrigation and drainage, issues with achieving optimal planting density, entrenched farming practices, and topographical limitations.

Table 4. Percent of rice farms mechanizing different farm operations, selected rice-producing regions, 2021-2022

REGION	OPERATION		
	Land Preparation ^L	Crop Establishment	Harvesting-Threshing
CAR	54.50	2.67	39.94
Ilocos Region	86.01	1.26	66.12
Cagayan Valley	90.32	3.05	74.76
Central Luzon	91.10	4.01	86.61
CALABARZON	83.90	2.32	60.74
MIMAROPA	84.07	2.90	77.15
Bicol Region	78.27	6.40	38.01
Western Visayas	85.57	7.07	37.37

REGION	OPERATION		
	Land Preparation ^L	Crop Establishment	Harvesting-Threshing
Central Visayas	58.50	3.00	19.50
Eastern Visayas	71.53	4.92	38.63
Zamboanga Peninsula	72.37	2.62	45.38
Northern Mindanao	77.65	5.41	45.60
Davao Region	86.41	6.33	56.04
SOCCSKSARGEN	77.37	3.77	54.12
CARAGA	75.56	4.56	78.57
BARMM	68.26	1.20	40.10

^L Plowing and harrowing, including preparation of the seedbed.

CONCLUSION

This study provided an up-to-date and comprehensive assessment of the status of rice mechanization in the Philippines using machinery intensity, available power, power ratio, and percentage of area mechanized as key indicators. Philippine rice production is slowly but steadily transitioning toward a more mechanized and machine-dependent production system. These trends reflect sustained progress in the modernization of rice farming and the increasing role of mechanization in enhancing production efficiency and reducing labor dependence. Nevertheless, mechanization development remains highly uneven across regions and provinces, indicating persistent disparities in access to machinery, mechanization services available, and supporting infrastructure.

Among rice production operations, land preparation exhibited the highest mechanization level, reflecting the widespread and sustained adoption of hand tractors and four-wheel tractors. Harvesting and threshing also showed substantial mechanization gains, driven largely by the rapid diffusion of rice combine harvesters. In contrast, crop establishment remained the least mechanized operation nationwide, suggesting continuing technological, operational, and economic constraints in mechanized transplanting and direct-seeding systems. This mechanization pattern is consistent with experiences in other Asian countries, where mechanization is generally adopted first in highly labor-intensive operations, whereas crop establishment progresses more slowly because of greater technical complexity, higher operational requirements, and the limited availability of suitable machinery and mechanization systems.

Overall, the study highlighted significant advancements in rice mechanization in the Philippines while revealing critical regional and operational gaps that may constrain the broader transformation of the rice sector. There is a need for more targeted and location-specific mechanization strategies, including the development and dissemination of appropriate machinery, strengthened machinery service provision, improved financing mechanisms, and enhanced technical and institutional support systems. Addressing these constraints will be essential to achieving more inclusive, balanced, and sustainable mechanization across all stages of rice production and postproduction operations, thereby contributing to improved productivity, labor efficiency, and long-term competitiveness of the Philippine rice industry.

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BIOLOGY OF THE RED- STRIPED SOFT SCALE INSECT, *Pulvinaria tenuivalvata* (Newstead) (HEMIPTERA: COCCIDAE), AN EMERGING PEST OF SUGARCANE IN THE PHILIPPINES

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ABSTRACT

The red-striped soft scale insect, *Pulvinaria tenuivalvata* (Newstead), has recently become a major threat to sugarcane production in the Philippines, causing concern among growers in Luzon and Negros Island regions. The present study was undertaken from August 2025 to January 2026 to document the biology of the pest on sugarcane under laboratory conditions. The results revealed that the incubation period of the egg was 2 to 3 days. The nymphs passed through three nymphal instars, with durations of 5 to 6 days each for the first and second nymphal instars, and 4 to 5 days for the third nymphal instar. The total nymphal period lasted about 16 to 19 days. All adults produced were females; the young adult female lasted 8 to 15 days, mature adult 17 days and senescing adult lasted 14 days. Total adult period was 44 to 46 days. Total developmental periods (egg to death) were 63 days. The number of eggs produced by female adults was about 197 eggs. All progenies observed were females, confirming parthenogenetic reproduction, thelytochus type. Extensive morphological and behavioral observations, supported by photographic documentation, revealed gradual changes in color, body shape, and dorsal features from hatching to adult maturity, providing critical baseline data for identifying life stages and monitoring population development. The information generated on durations of developmental stages, reproductive capacity, and adult longevity is essential for understanding population dynamics and predicting infestation patterns. These findings are particularly important for timing control measures, targeting vulnerable stages, and evaluating the potential role of biological control agents under Philippine conditions. The results also provide a scientific basis for developing monitoring protocols, improving identification of developmental stages in the field, informed decision-making, and the development of sustainable approaches to managing *P. tenuivalvata* populations and minimizing potential impacts on sugarcane productivity and farmers' income.

Key words: developmental period, invasive pest, parthenogenesis, *Saccharum officinarum*

INTRODUCTION

Pulvinaria tenuivalvata (Newstead) (Hemiptera: Coccoomorpha: Coccidae), commonly referred to as the red-striped soft scale insect (RSSI; also referred to as red-striped soft scale, RSSS, in earlier literature; Watson and Foldi 2002), is becoming one of the most important invasive, polyphagous insect pests attacking sugarcane in the Philippines. It poses a threat to sugarcane cultivation, alarming growers in Luzon Island (Navasero et al. 2023; Guerrero et al., 2024) and Negros Island region (SRA 2025). Originally recognized as a major pest in Egypt since the mid-1990s, the species damages

sugarcane directly by sap extraction and indirectly by honeydew excretion, which promotes sooty mold growth, interferes with photosynthesis, causes leaf withering, and reduces yield and sucrose content (Watson and Foldi 2002; Ghabbour and Hodgson 2000; Ali et al. 2000).

Pulvinaria tenuivalvata was described by Newstead in 1911 as *Lecanium tenuivalvatum* on citronella grass and elephant grass in Uganda and was later redescribed and illustrated by De Lotto in 1965 and Williams in 1982 (Ghabbour and Hodgson 2000). A key was provided by Williams (1982) as cited by Ghabbour and Hudson (2000) for the five species of *Pulvinaria* infesting Poaceae, namely, *P. iceryi* (Signoret), *P. sorghicola* De Lotto, *P. elongata* Newstead, and *P. tenuivalvata* (Newstead). Moreover, Ghabbour and Hodgson (2000) described and illustrated mounted specimens of the three nymphal instars of *P. tenuivalvata* with an accompanying key while Abdel-Razak et al. (2017) provided a detailed redescription and illustration of the adult female. A related name, *Pulvinaria saccharia* De Lotto, 1964, described from sugarcane in South Africa, was later synonymized with *P. tenuivalvata* (Abdel-Razak et al. 2017). Several misidentifications have also been recorded in the literature, including *Pulvinaria elongata* (Karem and El-Kahier 1992) and *Saccharolecanium krugeri* (Ali et al. 1997), underscoring the taxonomic complexity of the species.

Pulvinaria tenuivalvata is widely distributed across Africa and parts of Asia, with records from Egypt (El-Serwy et al. 2008; Ghabbour and Hodgson 2002; Watson and Foldi 2002), Ethiopia (De Lotto 1959), Kenya (De Lotto 1966), Mali (Ben-Dov 1993; Gavrilov-Zimin and Stekolshikov 2018), Senegal (Étienne and Matile-Ferrero 1993), Sierra Leone (Ben-Dov 1993), South Africa (De Lotto 1964), Tanzania (Ben-Dov 1993), Uganda (De Lotto 1965; Newstead 1911; Sasscer 1912), Zimbabwe (Hodgson 1967a; Hodgson 1969a), and the Philippines, where it has been documented in Luzon (Navasero et al. 2023) and Negros (Mago 2025). The species exhibits a broad host range across at least three plant families, with a strong association with Poaceae. Major hosts include sugarcane (*Saccharum officinarum*) (De Lotto 1964; De Lotto 1966; El-Serwy et al. 2008; El-Shazly et al. 2005; Hodgson 1967a), rice (*Oryza sativa*) (Étienne and Matile-Ferrero 1993; Williams 1982), maize (*Zea mays*) (El-Shazly et al. 2005), sorghum (*Sorghum bicolor*) (Étienne and Matile-Ferrero 1993), and several grasses such as *Cymbopogon citratus* (De Lotto 1965; Newstead 1911), *Imperata cylindrica* (El-Shazly et al. 2005), and *Pennisetum purpureum* (Gowdey 1917). Additional hosts from other families include *Convolvulus arvensis* (Convolvulaceae) (Abd-Rabou and Evans 2021) and *Sida acuta* (Malvaceae) (Navasero et al. 2023), indicating its polyphagous nature and capacity to persist in diverse agroecosystems. The morphology and systematics of *P. tenuivalvata* have been well studied (Watson and Foldi 2002). Diagnostic characters distinguishing this species from closely related taxa, such as *Saccharolecanium krugeri*, include differences in spiracular setae, dorsal setae morphology, leg proportions, claw dentition, and anal opening structure (Watson and Foldi 2002; Ali et al. 1997). The adult female is elongate-oval, measuring approximately 3.4–6.5 mm in length, with a membranous derm, shallow anal cleft, and poorly developed stigmatic clefts.

Soft scale insects (Hemiptera: Coccidae) constitute a diverse and economically important group of sap-feeding insects, many of which are serious agricultural pests (Kakoti et al. 2023). Continuous taxonomic studies have revealed considerable diversity within this group, with new species and genera still being described from different regions of the world (Kondo et al. 2026).

Sugarcane, *Saccharum officinarum* L. (Poaceae) and several other grasses, such as *Imperata cylindrica* (L.) Beauv. have been documented as host plants of *P. tenuivalvata*. However, studies have demonstrated a strong preference for sugarcane, emphasizing its economic importance (Abdel-Rahman et al. 2016). In the Philippines, additional host plants serving as bridging hosts—*Megathyrus maximus*, *Rottboellia cochinchinensis*, and *Sida acuta*—have been reported in infested sugarcane fields (Navasero et al. 2023; Guerrero et al. 2024).

The pest is active from May until December (Ghabbour and Hodgson 2000; Watson and Foldi 2002). It is parthenogenetic, and each female produces about 200 eggs. The RSSI is attacked by several aphelinid endoparasitoids, the more important are *Coccophagus scutellaris* (Dalman) and *Coccophagus semicircularis* (Förster) (Hymenoptera: Aphelinidae), which may kill up to 70% of the scales (Abd-Rabou 2011, 2008; Shalaby and Saleh 2009). Earlier, El-Samea (2006) reported an indigenous species, *Coccophagus ochraceus* Howard, as endoparasitoid of RSSI but not evaluated its impact on the pest. The neuropteran *Nimboa adela* (Monserrat) (Neuroptera: Coniopterygidae) was also reported as a predator of RSSI in Egypt (El-Serwy and Monserrat 2009). These natural enemies can play important roles in biological control when conserved or incorporated into integrated pest management programs. A proper understanding of soft scale insect biology is essential for accurate identification of the different nymphal stages, which are critical for monitoring pest populations and determining appropriate management timing (Ghabbour and Hodgson 2000; Abdel-Razak et al. 2017). Although Abd El Samea (2004) reported on the biological parameters of *P. tenuivalvata* reared on sugarcane under laboratory conditions in Egypt, the data generated cannot apply under Philippine conditions due to differences in environmental conditions, variety and cultural practices, among others, in sugarcane cultivation. This study, therefore, aims to generate local data on life history traits and habits/behavior that are crucial for the development of effective strategies for managing pest populations in sugarcane fields in the country.

The importance of this study lies in addressing the urgent need for locally generated scientific information on the biology, ecology, and behavior of *P. tenuivalvata* under Philippine agroecological conditions. As the pest continues to expand its distribution in major sugarcane-growing regions, the absence of region-specific biological data limits the development of effective monitoring systems, economic threshold levels, and integrated pest management (IPM) strategies. Understanding the pest's life history traits, including reproductive capacity, seasonal activity, and developmental stages, will allow for accurate timing of control measures, particularly targeting vulnerable nymphal instars thereby improving management efficiency and reducing unnecessary pesticide applications.

Moreover, documenting the pest's interaction with local natural enemies and environmental factors is essential to evaluate the potential role of biological control agents under Philippine conditions. While parasitoids such as *Coccophagus scutellaris* (Dalman) and *Coccophagus semicircularis* (Förster) have demonstrated significant impact elsewhere (Abd-Rabou 2011; Shalaby and Saleh 2009; Abd-Rabou 2008), their effectiveness, establishment, and ecological compatibility in local ecosystems remain insufficiently understood. Generating such knowledge can support the conservation or introduction of beneficial organisms and strengthen sustainable pest management approaches.

In addition, the economic implications of *P. tenuivalvata* infestation underscore the importance of this research. By reducing photosynthetic efficiency through honeydew accumulation and sap depletion (Ghabbour and Hodgson 2000; Watson and Foldi 2002), the pest directly threatens yield and sucrose content (Ali et al. 2000), which may affect farmer income, milling efficiency, and overall sugar industry productivity. Localized research will enable the formulation of evidence-based recommendations tailored to Philippine sugarcane varieties, climatic conditions, and cultivation practices, ensuring that management strategies are practical and effective for growers.

This study aimed to characterize the biology, developmental stages, and reproductive capacity of *Pulvinaria tenuivalvata* on sugarcane under laboratory conditions and to generate baseline information useful for pest monitoring and integrated pest management development. The study contributes to the scientific understanding of this emerging invasive pest by providing essential biological data needed for the development of effective management strategies. Addressing existing knowledge gaps, the findings support early detection, evidence-based decision-making, and the development of long-term integrated pest management approaches aimed at minimizing economic losses while promoting environmentally sound control practices.

MATERIALS AND METHODS

Test insect. Samples of *P. tenuivalvata* were obtained from the existing population in the screenhouse, collected from sugarcane fields in Batangas and Laguna, Luzon Island, Philippines which have been maintained since 2023 until now. The use of an established colony ensured a continuous and reliable source of experimental insects, allowing consistency in observations while minimizing variability associated with newly collected field populations. Maintaining the colony over an extended period also enabled the insects to acclimatize to controlled laboratory rearing conditions, thereby facilitating detailed monitoring of their developmental stages and biological traits.

The insects were reared at 27–29°C at 60–70% RH, and 12D:12D photoperiod, to approximate environmental conditions favorable for sugarcane cultivation and scale insect development. Maintaining stable temperature, humidity, and light regimes allowed the study to minimize environmental variability and ensured that observed biological responses were attributable primarily to intrinsic developmental processes rather than external fluctuations. Such controlled rearing conditions are essential for generating reproducible data on life history traits, developmental timing, and behavior, which are critical for understanding the biology of *P. tenuivalvata* and for developing effective management strategies.

Life history study. Infested leaves of sugarcane from the greenhouse were detached and brought to the laboratory to allow close handling and standardized processing under controlled/laboratory conditions. Adult females were turned upside down using a micro pin, and the eggs were dislodged onto small plastic plates for holding and incubation. This careful manipulation ensured minimal damage to the eggs while allowing efficient collection and separation from the maternal body. Isolating the eggs on plastic plates provided a clean and observable environment where hatching could be monitored accurately.

After hatching, any remaining unhatched eggs were carefully removed using a fine-pointed camel's hairbrush, and the plate containing the crawlers was placed between the leaf and stem of a potted seedling to allow them to transfer freely onto the plant. The use of a soft camel's hairbrush minimized physical injury to delicate crawler-stage nymphs, which are highly mobile yet fragile. Positioning the plates between the leaf and stem simulated natural conditions and encouraged voluntary movement of crawlers onto the host plant, reducing handling stress and ensuring successful establishment. At least 200 crawlers per potted sugarcane seedling were transferred in this manner to maintain adequate sample size and to ensure sufficient individuals for monitoring survival, development, and behavioral observations. Ten potted seedlings were prepared and labeled consecutively from 1 to 10.

After 24 h of infesting newly hatched crawlers and daily thereafter, 20 individuals were observed under the microscope, and pictures were taken using an iPad attached to the microscope (Zeiss, Stemi 305). The initial 24 h interval allowed the crawlers to settle and establish on the host plant before detailed observations commenced, ensuring that measurements and documentation reflected normal development rather than handling-induced stress. Daily observations thereafter enabled continuous tracking of morphological changes and developmental progression throughout the insect's life cycle.

Microscopic examination provided clear visualization of external morphological features, while digital imaging facilitated accurate documentation of each developmental stage. Measurements of the head, body length, and body width (in millimeters) were taken from individual images to ensure precision and consistency. Using photographic records minimized repeated handling of live specimens and allowed measurements to be verified or reanalyzed, if necessary, thereby improving data reliability.

Molting events were closely monitored, and the developmental periods and durations of the different stages (in days) were recorded and computed. Careful documentation of each molt made it possible to distinguish between successive instars and to determine the length of time spent in each stage. These data are essential for understanding growth patterns, stage-specific development rates, and the timing of vulnerable life stages that may be targeted in management strategies.

Morphological documentation. From the day of hatching until the death of the last adult in the culture, at least 20 individuals were photographed daily using an iPad attached to a microscope to document salient behavioral patterns and morphological changes throughout the life cycle of RSSI. Continuous photographic documentation from emergence to adult death ensured that all developmental stages were recorded systematically, allowing detailed observation of gradual morphological transformations as well as behavioral patterns associated with feeding, movement, settlement, and molting. This approach provided a visual record that complemented numerical measurements and facilitated accurate stage identification, particularly for subtle transitions between instars.

Capturing images throughout the life cycle also allowed comparison among individuals and across time, helping to identify variation in development and behavior within the population. The use of an iPad attached to a microscope enabled efficient image capture while maintaining sufficient magnification and clarity for analysis, ensuring that fine morphological features could be examined without excessive disturbance to the insects. Photographic records further served as permanent reference material that could be used for validation, illustration, and future comparative studies involving RSSI or related scale insect species.

About 3,000 photographs were taken from the egg stage until death of RSSI, representing a comprehensive visual dataset documenting the biology of the species under laboratory conditions. This extensive collection of images supports accurate interpretation of life history traits and provides valuable material for describing morphological characteristics, developmental stages, and enhancing understanding of the habits and behavior of RSSI throughout its life cycle.

Oviposition in RSSI. Adult female RSSI were monitored for oviposition from the day they molted into adults until the end of their lifespan. Eggs were observed on the ventral aspect of the female body and made visible by gently puncturing the cuticle using a bent micro pin. Dislodged eggs were collected onto small plastic plates for incubation. After hatching, the remaining unhatched eggs were removed using a fine-pointed camel's hairbrush, and crawlers were transferred onto potted sugarcane seedlings to allow natural settlement and feeding. The number of eggs and timing of oviposition were recorded daily, and representative photographs of egg deposition and ovisacs were captured using an iPad attached to a microscope. Counting started on the fourth day after molting of the third nymphal instar into young adult until the 29th day, allowing documentation of the onset, duration, and pattern of oviposition under laboratory conditions (27–29°C, 60–70% RH, 12D:12D photoperiod). Daily egg counts from the fourth day until the 29th represented the total number of eggs laid per female throughout its reproductive period.

Longevity of RSSI adults. Adult female RSSI were monitored from the day of adult emergence until death. Individuals were maintained on potted sugarcane seedlings under laboratory conditions (27–29°C, 60–70% RH, 12D:12D photoperiod). Daily observations were made to record survival, and any morphological or behavioral changes were documented. Photographs of at least 20 individuals were taken using an iPad attached to a microscope to capture developmental and behavioral traits throughout their lifespan. Adult longevity was recorded in days for each individual RSSI until all test insects had died. Adult longevity was recorded, providing information on the lifespan of adult females under controlled conditions. This parameter is critical for estimating reproductive potential and population growth, especially for a parthenogenetic species such as *P. tenuivalvata*.

Statistical analysis. The experiments were laid out in Completely Randomized Design (CRD). Mean values and standard deviations for the data on egg, nymphal and adult measurements, and egg counts of *P. tenuivalvata* were calculated to summarize developmental characteristics and variability among individuals. These descriptive statistics were essential for interpreting developmental trends, comparing life stages, and presenting quantitative evidence supporting the biological observations generated in the study. Two trials were conducted to validate the consistency and reproducibility of the observations, allowing comparison between trials and strengthening the robustness of the results generated from the study.

RESULTS AND DISCUSSION

Life cycle of RSSI. The RSSI underwent the egg, three nymphal instars, and adult stages observed across the two trials in the biological culture experiment, and the life cycle is shown in Figure 1.

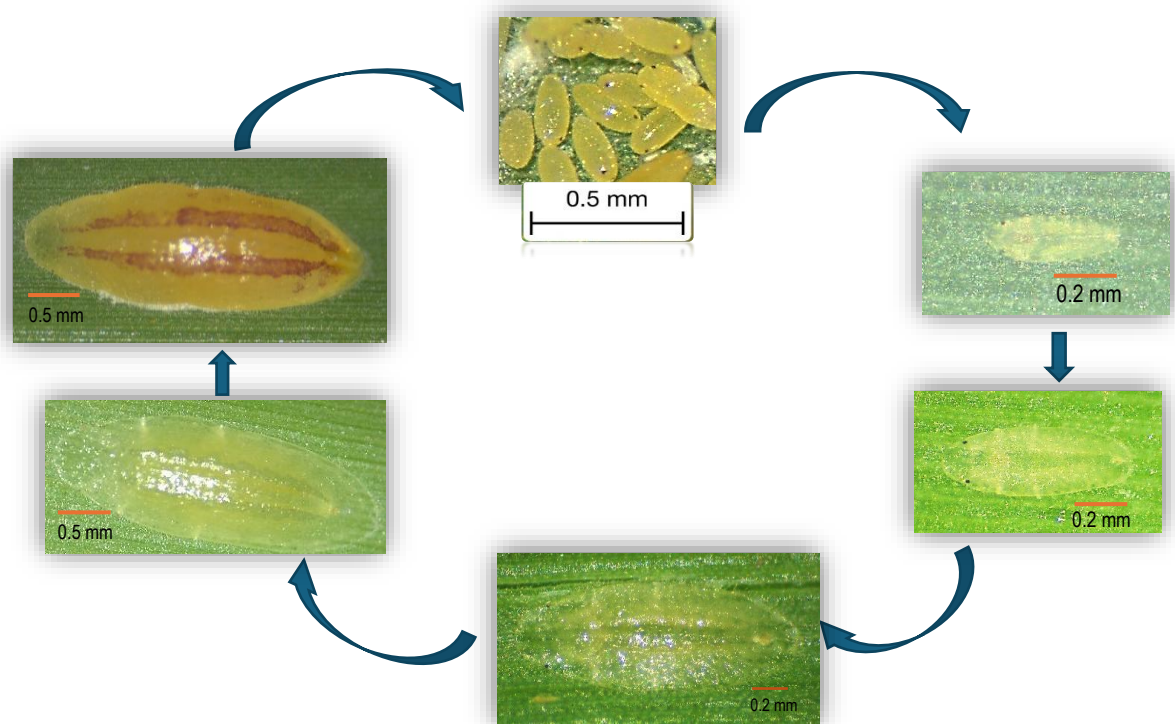


Figure 1. Life cycle of *Pulvinaria tenuivalvata*: a) eggs, b) first instar nymph, c) second instar, d) third instar, and adult (e) young, f) mature

The egg. Eggs are small, cylindrical with rounded ends; light yellow when newly laid turning darker when about to hatch (Fig. 2 and Table 1). The anterior portion of the egg is visible through two dark eye spots on the dorsum; each 0.27 ± 0.01 mm in length and 0.12 ± 0.00 mm in width; hatched in 2 to 3 days.

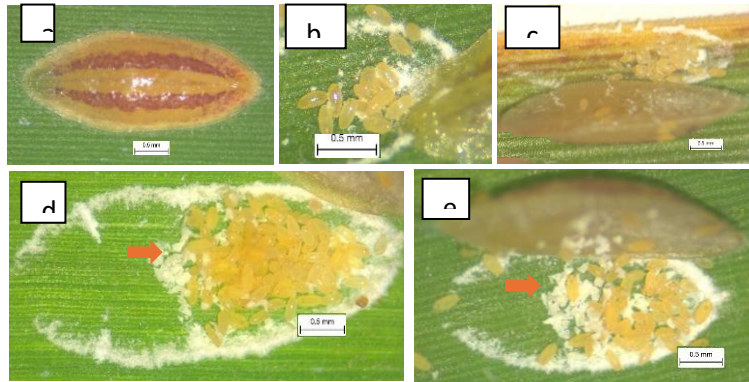


Figure 2. Eggs of (a) *Pulvinaria tenuivalvata*: b, c) newly laid eggs, d, e) egg clusters with newly hatched neonates as indicated by white chorions (orange arrows).

The nymph. No significant changes in body color among the nymphal instars were observed, except for the first instar or crawler stage (Fig. 3). The first-instar nymphs exhibit yellowish body color upon hatching, transforming to hyaline after 48 hours (Fig. 3a). First-instar nymphs with a very long apical seta on each anal plate. The initial yellowish coloration likely reflects newly emerged crawler-stage physiology, while the transition to a hyaline appearance indicates cuticular development and adaptation after settlement. This change may also be associated with feeding initiation and stabilization on the host plant.

However, upon transforming or molting to the second-instar nymph, subtle changes were observed, such as the eyes becoming smaller but solid, observed along the lateral side of the dorsum (Fig. 3b), accompanied by an elongated body form and settlement in a preferred feeding site toward the midrib on the nether surface of sugarcane leaf. These morphological changes suggest progression toward a more sessile feeding habit, with structural adaptations that favor attachment and sustained sap feeding. The third-instar nymph is similar in color and shape to the second-instar nymph but larger in size (Fig. 3c) and likewise settled on the preferred feeding site, indicating continued growth without dramatic external color differentiation. The body of the three nymphal stages was generally flattened, a characteristic that may facilitate close adherence to the leaf surface and reduce exposure to environmental disturbances.

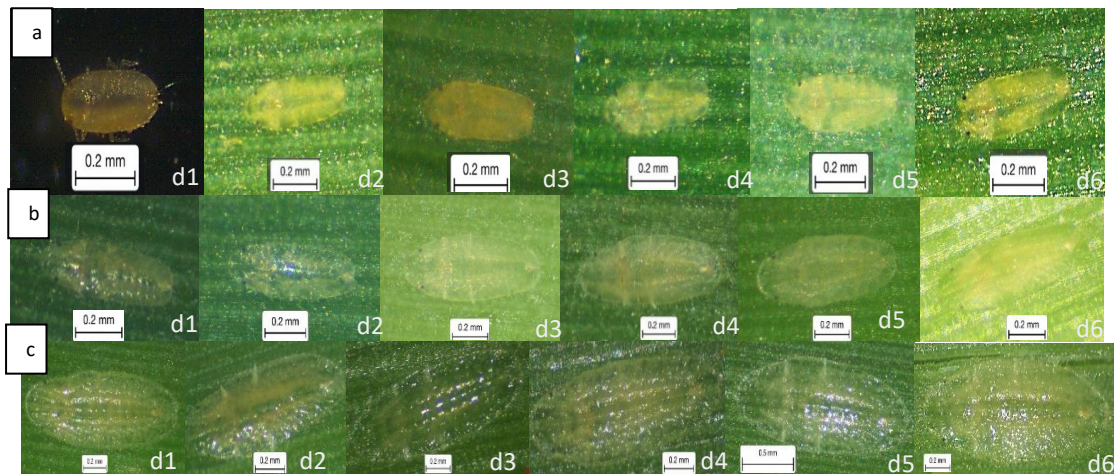


Figure 3. *Pulvinaria tenuivalvata*: first instar nymph (a) at day 1 to 6 (d1 to d6); second instar (b) at day 1 to 6 (d1 to d6); and third instar (c) at day 1 to 6 (d1 to d6).

The crawler stage or first-instar nymph is highly mobile, settling only for a while to suck plant sap then moved again upward along the leaf and settled when about to molt to the second instar. The preferred site was usually the youngest leaf along the midrib, and at the middle part of the nether surface. Nevertheless, both the second- and third-instars nymphs are stationary in their feeding sites, but changed feeding sites when disturbed, indicating retained mobility despite their tendency toward a more sedentary lifestyle. This behavior suggests an adaptive response that allows individuals to relocate to favorable feeding positions or escape unfavorable conditions. The first- and second-instar nymphs with attached molted skin on their dorsum, with very thin, hyaline-white chlorotic exuviae that were readily dislodged when touched or agitated are shown in Figure 4. The presence of exuviae provides clear visual confirmation of molting events and served as a useful diagnostic feature for identifying recently molted individuals.

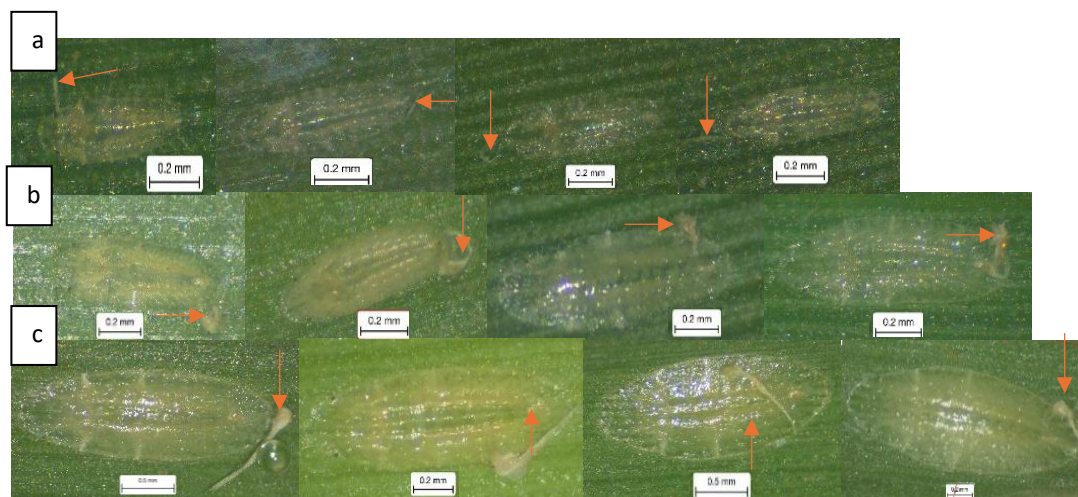


Figure 4. Representative samples of molting in *Pulvinaria tenuivalvata*: from first instar to second (a), second instar to third (b), and third instar to adult (c). Molted skin indicated by an arrow

The adult female. The elongated body of the young adult female was initially light yellow (Figure 5a), which later becomes convex and darker, with two distinct longitudinal light red to deep red stripes on the dorsum (Figure 5b and 5c). These progressive changes in body shape and pigmentation reflect maturation and physiological development toward the adult reproductive stage. The scale oviposited into a thin, whitish ovisac surrounding the periphery of the female's body (Figure 6). The microscopic morphological features of the adult RSSI (dorsal setae conical; the ventral tubular ducts narrow, submarginal, and the anal plates longer than wide) have been discussed in Navasero et al. (2023) and Guerrero et al. (2024). These morphological characteristics are important diagnostic features for species identification and provide additional confirmation of RSSI identity while also describing structural adaptations associated with reproduction, protection, and secretion. Such morphological structures are widely used as key diagnostic characters in the taxonomy and identification of soft scale insects (Coccidae), where detailed examination of dermal structures and tubular ducts is essential for distinguishing species and understanding relationships among taxa (Kondo et al. 2026).

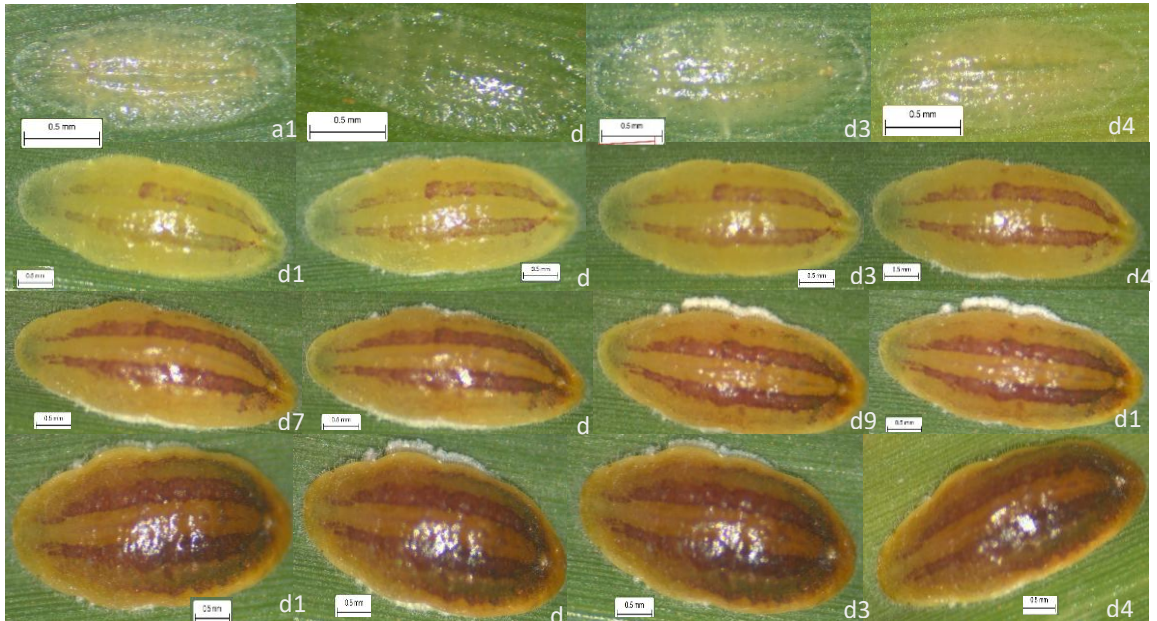


Figure 5. Adult female morphology of *Pulvinaria tenuivalvata*. (a) Newly emerged young adult female with an elongated, light-yellow body; (b) female exhibiting distinct longitudinal light red dorsal stripes; (c) female showing prominent deep red dorsal stripes along the dorsum.

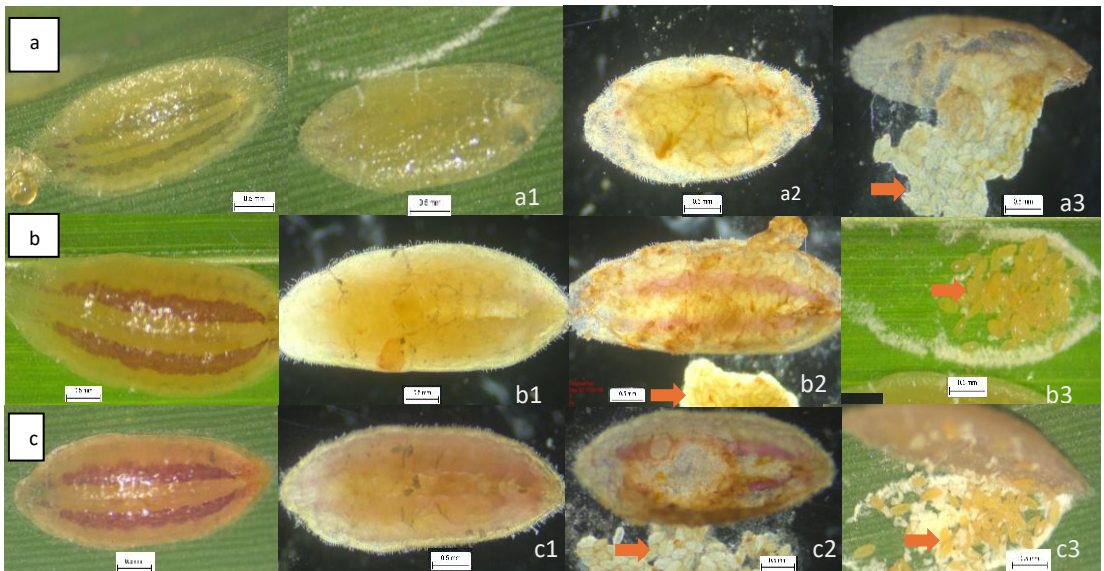


Figure 6. *Pulvinaria tenuivalvata*: Dorsal (a), ventral (a1), developing eggs (a2), and exposed immature eggs of young adult (a3); dorsal (b), ventral (b1), developing eggs (b2), and exposed laid eggs (with arrow) of a mature adult; dorsal (c), ventral (c1), developing eggs (with arrow) (c2), and exposed newly-hatched and about to hatch eggs (c3).

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The measurements and durations of the different life stages of RSSI are shown in Tables 1 and 2. The molting process from the nymphal stages to adult is shown in Figure 4.

Table 1. Measurement of the different developmental stages of *Pulvinaria tenuivalvata*

Developmental Stage	Mean±SD		
	Body Length (mm)	Body Width (mm)	
		Thorax	Abdomen
Egg	0.27 ± 0.01 (L)		
	0.12 ± 0.00 (W)		
First instar	0.49 ± 0.08	0.17 ± 0.03	0.17 ± 0.08
Second instar	0.78 ± 0.09	0.28 ± 0.08	0.26 ± 0.04
Third instar	1.11 ± 0.20	0.39 ± 0.07	0.37 ± 0.07
Young adult	2.96 ± 0.46	1.18 ± 0.17	1.14 ± 0.20
Mature adult	3.91 ± 0.44	1.48 ± 0.19	1.99 ± 2.36
Senescing adult	3.99 ± 0.35	0.89 ± 0.08	0.97 ± 0.04

L= Length: W= Width of egg

Table 2. Duration in days of the different life stages of *Pulvinaria tenuivalvata*.

Developmental Stage	Days
Egg	2-3
Nymph	
First Instar	5-6
Second	5-6
Third	4-5
Total nymphal period	16-19
Adult Female	
Young Adult	8-15
Mature Adult	17
Senescing Adult	14
Total Adult Period	44-46

The observed developmental stages of *Pulvinaria tenuivalvata* under Philippine conditions consisted of the egg stage, three nymphal instars, and adult female stage, which is consistent with earlier reports from Egypt describing the general developmental pattern of the species (Abd El-Samea 2004; Ghabbour and Hodgson 2001). The total nymphal period observed in the present study ranged from 16–19 days, while the total adult period ranged from 44–46 days. Comparable developmental durations were also reported in Egyptian populations of *P. tenuivalvata*, although slight variations in developmental time may occur due to differences in environmental conditions, host plant quality, and laboratory rearing conditions (Abdel-Moniem 2003; Abd El-Samea 2004). The progressive increase in body size from first instar to mature adult observed in this study likewise agrees with previous

descriptions of the species, where gradual enlargement and morphological differentiation accompany each molt (Ghabbour and Hodgson 2001).

Changes in morphology of RSSI particularly in color, size, and salient features of the dorsum were captured in more than a thousand photographs. The extensive photographic documentation provided a comprehensive visual record of developmental progression, allowing detailed observation of gradual changes that may be difficult to describe through measurements alone. Capturing variations in color enabled clear differentiation between developmental stages and maturation phases, while monitoring changes in size supported quantitative assessment of growth patterns throughout the life cycle. Similar observations on morphological progression and developmental changes of *P. tenuivalvata* were reported in Egypt, particularly on the immature stages and external morphology of the species (Ghabbour and Hodgson 2001; Abdel-Razak et al. 2017).

The focus on salient features of the dorsum allowed identification of diagnostic morphological traits, such as body shape, pigmentation patterns, and structural characteristics that become more pronounced as individuals develop from nymphs to adults. These visual records facilitated accurate comparison among individuals and between developmental stages, helping to confirm stage transitions, molting events, and maturation processes. The large number of photographs ensured that subtle variations and representative conditions were documented, reducing the likelihood of observational bias.

Representative samples illustrate key morphological transformations and serve as reference images for describing the life history of RSSI (Figs 2, 3, 4 and 5). These visual documentation is particularly valuable for future taxonomic verification, training purposes, and in aiding researchers and field practitioners in recognizing developmental stages and identifying the pest accurately under both laboratory and field conditions. Detailed morphological documentation of developmental stages is particularly valuable for scale insects, where subtle morphological characters are essential for accurate species identification and comparison with related taxa (Kondo et al. 2026).

Reproduction in RSSI. The RSSI reproduced without mating due to absence of males, and all progenies produced were females. This method of reproduction is called thelytokous type of parthenogenesis. This was also reported in *Pulvinaria psidii* (El-Menshaway and Moursi 1976), a highly polyphagous pest of guava, among other crops in the Philippines (Gabriel 1997) and *P. floccifera*, an important pest in Egypt (Abd-Rabou et al. 2012). The main advantages of thelytoky include increased population growth, easier establishment in new environments, and the ability to maintain highly adapted genotypes. Parthenogenetic reproduction is relatively common among scale insects and contributes to rapid population growth and successful establishment in new environments (Gullan and Kosztarab 1997).

Eggs of adult female RSSI were observed faintly on the ventral aspect of the body, and by puncturing the skin using a bent micro pin, eggs were easily seen and counted (Fig. 6 and Table 3). The faint visibility of the eggs beneath the ventral surface indicates internal egg development prior to or during oviposition, and the use of a bent micro pin allowed gentle manipulation without excessive damage to the specimen. This method facilitated clear visualization and confirmation of reproductive status, enabling accurate documentation of egg presence and developmental timing within the adult stage.

Eggs were usually observed within the ventral aspect of the abdomen on the 24th day after hatching or after 8 days of becoming a young adult (Table 3). On the 9th day, an average of 21.33 ± 18.90 eggs were dissected; 50.20 ± 31.78 on the 14th day; 84.60 ± 28.70 on the 19th day; 237.86 ± 153.64 on the 24th day; 255.60 ± 53.36 on the 30th day; and 245 ± 131.87 on the 34th day. However, eggs were laid on the 19th day (Table 3) until the 34th day of observation. In total, an average of 197 eggs were produced by a single adult female. The timing suggests that reproductive maturity occurs shortly after adult

emergence, reflecting the rapid onset of oviposition typical of parthenogenetic scale insects. Monitoring this period provided valuable information on reproductive biology, including the onset and duration of egg production, which is essential for understanding population growth dynamics. Observations extending until the 63rd day of the culture (day when the body of dead adult become detached from the leaf surface) ensured that the entire reproductive phase was captured, allowing assessment of the length of the oviposition period and contributing to a more comprehensive understanding of the life history and reproductive behavior of the species.

Table 3. Egg counts of adult *Pulvinaria tenuivalvata* dissected from the abdomen and those laid within the egg sac, including hatched eggs (crawlers).

Age of female adult (days)	Day of dissection	Mean±SD		
		Number of eggs dissected	Number of eggs laid	Number of eggs hatched
4	1	0	0	0
9	5	21.33 ± 18.90	0	0
14	10	50.20 ± 31.78	0	0
19	15	84.60 ± 28.70	3.00 ± 0.00	0
24	20	237.86 ± 153.64	30.14 ± 29.47	22.86 ± 19.08
30	25	255.60 ± 53.36	31.4 ± 5.77	17.2 ± 7.76
34	29	245 ± 131.87	27.6 ± 14.50	16.40 ± 4.72

Longevity of adult RSSI. Adult female RSSI lived for more than a month in the experimental samples. However, it was observed from the stock culture that adult lived for more than sixty days, monitored from about 20 marked adults. These observations suggest that when RSSI is not disturbed and the host remained healthy, RSSI lived longer. This extended lifespan indicates a prolonged reproductive phase, allowing females sufficient time to produce and deposit eggs, which contributes to the rapid increase and persistence of populations under favorable conditions. Longer adult longevity may also enhance the pest’s capacity to establish stable infestations in sugarcane fields, particularly because individuals remain actively feeding and secreting honeydew over an extended period.

The duration of adult survival is an important biological parameter, as it influences reproductive output, population dynamics, and the timing of management interventions. A lifespan exceeding one month suggests that adult females can overlap with multiple developmental cohorts, potentially leading to continuous infestation pressure. Understanding adult longevity, therefore, provides critical insight into the life cycle of RSSI and supports the development of effective monitoring and control strategies, particularly in determining optimal timing for targeting earlier developmental stages before populations expand significantly. Information on adult longevity and reproductive timing also enhances understanding of population growth potential, particularly considering the parthenogenetic nature of the species, which may facilitate rapid establishment and spread in sugarcane fields.

CONCLUSION

This study documented the life history and biological characteristics of the red-striped soft scale insect, *Pulvinaria tenuivalvata*, under Philippine conditions. The results confirmed that the insect undergoes egg, three nymphal instars, and adult stages and reproduces through thelytokous

parthenogenesis, enabling rapid population increase. To our knowledge, this is the first report documenting thelytokous parthenogenesis and complete developmental biology of *P. tenuivalvata* under Philippine conditions. The information generated on developmental stages, reproductive biology, and morphological changes represents the first detailed report of these biological characteristics of *Pulvinaria tenuivalvata* under Philippine conditions and provides important baseline knowledge for accurate life-stage identification and a better understanding of the population dynamics of this emerging sugarcane pest. These findings contribute to improving monitoring systems by providing accurate diagnostic information on the developmental stage and reproductive biology of RSSI and can support the development of integrated pest management strategies for *P. tenuivalvata* in Philippine sugarcane production systems by enabling timely detection, stage-specific control measures, and improved population assessment in the field. The results also provide a scientific basis for informed decision-making and sustainable approaches aimed at minimizing the potential impacts of *P. tenuivalvata* on sugarcane productivity and farmers' income. Further studies on the pest's biology on alternative grass hosts and under different host-plant conditions may help refine management strategies and enhance long-term control efforts.

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FACTORS IMPACTING CONSUMER SATISFACTION FOR HYDROPONICALLY GROWN TOMATOES IN HINO CITY, JAPAN

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ABSTRACT

Small-scale tomato farmers play a significant role in Japan, where understanding consumer preferences is essential to optimize production and meet market demand. This study aimed to identify the key attributes that contribute to consumer satisfaction and to determine how demographic and purchasing behaviors affect preferences for hydroponically grown tomatoes from a small-scale farm in Hino City, Tokyo, using a data-driven decision-making approach. Data were collected from 154 respondents using a structured questionnaire. Factor analysis revealed two primary dimensions of satisfaction: appearance (freshness, color, and size) and taste (flavor and sweetness). Demographic factors such as age and income significantly influenced satisfaction. Younger consumers prioritized taste, older consumers prioritized appearance, and higher-income groups expressed greater satisfaction with the visually appealing tomatoes. Distribution channels, such as unstaffed vegetable shops and supermarkets, enhanced consumers' perceptions of appearance. These findings demonstrated how data-driven approaches can help small-scale farmers meet consumer demands better and enhance profitability and sustainability. The methodology of this study was found to be applicable to other regions, particularly in Southeast Asia, where a high density of small-scale farmers could use these insights to optimize production, improve marketing strategies, and strengthen resilience in competitive markets.

Key words: agribusiness, consumer behavior, data-driven decision making

INTRODUCTION

Agriculture remains the primary source of food and nutrition globally, with small-scale farmers supplying approximately 80% of the world's food demand (Samberg et al. 2016). In Asia, particularly Southeast Asia, small-scale farmers are the backbone of agricultural production and play a critical role in ensuring food security for rapidly growing populations (UNCTAD 2015). However, these farmers face increasing challenges, including climate variability, changing consumer behavior, and intensifying competition within agri-food markets (Falvey 2019; Mikolajczyk et al. 2021; Sebastian and Bernardo 2019). These pressures have heightened the need for production and marketing strategies that are both resilient and responsive to local consumer demand.

Greenhouse-based and hydroponic production systems have emerged as important technological responses to environmental uncertainty by enabling controlled growing conditions and more stable yields (Savvas and Gruda 2018). Across Asia, small-scale farmers are increasingly adopting greenhouse technologies to improve productivity and reduce climate-related risks. Empirical studies have demonstrated the effectiveness of greenhouse cultivation for crops such as onions in the Philippines (Pascual et al. 2018), leafy vegetables in Indonesia (Athifa et al. 2019), and urban lettuce production (Manongko et al. 2023). In Japan, greenhouse systems account for approximately 80% of national tomato production, reaching 720,000 metric tons in 2021 (MAFF Japan 2022). Despite this technological advancement, many new entrants to greenhouse tomato farming, particularly in urban and peri-urban areas, continue to face economic difficulties, including challenges in market positioning and recovery of initial investment costs.

For small-scale greenhouse producers, understanding consumer behavior and satisfaction is essential for aligning production and marketing decisions with local demand. Prior research indicates that consumer evaluation of fresh vegetables is influenced by multiple attributes, including taste, freshness, appearance, variety, production origin, and certification, with preferences varying across regions and marketing channels (Duc et al. 2023; Grunert 2024). Such heterogeneity makes it difficult for small-scale farmers to accurately identify the most influential satisfaction drivers based solely on intuition or informal observation. Misinterpretation of consumer preferences can lead to inappropriate strategies and investments, increasing financial risks. In particular, previous studies highlight that consumers often associate higher satisfaction with product diversity, store atmosphere, and short supply chain channels, while factors such as location may play a less significant role depending on the context (Azhari et al. 2023; Platania et al. 2015). Furthermore, studies on direct marketing and retail distribution channels emphasize the importance of understanding where consumers purchase products, as channel choice significantly shapes perceived quality, freshness, and consumer satisfaction (Gunden et al. 2010).

Several studies have examined agricultural development and tomato consumer behavior in Hino City, Tokyo, using a comprehensive analytical perspective. Institutional and municipal support systems for new farmers, focusing on policy frameworks, land access, and subsidy mechanisms, were investigated (Terano et al. 2023). Building on the institutional context, Shimoguchi et al. (2024) analyzed tomato purchasing behavior, consumer satisfaction, and brand familiarity among consumers who had prior experience purchasing from a specific new farm (NF Farm). Using the same survey framework and study location, this research was extended by examining the broader local tomato market through consumer segmentation analysis, incorporating all valid consumer responses regardless of farm-specific purchasing experience (Gunasekara et al. 2024).

Data-driven decision-making (DDDM) offers a systematic approach to understanding complex consumer behavior by grounding managerial decisions in empirical evidence rather than assumptions based on personal experience alone. DDDM emphasizes the structured collection, analysis, and interpretation of data to support strategic and operational decisions, enabling organizations to improve accuracy, efficiency, and consistency in decision processes (Joubert 2024). Empirical research across multiple sectors demonstrates that organizations adopting data-driven approaches achieve superior performance outcomes, innovation capacity, and more effective resource allocation compared to intuition-based decision systems (ZareRavasan 2021).

Evidence from non-agricultural industries further highlights the broad applicability of DDDM. In advanced manufacturing systems, data-driven decision frameworks have been shown to improve productivity, process stability, and operational efficiency by enabling real-time monitoring, analytical modeling, and evidence-based managerial control (Zhang et al. 2016). Similarly, further studies in the financial sector report a positive and statistically significant relationship between DDDM practices and organizational productivity, underscoring the value of data analytics for performance improvement even in highly regulated and service-oriented environments (Prakash 2024). These findings suggest that

the principles of DDDM are transferable across sectors when appropriately adapted to context-specific constraints and decision needs. Within food systems, data-driven approaches have also demonstrated strong potential to enhance planning, monitoring, and policy responsiveness. Data-driven models integrating market prices, climatic indicators, and demographic variables have significantly improved the timeliness and spatial precision of food insecurity crisis prediction compared to expert-based assessment frameworks alone (Lentz et al. 2019).

Despite these demonstrated benefits, the application of DDDM within small-scale agribusiness, particularly at the farm level, remains limited. Small-scale farmers often face significant barriers to adoption, including limited financial resources, technical capacity, data management skills, and institutional support (Brandy 2023; John et al. 2023). Furthermore, data analytics is often associated with large-scale big-data infrastructures, machine learning, or artificial intelligence, which can discourage adoption among smallholders who lack the experience or resources to implement such systems (Joubert 2024). However, prior research studies emphasize that effective DDDM does not necessarily require complex, data-intensive models. Even relatively simple analytical techniques such as descriptive statistics, regression analysis, and multivariate analysis can generate meaningful and practical insights when aligned with clearly defined decision objectives and modest data availability (Lentz et al. 2019).

Consequently, there remains a critical research gap in demonstrating how DDDM can be practically adopted to the realities of small-scale consumer-oriented agribusinesses. In particular, there is limited empirical evidence on how small-scale agribusinesses can use consumer data to systematically identify drivers of satisfaction, reduce decision uncertainty, and support market-oriented production and marketing strategies. Addressing this gap is essential to enabling small-scale farmers to leverage data analysis as a practical decision-support tool.

This study adopted a case study approach focusing on a small-scale hydroponic tomato farm (NF Farm) located in Hino City, Tokyo. NF Farm represented a typical example of urban, consumer-oriented greenhouse farming, where production technologies are relatively advanced, but market-oriented decision support remains limited. Therefore, this study sought to examine how DDDM can be applied in practice to support small-scale agribusiness through a case study of a hydroponic tomato farm, by identifying critical drivers of consumer satisfaction and translating them into practical production and marketing strategies. This research contributed empirically and methodologically to the literature while offering practical value for small-scale farmers by adapting data-driven methods typically used in large-scale agribusiness to a small-farm context. Beyond the case setting, the approach provides a replicable framework for small-scale agribusiness, particularly in Southeast Asia, where localized consumer insights are essential for long-term profitability and sustainable farm management.

MATERIALS AND METHODS

This study was based on the NF Farm, a small-scale hydroponic greenhouse tomato producer in Hino City, Tokyo, Japan. This farm was selected as the focus of this study because it represents a new entrant in the Japanese tomato agribusiness sector that utilizes smart hydroponic technologies. NF Farm primarily serves the local market in Hino City, distributing its tomatoes through a variety of channels, including local supermarkets, direct farmers shop (DFS) (in Japanese, “choku-bai-jo”), and unstaffed vegetable sales shop (UVSS) (in Japanese, “mujin-ten”).



Figure 1. Multiple distribution channels of NF Farm

Data collection. The study sample comprised consumers who purchased tomatoes from NF Farm. By approaching these buyers through various local distribution channels, including local supermarkets, DFS, and UVSS, this sampling strategy captured a highly diverse participant profile. Data were collected between May 1 and June 30, 2022, using a structured questionnaire via face-to-face at selected market locations. QR codes linked to Google Forms were also utilized to facilitate online participation; these were displayed on tomato shelves in DFS and UVSS outlets, printed on NF Farm product packages, and advertised on farm's business website and social media platforms. The questionnaire was designed to gather information on consumer demographics (e.g., age, gender, family structure, and annual household income), purchasing behavior (e.g., purchase location, spending per purchase, and frequency of buying tomato types), and satisfaction with NF Farm tomatoes. Participants were asked to rate eight tomato attributes-including freshness, color, peel hardness, flavor, acidity level, sweetness, price, and size, using a 4-point Likert scale ranging from 1 (very unsatisfied) to 4 (very satisfied).

Data for this study were obtained from a broader consumer survey (N = 470 total responses) conducted in Hino City. Distinct subsamples from this survey have been used across related studies depending on research objectives and analytical requirements. For instance, a consumer segmentation study analyzed 316 valid responses from local tomato consumers to evaluate overall market structure and consumer heterogeneity, regardless of farm-specific purchasing experience (Gunasekara et al. 2024). Conversely, a consumer satisfaction and brand familiarity study focused exclusively on 213 respondents who had prior experience purchasing tomatoes from NF Farm (Shimoguchi et al. 2024). For the present study, an initial subset of 169 responses from NF Farm consumers were extracted; following data cleaning to remove incomplete and invalid responses, 154 valid responses were retained for the final analysis. These sample size variations reflect purposeful screening procedures aligned with distinct research objectives rather than inconsistencies in data collection.

Data analysis. Descriptive statistics were first utilized to summarize respondents' demographic characteristics and purchasing behaviors, establishing a baseline overview of the consumer sample. Factor analysis (FA) was subsequently conducted to identify the latent dimensions underlying consumer satisfaction with the hydroponically grown tomatoes. The suitability of the dataset for factor extraction was verified using the Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy and Bartlett's test of sphericity (Kaiser 1974; Bartlett 1950). Factors were extracted based on cumulative explained variance, and variables with factor loadings greater than 0.7 were retained, following the established guidelines for interpretive strength (Hair et al. 2010). In addition, both Varimax and Promax rotation methods were tested to enhance factor interpretability and confirm the robustness of the factor structure.

Analysis of Variance (ANOVA) was performed to examine differences in the identified satisfaction factors across demographic groups and purchasing behavior categories. Wherever significant differences were detected, Tukey’s honestly significant difference test was used for post-hoc pairwise comparisons (Wilcox et al. 2000). In addition, cross-tabulation and Chi-square tests of independence were used to examine associations between categorical variables for groups showing significant or notable differences, with statistical significance established at the 5% level (Hair et al. 2010).

RESULTS AND DISCUSSION

This section presents and discusses empirical findings in relation to existing literature and their implications for small-scale hydroponic tomato farming, with a focus on NF Farm.

Respondents profile. The descriptive results of the respondents’ demographic characteristics (Table 1) show that those within the age groups of 40–59 years (51.94%), alongside the 20–39 years and 60–79 years (22.08% each), represent a relatively mature population, with an average age of 49.5 years. Younger (< 19 years) and older (> 80 years) participants comprised minor proportions of the study population, accounting for 2.60% and 1.30%, respectively. Respondents were predominantly female (74.68%) and most belonged to families with children (54.55%), followed by couples (27.92%) and single individuals (17.53%). Regarding annual household income, upper-tier earners making of over 7 million JPY represented the largest segment at 38.31%, followed by those earning between 3.01 and 5 million JPY (24.68%) and 5.01 and 7 million JPY (20.78%). This profile indicates that NF Farm’s consumer base mainly consists of middle-aged, family-oriented, and relatively high-income households, which is relevant when interpreting subsequent satisfaction and preference patterns.

Table 1. Demographic results of respondents (n = 154)

Demographic Variable	Percentage (%)
Age	
Below 19	2.60
20 to 39	22.08
40 to 59	51.94
60 to 79	22.08
Over 80	1.30
Gender	
Female	74.68
Male	25.32
Family Type	
Single	17.53
Husband and wife	27.92
Family with kids	54.55
Annual Household Income (Million JPY)	
Below 2	5.19
2.01 to 3	11.04
3.01 to 5	24.68

Demographic Variable	Percentage (%)
5.01 to 7	20.78
Over 7.01	38.31

Source: Survey results by author 2022

Satisfaction attributes. Table 2 presents the average satisfaction scores and standard deviations (SD) for the tomato attributes. Freshness received the highest satisfaction score of 3.56 (SD = 0.57), followed by color at 3.49 (SD = 0.60) and flavor at 3.44 (SD = 0.68). The lower SD for freshness and color suggests a highly consistent perception of these qualities across respondents. Attributes such as size and acidity were rated slightly lower, yielding scores of 3.40 (SD = 0.61) and 3.32 (SD = 0.62), respectively, but still reflected moderate satisfaction. On the other hand, price scored the lowest at 3.01 (SD = 0.70), demonstrating that consumers were least satisfied with this aspect. Collectively, these results indicate that appearance, quality and freshness contribute much more strongly to consumer satisfaction than price. This finding is consistent with previous studies highlighting the importance of appearance and freshness in fresh produce evaluation (Causse et al. 2010; Grunert 2024; Gunden et al. 2010).

Table 2. Descriptive statistics of consumer satisfaction attributes for hydroponically grown tomatoes (n=154)

Variable	Mean	Standard Deviation (SD)
Freshness	3.56	0.57
Color	3.49	0.60
Flavor	3.44	0.68
Size	3.40	0.61
Acidity	3.32	0.62
Hardness of peel	3.27	0.66
Sweetness	3.27	0.66
Price	3.01	0.70

Source: Survey results by Author 2022

Underlying dimensions of consumer satisfaction.

Factor analysis suitability test. Before conducting factor analysis (FA), the suitability of the dataset was assessed using the Kaiser–Meyer–Olkin (KMO) measure of sampling adequacy and Bartlett’s test of sphericity. The KMO value was 0.89, indicating adequate sampling, and Bartlett’s test was statistically significant ($\chi^2 = 980.03$, $df = 28$, $p < 0.001$), confirming that the data matrix was appropriate for factor modelling. Based on these results, factor analysis was conducted, and the results are presented in Table 3.

Factor 1 is defined by robust loadings for freshness (0.81), color (0.80), and size (0.78), clearly representing the “appearance quality” dimension of tomatoes. Factor 2 is defined by sweetness (0.84) and flavor (0.76), representing “taste quality” dimension. These two dimensions align with previous research identifying visual cues as primary drivers of fresh produce evaluation (Causse et al. 2010;

Grunert 2024), while sweetness and flavor are widely recognized as key determinants of tomato preference and purchasing decisions (Bawajeeh et al. 2020; Hoffman et al. 2016).

This clear separation is also consistent with retail-based studies showing that product-related attributes, particularly appearance and taste, are dominant determinants influencing consumer satisfaction (Azhari et al. 2023). Following factor extraction, average factor scores were computed to examine how satisfaction levels across these two dimensions varied across consumer demographics and purchasing behavior.

Table 3. Factor loadings of attributes on appearance and taste satisfaction (n=154).

Variable	Factor 1	Factor 2
Freshness	0.81	0.36
Color	0.80	0.40
Size	0.78	0.39
Hardness of peel	0.63	0.53
Acidity	0.59	0.59
Price	0.44	0.47
Flavor	0.37	0.76
Sweetness	0.36	0.84

Demographic influences on appearance and taste satisfaction. Table 4 presents the average satisfaction scores for appearance and taste segmented by demographic characteristics. Younger consumers below 19 years old exhibited a strong preference for taste (0.61) and a slight preference for appearance (0.09). In contrast, older consumers over 80 years old showed a higher preference for appearance (0.31) while showing a strong negative directional preference for taste (-1.81, $p < 0.01$). This is consistent with earlier findings that revealed age-related changes in taste perception often led older consumers to focus more on visual and textual attributes than on flavor (Methven et al. 2012; Ogawa et al. 2017). However, no statistical significance was observed between age and taste satisfaction. Thus, it is noteworthy that this finding did not reach true statistical significance due to the small sample size. Further research using a larger sample of older consumers is required to confirm these findings.

With regards to gender, the appearance and taste scores for both males and females were close to zero, suggesting that gender did not significantly influence satisfaction. Additionally, family composition showed no strong or statistically significant relationship with either appearance or taste satisfaction factors, yielding highly similar baseline across groups and indicating that family type may not be the primary driver of tomato satisfaction.

In contrast, notable variations in appearance satisfaction can be identified according to income level. High-income households earning over 7 million JPY reported a significantly higher satisfaction score for appearance (0.21, $p < 0.05$), which may be attributed to their greater access to and expectation of premium quality products. Conversely, while statistically insignificant, the middle-to-high income group earning 5.01 to 7 million JPY recorded negative mean scores for both appearance and taste attributes of the NF Farm tomatoes.

While these localized ANOVA revealed specific significant and directional trends were observed, some categorical associations were not confirmed by Chi-square tests, suggesting that broad demographic effects across the full sample should be interpreted cautiously. Nevertheless, these trends remain practically and highly relevant for localized market targeting strategies at NF Farm. Overall, these findings are consistent with previous studies indicating that demographic characteristics, specifically age and income, exert a powerful influence on consumer satisfaction, perceived quality benchmarks, and willingness to pay (Platania et al. 2015).

Table 4. Average scores of appearances and taste satisfaction by demographic factors (n=154).

Variable	Appearance factor score	Taste factor score
Age (years)		
Below 19	0.09	0.61
20 to 39	0.08	0.09
40 to 59	0.03	-0.03
60 to 79	-0.17	0.01
Over 80	0.31	-1.81*
Gender		
Male	0.07	0.01
Female	-0.02	0.00
Family type		
Single	0.06	0.09
Husband and wife	-0.09	0.01
Family with kids	0.03	-0.03
Annual Household Income (Million JPY)		
Below 2	-0.04	0.24
2.01 to 3	-0.41	0.15
3.01 to 5	0.12	0.01
5.01 to 7	-0.29	-0.27
Over 7.01	0.21*	0.07

Note: Significance code explanation * $p \leq 0.05$

Purchasing behavior and satisfaction patterns. The average satisfaction is based on spending per purchase, purchase location, and tomato type (Table 5). The relationship between spending levels and satisfaction demonstrates that moderate consumers, specifically those who spent 501–700 JPY and 701–1,000 JPY were satisfied with both appearance and taste attributes. However, consumers who spent more than 1,001 JPY showed higher dissatisfaction with taste (-2.70), despite only a slight drop in appearance satisfaction (-0.18). This pronounced mismatch between appearance satisfaction and taste dissatisfaction at higher price levels suggests that expectations increase with price, highlighting the importance of aligning sensory quality with premium positioning to retain the high-value consumer segment. This finding is consistent with previous research indicating that higher price levels increase consumer expectations regarding taste and overall quality (D’Amico et al. 2024).

Furthermore, the distribution channels significantly influenced satisfaction levels. Tomatoes

from UVSS outlets achieved significantly higher appearance satisfaction (0.13, $p \leq 0.001$), likely driven by heightened consumer perception of fresher, locally sourced products. This finding aligns with studies on direct marketing channels, in which consumers associate local and direct purchase outlets with higher perceptions of freshness and quality (Gunden et al. 2010; Platania et al. 2015). In contrast, the differences between tomatoes from DFS outlets and supermarkets were not significant, though supermarket consumers had a high baseline satisfaction with the appearance of tomatoes (0.31). Notably, DFS consumers recorded negative mean factor scores, indicating low satisfaction with both appearance (-0.05) or taste (-0.12) of the NF Farm tomatoes.

Satisfaction levels also varied explicitly across product varieties (Table 5). Among the different tomato types, medium tomatoes yielded significantly lower taste satisfaction (-0.25, $p \leq 0.01$), suggesting an immediate need to improve their flavor profile. In contrast, big tomatoes were rated highest across both satisfaction dimensions, generating positive scores for appearance (0.15) and taste (0.35). This indicates that big tomatoes are successfully meeting consumer expectations for sensory quality. This aligns directly with previous studies showing that consumers who purchase large tomatoes strongly prioritize firmness, juiciness, and flavor (Oltman et al. 2014).

Table 5. Average scores of appearances and taste satisfaction by tomato purchasing behavior (n=154)

Variable	Appearance Factor Score	Taste Factor Score
Paying Price per Purchase [JPY]		
Below 100	-0.97	0.27
101 to 300	-0.04	-0.06
301 to 500	-0.03	-0.03
501 to 700	0.14	0.35
701 to 1000	0.36	0.16
Over 1001	-0.18	-2.70
Tomato distribution channels		
Direct Farmers Shop	-0.05	-0.12
Unstaffed Vegetable Sales Shop	0.13**	0.02
Supermarket	0.31	0.00
Tomato Type		
Cherry	-0.02	0.02
Medium	0.03	-0.25*
Big	0.15	0.35

Note: Significance code explanation * $p \leq 0.05$

Taste satisfaction by age group. The cross-tabulation frequencies present the distribution of respondents' taste satisfaction across age groups (Fig. 2). In the age group below 19 years, three of the four respondents reported being satisfied, suggesting that younger individuals tend to respond positively to the taste of tomatoes. However, the 20–39, 40–59, and 60–79 years age groups had higher

numbers of unsatisfied responses than satisfied responders; over 80 years age group responses were evenly split, with one unsatisfied and one satisfied, due to the small sample size, which should be interpreted with caution. The association between age and taste satisfaction was not statistically significant ($\chi^2 = 2.31, p = 0.67$). Although not statistically significant, these observed patterns are consistent with previous findings on age-related variation in taste perception (Methven et al. 2012).

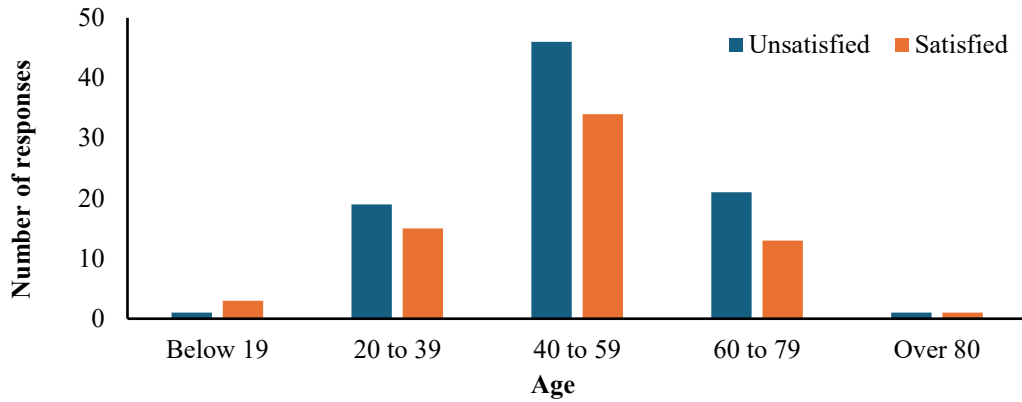


Figure 2. Taste satisfaction by age group

Note: No statistically significant association between age group and taste satisfaction ($\chi^2 = 2.31, df = 4, p = 0.67$).

Appearance satisfaction by income levels. Respondents’ satisfaction with tomato appearance varied across annual household income categories (Fig. 3). In this category, more respondents were satisfied than unsatisfied, suggesting that all household income groups were satisfied with the appearance of tomatoes. The Chi-square test results ($\chi^2 = 9.11$) and p-value (0.058) are slightly above the conventional threshold of 0.05, indicating that the results are not statistically significant but suggest a potential association. The marginal significance suggests a possible association between income and satisfaction with appearance, which may become clearer with a larger sample size. This trend is consistent with previous studies indicating that higher-income consumers tend to place greater importance on appearance and quality attributes (Grunert 2024; Platania et al. 2015).

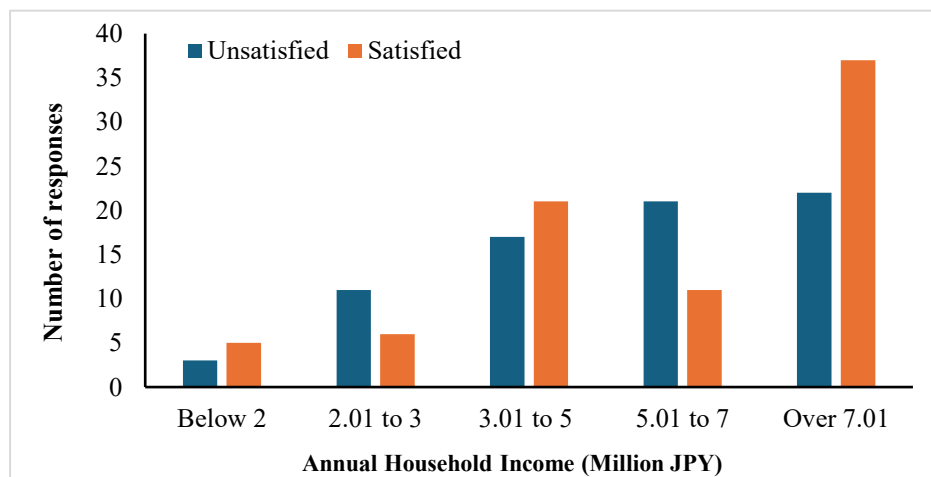


Figure 3. Appearance satisfaction by income level

Note: Marginally non-significant association between income level and appearance satisfaction ($\chi^2 = 9.11, df = 4, p = 0.058$).

Taste satisfaction by tomato type. When examining the distribution of consumer responses (Fig. 4), cherry tomatoes received the highest overall volume of responses. While consumers generally prefer smaller tomatoes for their perceived taste and sweetness (Casals et al. 2018), cherry tomatoes in this study received slightly more unsatisfied responses than satisfied responses. It is noteworthy that Japanese consumers commonly use cherry tomatoes in practical daily lunchboxes (“Bento”). This indicates that, while they are highly appreciated for their convenient size and utility, they do not currently generate strong positive consumer evaluations of taste. Medium tomatoes similarly experienced more dissatisfaction than satisfaction. Big tomatoes were proportionally more satisfactory than medium and cherry tomatoes, though their overall response rate was low. Ultimately, cross-tabulation analysis did not reveal a statistically significant categorical relationship between tomato type and taste satisfaction ($\chi^2 = 1.90$, $df = 2$, $p = 0.39$). This suggests that while localized differences exist, the preference patterns are not strong enough to signify a consistent, sample-wide association.

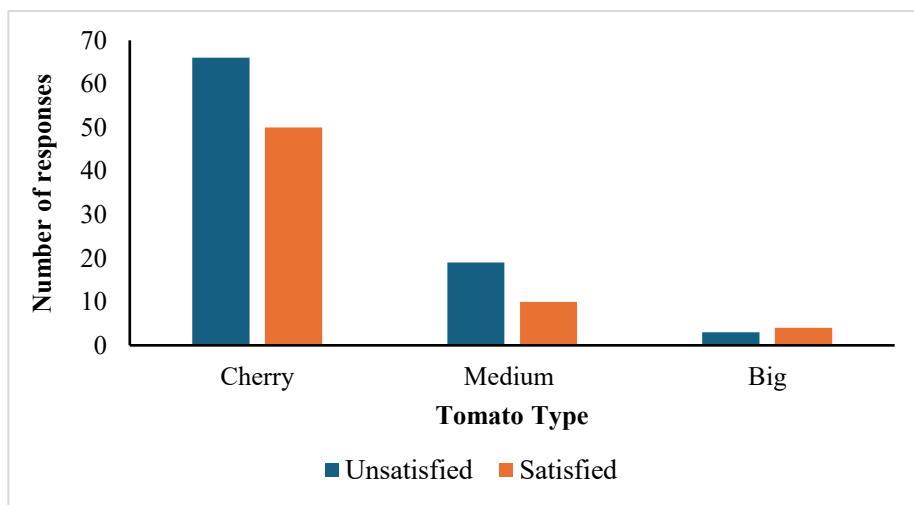


Figure 4. Taste satisfaction by tomato type

Note: No statistically significant association between tomato type and taste satisfaction ($\chi^2 = 1.90$, $df = 2$, $p = 0.39$).

Appearance satisfaction and distribution channels. Across purchase locations (Fig. 5), the unstaffed vegetable sales shop (UVSS) yielded the largest proportion of respondents satisfied with the tomato appearance. This favorable response is likely driven by the perception of fresher, locally sourced products. Specifically, the UVSS is located directly in front of the tomato farm, allowing the farmer to refill the stall with freshly harvested tomatoes multiple times a day, thereby minimizing transportation time and maximizing visible freshness. In contrast, the direct farmers' shop (DFS) showed nearly balanced satisfaction scores, even though previous literature indicates that consumers who use DFS outlets typically value local production and freshness (Bavorova et al. 2015). Supermarket purchasers, representing a smaller segment of the sample, were similarly split between satisfied and unsatisfied. Ultimately, a Chi-square test indicated no statistically significant categorical association between distribution channels and overall appearance satisfaction ($\chi^2 = 0.56$, $df = 2$, $p = 0.76$). This suggests that while the UVSS model offers a highly favorable consumer experience, the statistical variance across groups was not dominant enough to signify a sample-wide association (Ramadhan et al. 2024).

This finding suggests that while purchase location may influence perceived quality, the strength of this relationship is not statistically significant in this sample. This result is consistent with previous studies showing that purchase location can influence consumer perceptions of product quality and freshness, although the strength of this relationship may vary depending on context and consumer characteristics (Gunden et al. 2010).

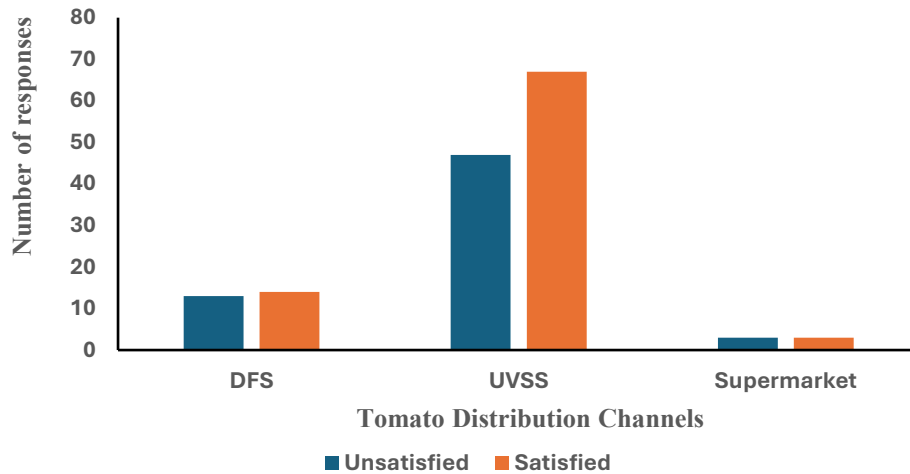


Figure 5. Appearance satisfaction by distribution channels

Note: No statistically significant association between distribution channels and appearance satisfaction ($\chi^2 = 0.56$, $df = 2$, $p = 0.76$).

Strategic implications for NF Farm and other small-scale farmers. The findings of this study offered valuable insights for NF Farm and other hydroponic tomato farms. To enhance consumer satisfaction, NF Farm should maintain high standards of appearance and taste, particularly in premium products (D’Amico et al. 2024). Enhancing the flavor profile of medium tomatoes, possibly through selective breeding (Matsukura 2016) and improved nutrient management (Sato et al. 2006), can increase consumer satisfaction. Additionally, expanding distribution through UVSS outlets, where consumers report higher satisfaction, may boost NF Farm’s appeal by emphasizing freshness and local sourcing, particularly for high-income consumers. Furthermore, NF Farm should further investigate the reasons why certain income groups and consumers purchasing through DFS are dissatisfied with its tomatoes. Overall, improving the appearance and taste attributes can contribute to building consumer loyalty, which is essential for sustaining market success.

Even though some consumers reported moderate dissatisfaction with certain attributes, purchasing behavior remained positive. Informal interactions during survey administration revealed that several respondents continued to purchase NF Farm tomatoes to support the farmer. This suggests that social support motives and local loyalty may complement product-based satisfaction in shaping repeat purchasing decisions. For small-scale urban farms, maintaining strong community relationships may therefore be as important as improving product attributes.

Although this study was conducted in Japan, its methodology and insights are widely applicable. Factor analysis to assess consumer satisfaction and identify influential attributes is relevant to tomatoes and offers valuable guidance for small-scale farmers in Southeast Asia and other regions with local preferences and market conditions. Using data-driven approaches, farmers can make informed decisions regarding product development, marketing, and resource allocation by understanding

consumer needs (Lentz et al. 2019). This adaptable methodology allows small-scale farmers to align production with consumer demand, optimizing profitability and sustainable practices, regardless of the crop or region.

CONCLUSION

This study investigated the determinants of consumer satisfaction with hydroponically grown tomatoes from a small-scale farm in Hino City, Tokyo, using a DDDM approach. Based on 154 valid consumer responses, factor analysis identified two main dimensions of satisfaction: appearance quality (freshness, color, and size) and taste quality (sweetness and flavor). These findings confirm that both appearance and sensory attributes significantly shape consumer evaluation of fresh tomatoes, with appearance emerging as a particularly influential factor.

Consumer satisfaction patterns were distinctly shaped by demographic characteristics and purchasing behaviors. Younger consumers showed relatively stronger preference for taste attributes, whereas older consumers emphasized appearance characteristics. Higher-income households reported greater satisfaction with appearance, suggesting that appearance quality plays a critical role in premium market segments. Distribution channels also affected perception, with unstaffed vegetable sales shops associated with higher appearance satisfaction, likely due to freshness cues and proximity to production. Methodologically, this study demonstrates that small-scale farms can use practical, accessible data-driven analytical tools without relying on complex big-data systems. Even with moderate sample sizes, structured statistical techniques can generate actionable managerial insights by translating consumer feedback into empirical evidence, thereby reducing decision uncertainty and aligning production strategies with market demand.

This study has several limitations that should be considered when interpreting the results. This research was conducted based on a single case study site (NF Farm in Hino City, Tokyo) and focused solely on hydroponically grown tomatoes. Therefore, these findings may not be generalizable to other geographic regions, farming systems, or crop types. Although this study demonstrates DDDM's potential to enhance consumer satisfaction, many small-scale farmers face challenges understanding or implementing it due to limited technical knowledge or resource constraints.

For further study, replication of this methodology across multiple regions and crops is suggested to address these limitations and validate its applicability and adaptability. Additionally, collaborative efforts involving third-party organizations, agricultural extension services, and digital platforms may also be explored to provide small-scale farmers with accessible, affordable, and user-friendly data analysis tools, helping bridge the gap between data availability and practical decision-making and ultimately supporting more inclusive and sustainable agribusiness development.

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CONFLICT OF INTEREST

The authors declare that they have no affiliations with or involvement in any organization or entity with any financial interest in the subject matter or materials discussed in this manuscript. All authors confirm that they have complied with the Code of Ethics of the Journal of the International Society for

Southeast Asian Agricultural Sciences (J ISSAAS) and affirm that the research presented is original, free from plagiarism, and ethically conducted in accordance with the journal's guidelines.

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SEAGRASS ECOSYSTEMS, THEIR CARBON STORAGE, AND POTENTIAL FOR REDUCING CARBON EMISSIONS

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ABSTRACT

Seagrass ecosystems are highly productive coastal habitats that play a vital role in maintaining marine biodiversity, supporting fisheries, and regulating global carbon cycles. As marine angiosperms inhabiting shallow coastal waters, seagrasses form extensive meadows that provide essential ecosystem services, including sediment stabilization, nutrient cycling, and habitat for diverse marine organisms. Increasing attention has been given to their role as blue carbon ecosystems, capable of capturing and storing atmospheric carbon dioxide in both biomass and underlying sediments over long timescales. Despite occupying less than 0.2% of the global ocean floor, seagrass meadows contribute significantly to oceanic carbon burial. However, these ecosystems are experiencing rapid global decline due to coastal development, eutrophication, sedimentation, and climate-related disturbances, leading to biodiversity loss and carbon release. This review synthesizes current knowledge on seagrass diversity, distribution, ecosystem functions, and blue carbon potential, with a particular focus on Southeast Asia. It further examines the environmental and biological factors influencing carbon storage, major anthropogenic threats, and emerging restoration strategies, highlighting key knowledge gaps and future research directions to support effective conservation and climate mitigation efforts.

Key words: carbon sequestration; coastal resilience; climate change mitigation; ecosystem services; restoration ecology

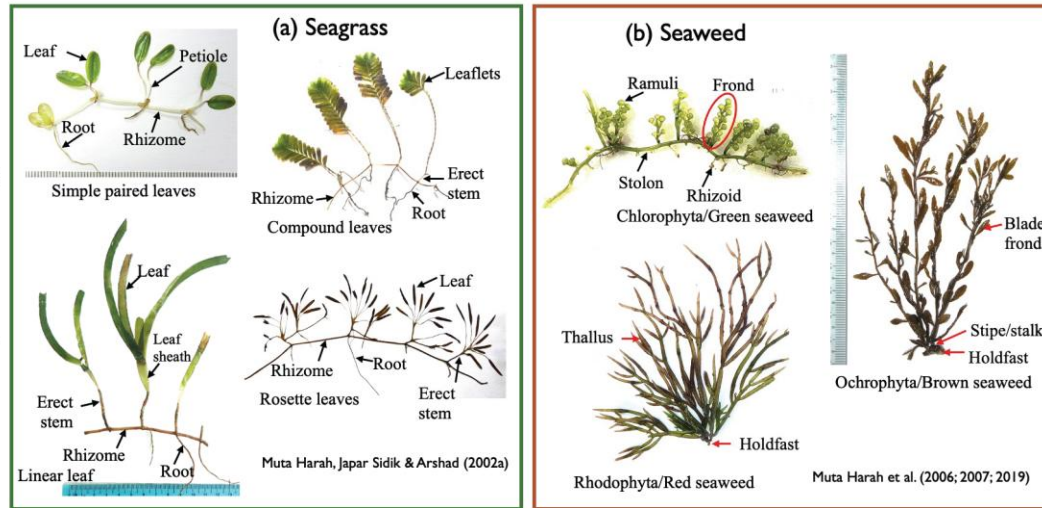
INTRODUCTION

Seagrasses are underwater marine angiosperms from the class Monocotyledoneae. They are the only group of flowering plants (monocotyledonous angiosperms) that have successfully adapted to life in marine and estuarine environments. Unlike algae, seagrasses have true vascular tissues, including roots, stems, and reproductive organs such as flowers and seeds, allowing them to complete their entire life cycle submerged in seawater (Fig. 1).

Seagrass ecosystems are some of the most productive and ecologically important coastal habitats in the world. These marine angiosperms form extensive underwater meadows in shallow coastal waters where enough light penetrates the seabed, enabling photosynthesis and primary production. Seagrasses possess well-developed root and rhizome systems that anchor them within sediments and facilitate nutrient uptake, allowing them to thrive in a variety of marine environments ranging from sheltered lagoons and estuaries to open coastal shelves (Green and Short 2003; Orth et al. 2006). Globally, approximately 72–80 seagrass species have been identified, distributed across tropical and temperate regions and forming important ecological links between mangroves, coral reefs, and open marine systems (Green and Short 2003; Orth et al. 2006; Short et al. 2011).

Seagrass ecosystems, their carbon storage.....

- Angiosperms (flowering plants)
- With a vascular system inter-connecting all organs (stem, leaves and roots), well developed air channel (AC) system
- Leaves generally green
- Produce flowers, fruits and seeds



- Multicellular macroscopic marine algae
- Prostrate axis or stolon, rarely extensive
- Rachis bearing thallus/lamella
- Thallus green, brown, and red
- Produce sporangium and spores

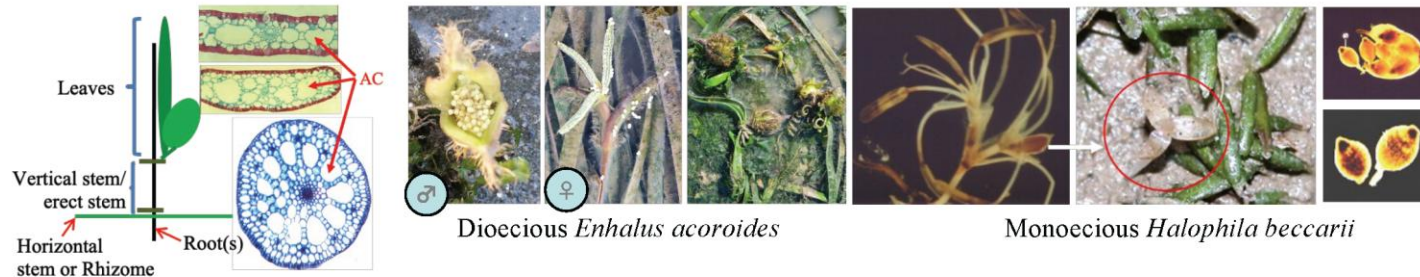


Figure 1. Characteristics of seagrass and seaweeds and their differences

Beyond their biological diversity, seagrass meadows provide a wide array of ecosystem services that support both marine biodiversity and human livelihoods. These ecosystems serve as essential nursery and feeding grounds for numerous fish and invertebrate species, including commercially important fisheries, while also supporting megafauna such as sea turtles and dugongs (Orth et al. 2006; Unsworth et al. 2019). Dense seagrass canopies reduce wave energy, stabilize sediments, and improve water clarity by trapping suspended particles, thereby contributing to shoreline protection and coastal resilience (Koch et al. 2009; Orth et al. 2006). In many tropical coastal regions, particularly within Southeast Asia, seagrass meadows also play a significant role in sustaining local fisheries and food security for coastal communities (Nordlund et al. 2016).

In recent decades, seagrass ecosystems have gained increasing scholarly attention due to their vital role in global carbon cycling. These meadows are now recognized as a key type of blue carbon ecosystem, alongside mangroves and salt marshes, that can capture and store large amounts of atmospheric carbon dioxide (CO₂) (Duarte et al. 2013; McLeod et al. 2011). Through photosynthesis, seagrasses convert dissolved inorganic carbon into organic matter, which is stored in plant biomass and buried in underlying sediments (Duarte et al. 2013; Fourqurean et al. 2012). Because seagrass sediments are often low in oxygen, decomposition slows down, allowing organic carbon to remain stored for centuries or even thousands of years (Duarte et al. 2013; McLeod et al. 2011). Despite covering less than 0.2% of the global ocean floor, seagrass ecosystems play a significant role in marine carbon sequestration and are estimated to contribute about 10% of the ocean's annual carbon burial (Fourqurean et al. 2012).

The blue carbon potential of seagrass ecosystems is especially important in Southeast Asia, which hosts one of the highest diversities of seagrass species worldwide (Fortes et al. 2018; Short et al. 2011). The region features extensive tropical coastlines and shallow-water habitats that support a variety of seagrass species across diverse environmental conditions, including estuaries, lagoons, coral-reef flats, and subtidal shoals (Fortes et al. 2018; Green and Short 2003). Countries like Indonesia, Malaysia, the Philippines, and Thailand are home to large seagrass meadows that play vital roles in regional biodiversity, fisheries productivity, and coastal ecosystem stability (Fortes et al. 2018; Japar Sidik et al. 2006; Nordlund et al. 2016; Prathep 2003; Unsworth et al. 2019). These ecosystems also serve as important carbon sinks in tropical coastal environments, thereby enhancing their role in climate change mitigation and sustainable coastal management (Duarte et al. 2013; Fourqurean et al. 2012). The assessments have further emphasized the large carbon storage capacity of tropical seagrass sediments, showing their importance as natural climate solutions in global efforts to reduce carbon (Alongi 2014; Fourqurean et al. 2012).

Nevertheless, despite their ecological and climatic significance, seagrass ecosystems are undergoing a rapid global decline. The loss of seagrass habitats has been estimated at approximately 7% annually in certain regions, predominantly due to anthropogenic disturbances such as coastal development, eutrophication, sedimentation, dredging, and climate-related stressors (Waycott et al. 2009). The deterioration of seagrass meadows not only results in biodiversity loss and diminished fisheries productivity but may also release stored sediment carbon, thereby potentially transforming these ecosystems from long-term carbon sinks into sources of greenhouse gas emissions (Macreadie et al. 2017; Fourqurean et al. 2012; Pendleton et al. 2012).

Given the increasing recognition of seagrass ecosystems as vital components of coastal resilience and climate mitigation, there is an urgent need to synthesize current knowledge on their ecological functions, carbon sequestration capacity, and conservation challenges, especially in Southeast Asia. This review aims to provide a comprehensive overview of seagrass ecosystems, with particular emphasis on their distribution, ecological roles, and blue carbon potential in Southeast Asia. Furthermore, the review examines the environmental and biological factors influencing carbon storage, identifies major human threats to seagrass habitats, and discusses emerging restoration and

conservation strategies to enhance their contributions to climate change mitigation and sustainable coastal management.

SEAGRASS DIVERSITY AND DISTRIBUTION IN SOUTHEAST ASIA

Southeast Asia is widely recognized as a global hotspot for seagrass biodiversity, supporting a significant portion of the world's seagrass species within its tropical coastal waters (Short 2025; Fortes et al. 2018; Short et al. 2011). The region is part of the Indo-Pacific, which has the greatest diversity of seagrass species worldwide. This high diversity results from the presence of various coastal environments, including estuaries, lagoons, coral reef flats, intertidal mudflats, and shallow continental shelves, all of which provide suitable conditions for seagrass establishment and growth (Green and Short 2003; Short et al. 2007). These habitats are typically characterized by warm tropical temperatures, relatively stable salinity levels, and shallow water depths that allow enough light penetration for seagrass photosynthesis and productivity (Orth et al. 2006; Hemminga and Duarte 2000).

Seagrass species richness in Southeast Asia varies among countries, ranging from 7 to 19 species (Table 1), with the highest diversity observed in the Philippines, Indonesia, and Malaysia (Zakaria et al. 2025; Salim et al. 2025; Kurniawan et al. 2024; Che Alias et al. 2024; Fortes et al. 1998). Throughout the region, seagrass meadows are found in diverse coastal environments, reflecting the influence of environmental factors such as sediment type, hydrodynamic conditions, and nutrient levels (Kilminster et al. 2015; Green and Short 2003; Hemminga and Duarte 2000). Dominant genera in the area include *Enhalus*, *Thalassia*, *Halophila*, *Halodule*, *Cymodocea*, and *Syringodium*, each exhibiting unique morphological traits and ecological adaptations that enable them to thrive in various habitats. Larger, canopy-forming species such as *Enhalus acoroides* and *Thalassia hemprichii* are typically found on more stable substrates, while smaller, fast-growing species such as *Halophila* spp. and *Halodule* spp. are more common in dynamic or disturbed environments (Kilminster et al. 2015; Hemminga and Duarte 2000).

Several Southeast Asian countries, including Indonesia, Malaysia, the Philippines, Thailand, and Vietnam, support extensive seagrass meadows that greatly contribute to marine biodiversity and ecosystem productivity (Fortes et al. 2018; Short et al. 2007). These habitats serve as vital nursery grounds for fish, crustaceans, and other marine organisms while also supporting artisanal fisheries and coastal livelihoods in tropical communities (Nordlund et al. 2016; Unsworth et al. 2019). In Malaysia, at least 17 seagrass species have been recorded across coastal regions in Peninsular Malaysia, Sabah, and Sarawak, representing some of the highest national diversities in the region (Zakaria et al. 2025; Fortes et al. 2018; Bujang et al. 2006). These meadows occur across diverse habitats, including estuarine systems, coastal lagoons, intertidal mudflats, and reef-associated shoals (Zakaria et al. 2025; Bujang et al. 2018), with species composition reflecting local environmental factors such as sediment type, hydrodynamic exposure, and nutrient availability (Kilminster et al. 2015; Yaakub et al. 2014).

Notably, the recent discovery of *Halophila nipponica* in Malaysian waters highlights the evolving understanding of seagrass diversity in the region and emphasizes the importance of ongoing monitoring and taxonomic refinement (Zakaria et al. 2025; Che Alias et al. 2024).

Despite their ecological importance, the spatial distribution of seagrass ecosystems in Southeast Asia is only partially documented due to limited long-term monitoring and inconsistent regional mapping efforts (Fortes et al. 2018; Short et al. 2011). Recent advances in remote sensing technologies and geographic information systems have improved the ability to map and monitor seagrass habitats; however, additional efforts are needed to create comprehensive baseline data on seagrass distribution, habitat characteristics, and ecosystem functions to support effective conservation and management strategies throughout the region (McKenzie et al. 2020; Phinn et al. 2012).

Table 1. Seagrass species distribution in Southeast Asia by country/territory.+

No.	Family and species	BN	ID	CM	MM	MY	PH	SG	TH	VN	AN ⁺
	Seagrass area (km²)	1.5	8,812.9	324.9	4.3	16.3	27,262.2	0.3	148.5	157.4	8.3
	1. Family Hydrocharitaceae										
1.	<i>Enhalus acoroides</i> (L. f.) Royle	•	•	•	•	•	•	•	•	•	•
2.	<i>Thalassia hemprichii</i> (Ehrenb.) Aschers.	•	•	•	•	•	•	•	•	•	•
3.	<i>Halophila beccarii</i> Aschers.	•	•	•	•	•	•	•	•	•	•
4.	<i>Halophila decipiens</i> Ostenfeld		•	•	•	•	•	•	•	•	•
5.	<i>Halophila gaudichaudii</i> J. Kuo						•				
6.	<i>Halophila major</i> (Zoll.) Miq.		•		•	•	•		•	•	
7.	<i>Halophila minor</i> (Zoll.) den Hartog		•	•	•	•	•	•	•	•	
8.	<i>Halophila ovalis</i> (R. Br.) Hook. f.	•	•	•	•	•	•	•	•	•	•
9.	<i>Halophila ovata</i> Gaudich. and in Freycinet						•				•
10.	<i>Halophila nipponica</i> J.Kuo					•					
11.	<i>Halophila spinulosa</i> Aschers.	•	•		•	•	•	•			
12.	<i>Halophila sulawesii</i> J. Kuo		•								
13.	<i>Halophila</i> sp. 1						•				
14.	<i>Halophila</i> sp. 2 (<i>Halophila tricostata</i> Greenway)					•	•				
	2. Family Cymodoceaceae										
15.	<i>Cymodocea rotundata</i> Ehrenb. et Hempr. ex Aschers.	•	•	•	•	•	•	•	•	•	•

Seagrass ecosystems, their carbon storage.....

No.	Family and species	BN	ID	CM	MM	MY	PH	SG	TH	VN	AN ⁺
	Seagrass area (km²)	1.5	8,812.9	324.9	4.3	16.3	27,262.2	0.3	148.5	157.4	8.3
16.	<i>Cymodocea serrulata</i> (R. Br.) Aschers. et Magnus		•	•	•	•	•	•	•	•	•
17.	<i>Halodule pinifolia</i> (Miki) den Hartog	•	•	•	•	•	•	•	•	•	•
18.	<i>Halodule uninervis</i> (Forssk.) Aschers.		•	•	•	•	•	•	•	•	•
19.	<i>Syringodium isoetifolium</i> (Aschers.) Dandy		•	•	•	•	•	•	•	•	•
20.	<i>Thalassodendron ciliatum</i> (Forssk.) den Hartog		•			•	•			•	
	3. Family Ruppiaceae										
21.	<i>Ruppia maritima</i> L.		•	•		•	•		•		
22.	<i>Ruppia brevipedunculata</i> Shuo Yu & den Hartog		•								
	4. Family Zosteraceae										
23.	<i>Zostera japonica</i> Aschers. et Graebn.									•	
	Total number of species	7	17	12	13	17	19	12	13	14	9

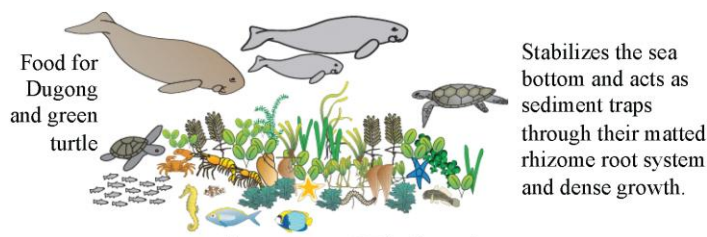
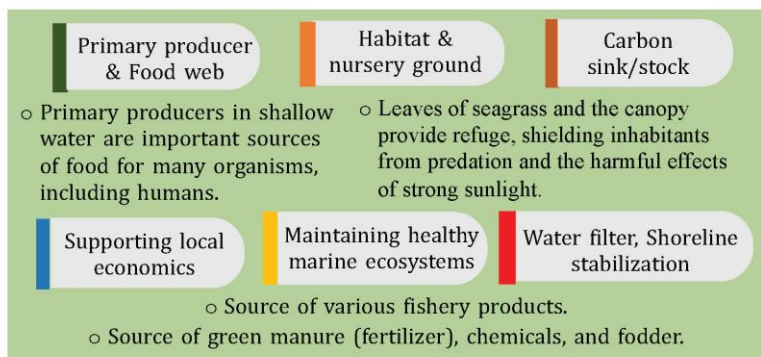
Country codes and references used to compile this list as follows: BN, Brunei (Lamit et al. 2017; Fortes 1988); ID, Indonesia (Salim et al. 2025; Kurniawan et al. 2024; Tuntiprapas et al. 2015; Wawan 2011; Kuo 2007); CM, Cambodia (Vibol et al. 2010; UNEP 2008); MM, Myanmar (BOBLME 2015; Nguyen et al. 2014; Novak et al. 2009; Soe-Htun et al. 2009); MY, Malaysia (Zakaria et al. 2025; Che Alias et al. 2024; Nguyen et al. 2014; Japar Sidik and Muta Harah 2011); PH, Philippines (Kim et al. 2017; Fortes 2013; Waycott et al. 2002; Fortes 1989); SG, Singapore (Yaakub et al. 2013); TH, Thailand (Tuntiprapas et al. 2015; Nguyen et al. 2014); VN, Viet Nam (Nguyen et al. 2014; 2013); AN, Andaman and Nicobar Islands (Tangaradjou et al. 2010; Jagtap et al. 2003), the “+” denoting this is a union territory of India.

ECOSYSTEM FUNCTIONS AND SERVICES OF SEAGRASS MEADOWS

Seagrass meadows provide a wide range of ecological functions that support the stability of coastal ecosystems and marine biodiversity (Fig. 2). As highly productive marine habitats, seagrasses play a major role in primary production in shallow coastal areas and create structurally complex habitats that support numerous marine species (Orth et al. 2006; Hemminga and Duarte 2000). The dense canopy formed by seagrass leaves and rhizomes provides shelter, feeding grounds, and nursery habitats for many fish, crustaceans, and invertebrates, including species of commercial and ecological importance (Unsworth et al. 2019; Heck et al. 2003). A key ecological role of seagrass ecosystems is their function as nursery habitats for juvenile fish and invertebrates. Many marine species rely on seagrass meadows during early life stages because the complex vegetation offers protection from predators and supplies abundant food resources (Unsworth et al. 2019; Heck et al. 2003). Studies have shown that fish abundance and diversity are often significantly greater in seagrass habitats than nearby unvegetated areas, emphasizing the importance of seagrass meadows in supporting coastal fisheries productivity (Nordlund et al. 2016; Orth et al. 2006).

In addition to supporting marine biodiversity, seagrass ecosystems play a crucial role in regulating coastal physical processes. Dense seagrass canopies reduce wave energy and water flow, promoting sediment deposition and stabilizing seabed substrates (Christianen et al. 2013; Koch et al. 2009). The root–rhizome network further binds sediments, reducing erosion and helping to maintain coastal geomorphological stability (Koch et al. 2009; Hemminga and Duarte 2000). By trapping suspended particles and enhancing sediment stabilization, seagrass meadows also improve water clarity and support the conditions necessary for benthic primary producers like corals and other seagrasses (Orth et al. 2006). Seagrasses also play a key part in nutrient cycling and water quality regulation within coastal ecosystems. Through nutrient uptake from sediments and the water column, seagrasses influence the cycling and retention of essential nutrients such as nitrogen and phosphorus (McGlathery et al. 2007; Hemminga and Duarte 2000). The interaction among seagrass plants, sediments, and microbial communities enhances nutrient transformation processes, which can help reduce eutrophication and sustain ecosystem productivity in coastal waters (Waycott et al. 2009; McGlathery et al. 2007).

Seagrass Ecosystem Benefits



Seagrass and Biodiversity

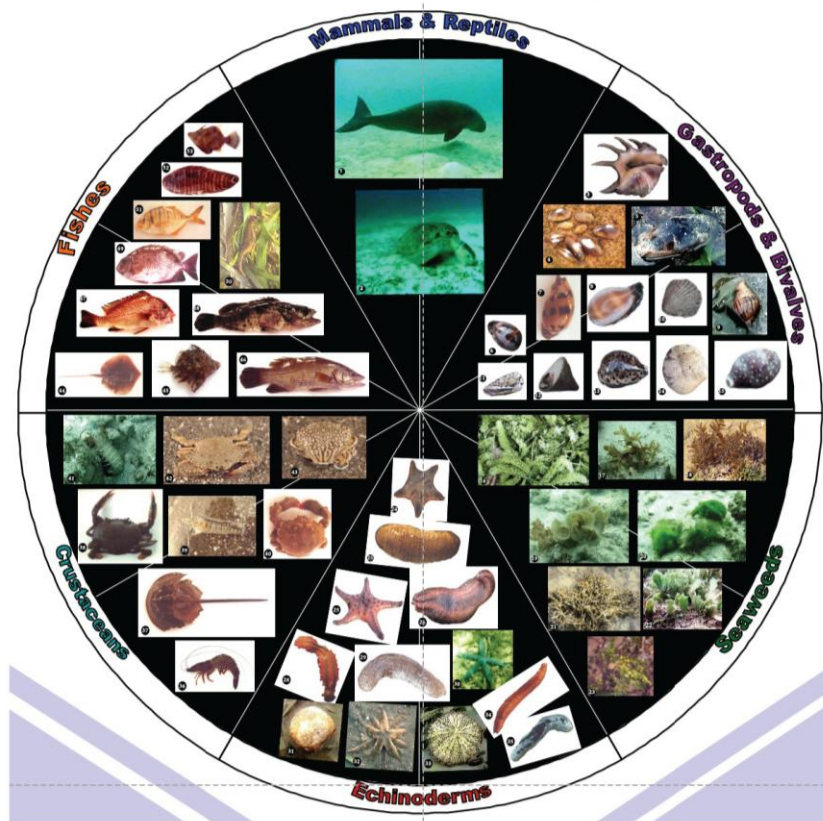


Figure 2: Importance and biodiversity of seagrass ecosystems

Beyond their ecological significance, seagrass ecosystems offer many socio-economic benefits to coastal communities. Seagrass meadows support fisheries resources, contribute to food security, and provide livelihoods for millions of people worldwide, especially in tropical regions where coastal populations rely heavily on marine resources (Unsworth et al. 2019; Nordlund et al. 2016). Additionally, seagrass ecosystems help stabilize sediments, protect shorelines, and improve water quality, supporting the long-term sustainability of coastal environments and their ecosystem services (Koch et al. 2009; Orth et al. 2006).

Given their multiple ecological and socio-economic roles, conserving and managing seagrass ecosystems is increasingly important for maintaining coastal resilience and supporting sustainable ocean economies. These ecosystem services also provide the foundational basis for the progressive acknowledgment of seagrass meadows as essential blue carbon ecosystems, thereby playing a pivotal role in worldwide carbon sequestration and climate change mitigation (Fig. 3).

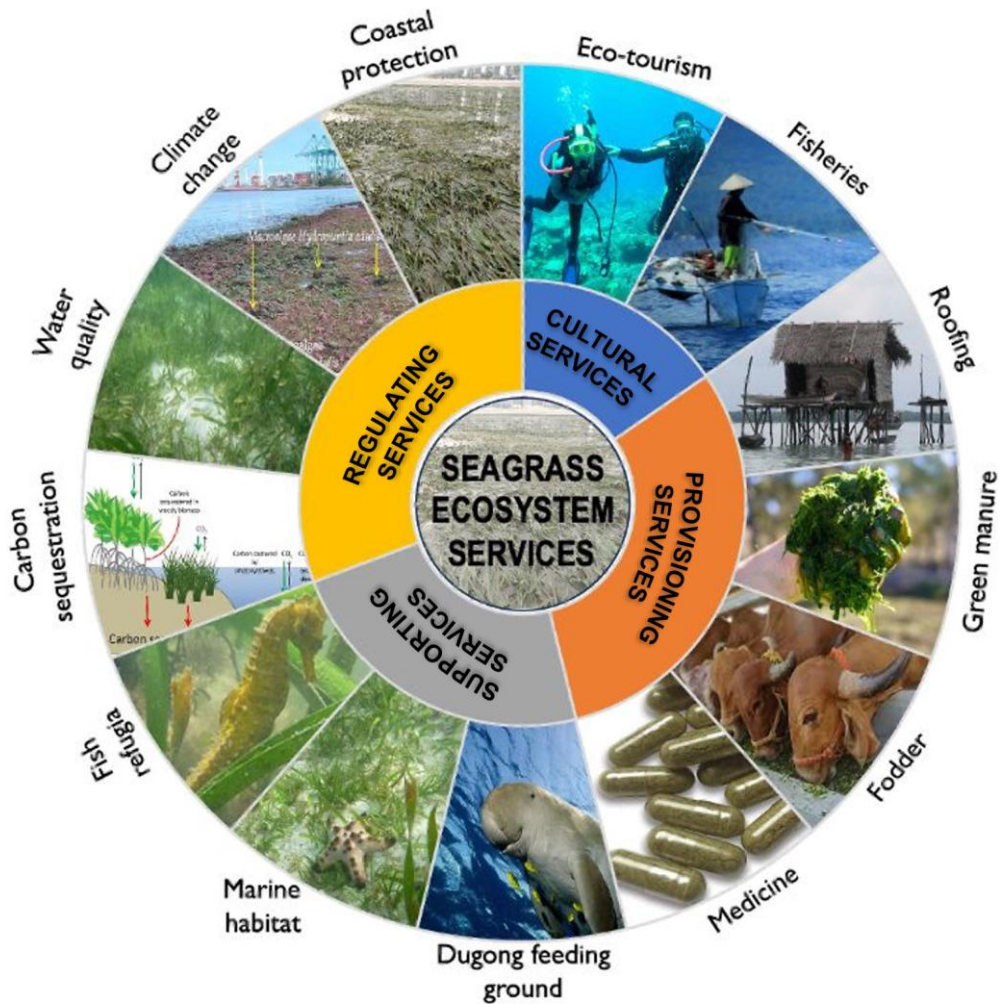


Figure 3: Seagrass ecosystem services

BLUE CARBON POTENTIAL OF SEAGRASS ECOSYSTEMS

Seagrass ecosystems are increasingly recognized as some of the most vital blue carbon habitats, playing a critical role in the long-term sequestration and storage of atmospheric carbon dioxide in coastal marine environments (Duarte et al. 2013; McLeod et al. 2011). Blue carbon refers to the carbon captured and stored by vegetated coastal ecosystems such as seagrasses, mangroves, and salt marshes, which collectively help combat climate change by removing carbon dioxide from the atmosphere and storing it in plant biomass and marine sediments (Pendleton et al. 2012; McLeod et al. 2011).

Seagrasses absorb carbon through photosynthesis by converting dissolved inorganic carbon into organic matter, which is incorporated into plant tissues such as leaves, roots, and rhizomes (Duarte et al. 2013; Hemminga and Duarte 2000). A large portion of this organic carbon is subsequently transferred to surrounding sediments via plant litter deposition, root turnover, and sediment trapping processes linked to the seagrass canopy structure (Duarte et al. 2013; Kennedy et al. 2010). Over time,

the accumulation of organic matter in anoxic sediments creates long-term carbon reservoirs beneath seagrass meadows.

One of the key features of seagrass ecosystems is their remarkably ability to store carbon in sediments over extended periods. Seagrass sediments often contain large amounts of organic carbon that can remain buried for centuries or even thousands of years because of slow decomposition rates under low-oxygen conditions (Duarte et al. 2013; Fourqurean et al. 2012). Although seagrass meadows cover less than 0.2% of the global ocean floor, they are responsible for about 10% of the ocean's annual carbon burial, highlighting their important role in global carbon sequestration (Fourqurean et al. 2012).

Global assessments estimate that seagrass ecosystems store significant amounts of carbon in their sediments and biomass, with global seagrass carbon reserves reaching several petagrams of carbon (Macreadie et al. 2017; Fourqurean et al. 2012). Carbon burial rates in seagrass meadows are among the highest observe in marine ecosystems, often surpassing those in terrestrial forests on a per-area basis (Alongi 2014; Duarte et al. 2013). These findings have increased recognition of seagrass ecosystems as valuable natural climate solutions that can aid carbon mitigation. The potential of seagrass ecosystems for blue carbon storage is particularly significant in tropical areas such as Southeast Asia, where high primary productivity and suitable conditions foster the growth of extensive seagrass meadows (Fortes et al. 2018; Alongi 2014). Tropical seagrass systems frequently have high biomass and sediment carbon storage, especially in habitats with fine sediments and stable water movement (Macreadie et al. 2017; Kennedy et al. 2010). Therefore, protecting and restoring seagrass ecosystems in tropical coastal areas is a promising way to boost coastal carbon storage and aid climate change mitigation efforts.

However, the ability of seagrass ecosystems to serve as effective carbon sinks heavily relies on ecosystem integrity and long-term habitat stability. Disturbances such as coastal development, eutrophication, dredging, and physical damage can degrade and loss of seagrass meadows, which may then release stored sediment carbon back into the water column and atmosphere (Macreadie et al. 2017; Pendleton et al. 2012). Therefore, conserving and restoring seagrass habitats are increasingly seen as essential parts of global blue carbon strategies.

FACTORS INFLUENCING CARBON STORAGE IN SEAGRASS MEADOWS

The ability of seagrass ecosystems to store and sequester carbon varies widely across different geographic regions and habitat types, influenced by multiple interacting biological and environmental factors. Carbon stocks within seagrass meadows are affected by elements such as species composition, plant morphology, sediment characteristics, hydrodynamic conditions, and ecosystem productivity, all of which control both the generation of organic carbon and its long-term preservation in the sediments below (Duarte et al. 2013; Fourqurean et al. 2012; Kennedy et al. 2010). Biological traits regulate carbon production, while sediment properties and hydrodynamic conditions influence organic carbon burial and preservation. Both autochthonous and allochthonous inputs contribute to carbon stocks, collectively determining the magnitude and persistence of blue carbon in coastal ecosystems. In tropical coastal systems, especially in Southeast Asia, landscape connectivity to nearby habitats like mangroves and estuaries further influences carbon storage. These habitats supply additional organic inputs and enhance sediment carbon accumulation (Fortes et al. 2018; Rozaimi et al. 2017; Miyajima et al. 2015). Understanding these interactions is essential for accurately estimating blue carbon stocks and identifying habitats with high potential for long-term carbon sequestration.

Biological Controls: Species Traits and Morphology

Species composition and plant morphology are crucial in determining the carbon storage potential of seagrass ecosystems. Large canopy-forming species such as *Enhalus acoroides* and

Thalassia hemprichii generally produce more above- and belowground biomass than smaller pioneer species, leading to higher organic carbon inputs into surrounding sediments (Duarte et al. 2013; Hemminga and Duarte, 2000). Their extensive root and rhizome systems improve sediment stability, help trap suspended particles, and support long-term carbon burial by reducing sediment resuspension (Koch et al. 2009; Orth et al. 2006).

In contrast, smaller species such as *Halophila* spp. and *Halodule* spp. typically have lower biomass, shorter life cycles, and faster turnover rates and are often adapted to dynamic or disturbed environments (Kilminster et al. 2015). While these species contribute to primary production and early colonization, their relatively shallow root systems and lower biomass result in smaller sediment carbon pools than those of larger climax species (Duarte et al. 2013; Hemminga & Duarte, 2000). Consequently, variations in species composition and morphological traits across various areas cause variation in carbon storage capacity among seagrass meadows.

Sediment Controls on Carbon Retention

Sediment properties are crucial for organic carbon accumulation and long-term preservation in seagrass ecosystems. Fine-grained sediments, such as silts and clays, generally support higher levels of organic carbon because they can facilitate the deposition and retention of organic particles while restricting oxygen penetration into the sediment column (Fourqurean et al. 2012; Kennedy et al. 2010). Limited oxygen availability slows microbial decomposition, enabling organic carbon to be preserved over longer periods.

In contrast, coarse sandy substrates are more permeable, allowing greater water exchange and oxygen penetration, which can accelerate microbial decomposition and reduce long-term carbon storage capacity (Macreadie et al. 2017). This pattern is especially clear in tropical seagrass systems, where meadows located in muddy, estuarine, or mangrove-influenced environments often have substantially higher sediment carbon stocks than those on exposed sandy substrates (Rozaimi et al. 2017; Miyajima et al. 2015). These results highlight the importance of sediment grain size and depositional environments in regulating carbon retention within seagrass meadows.

Sources and Inputs of Organic Carbon

Although seagrasses produce organic carbon through their own primary production, much of the carbon stored in seagrass sediments originates from external sources. Many studies have shown that sediment carbon pools can include contributions from mangroves, phytoplankton, macroalgae, and terrestrial organic matter transported from nearby ecosystems (Duarte and Krause-Jensen 2017; Howard et al. 2017; Oreska et al. 2017; Miyajima et al. 2015; Kennedy et al. 2010).

Seagrass canopies reduce current flow and enhance the capture of suspended particles, causing the accumulation of allochthonous organic matter in meadow sediments (Duarte and Krause-Jensen, 2017). As a result, seagrass ecosystems act not only as sources of carbon but also as effective sediment traps that collect and hold organic material from surrounding areas. This process is especially important in tropical coastal systems where seagrass meadows are located near mangrove forests. Organic matter exported from mangroves can be transported into nearby seagrass habitats and later buried in sediments, greatly contributing to overall carbon stocks (Miyajima et al. 2015; Kennedy et al. 2010). In Southeast Asia, research indicates that a significant portion of carbon in seagrass sediments may originate from mangroves, underscoring the role of cross-ecosystem carbon transfer in coastal blue carbon dynamics (Fortes et al. 2018; Rozaimi et al. 2017).

Hydrodynamic and Environmental Conditions

Hydrodynamic conditions and environmental gradients further affect carbon storage by affecting sediment stability and organic matter accumulation. Seagrass meadows in sheltered areas, such as lagoons, estuaries, and enclosed bays, typically experience lower wave energy and increased sediment deposition, which promotes organic carbon accumulation and long-term storage (Kennedy et al. 2010; Koch et al. 2009). Conversely, meadows exposed to strong currents and wave action face higher sediment resuspension, which can reduce carbon retention.

Environmental factors such as water depth, light availability, and nutrient levels also affect seagrass productivity and its ability to sequester carbon. High primary productivity boosts the input of organic material into sediment carbon stores through litter deposition and root turnover (Duarte et al. 2013). However, excessive nutrient enrichment can destabilize seagrass habitats by encouraging algal overgrowth and reducing light availability, which can lead to meadow degradation and potential carbon loss (Waycott et al. 2009).

THREATS TO SEAGRASS ECOSYSTEMS AND IMPLICATIONS FOR CARBON LOSS

Despite their ecological importance and significant role in carbon sequestration, seagrass ecosystems are declining globally. Human activities such as coastal development, eutrophication, sedimentation, destructive fishing practices, and climate change have sped up the deterioration and loss of seagrass habitats in many regions (Waycott et al. 2009; Orth et al. 2006). These threats not only reduce seagrass coverage and biodiversity but also affect the stability of carbon stored in seagrass sediments. Coastal development and land reclamation are especially major threats in rapidly growing coastal areas like Southeast Asia. Activities such as dredging, port construction, and shoreline modification can directly remove seagrass beds or disturb sediment dynamics and water quality, leading to habitat loss (Fortes et al. 2018; Unsworth et al. 2018). Increased sedimentation related to coastal development can decrease light penetration in the water, limiting photosynthesis and ultimately causing seagrass decline (Orth et al. 2006). In Malaysia, human activities like coastal development, land reclamation, and natural phenomena (e.g., climate change) pose major threats in fast-growing coastal regions (Fig. 4).

Eutrophication caused by nutrient runoff from agriculture, sewage discharge, and aquaculture is another major factor in seagrass loss. Elevated nutrient levels can promote the growth of phytoplankton and epiphytic algae, thereby reducing light available to seagrass leaves and hindering plant growth (Waycott et al. 2009; Burkholder et al. 2007). Long-term eutrophication can lead to widespread meadow degradation and ecosystem collapse. Physical disturbances like boat anchoring, trawling, and coastal construction can also harm seagrass beds by uprooting plants and disrupting sediment stability (Waycott et al. 2009; Burkholder et al. 2007). These activities often fragment seagrass meadows and weaken their role as sediment stabilizers and carbon sinks (Unsworth et al. 2018; Orth et al. 2006). The decline of seagrass ecosystems has serious implications for blue carbon storage.

Seagrass Ecosystem, Climate Change, and Human Activities

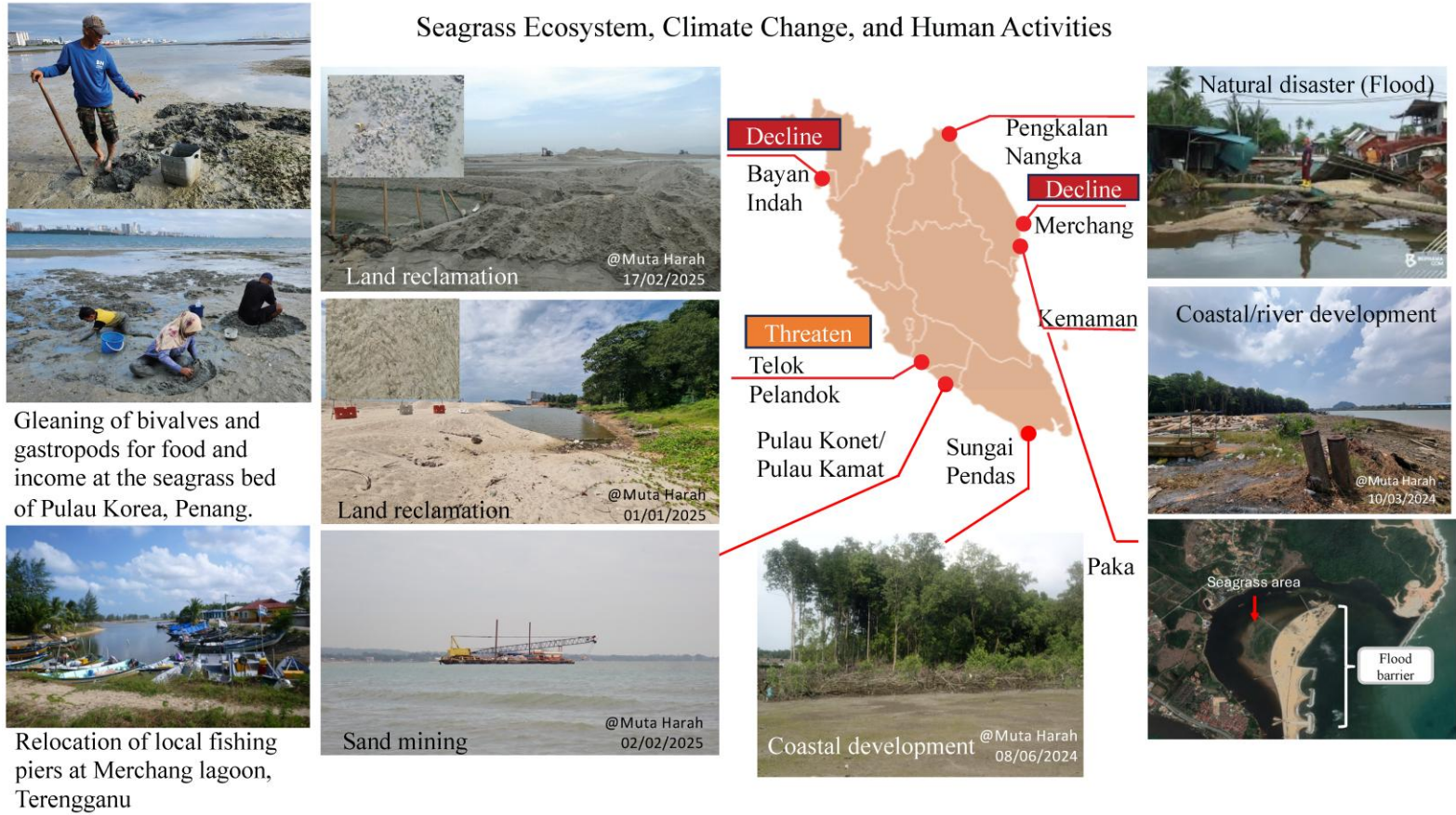


Figure 4. Rapid coastal development and rising pollution threaten to erode seagrass habitats. Once the root mat is disturbed, centuries of stored carbon can be released within years

When seagrass meadows are disturbed or destroyed, organic carbon buried in sediments can become exposed to oxygen, speeding up microbial decomposition and releasing stored carbon into the water or atmosphere (Macreadie et al. 2017; Pendleton et al. 2012). In such situations, seagrass ecosystems may change from long-term carbon sinks to sources of greenhouse gases.

Previous studies have shown that the loss of vegetated coastal ecosystems, including seagrasses, mangroves, and salt marshes, may significantly contribute to global carbon emissions associated with coastal habitat degradation (Pendleton et al. 2012). As a result, protecting existing seagrass meadows and restoring degraded habitats have become key priorities in blue carbon conservation efforts to combat climate change. Given the rapid coastal development across much of Southeast Asia, conserving seagrass ecosystems is especially crucial in this region. Improving coastal management policies, enhancing environmental monitoring, and promoting ecosystem-based management approaches will be vital to reducing human pressures and maintaining the carbon sequestration capacity of seagrass ecosystems.

SEAGRASS RESTORATION AND CONSERVATION FOR BLUE CARBON

The growing recognition of seagrass ecosystems as key blue carbon sinks underscores the need to protect existing meadows and restore degraded habitats. Seagrass meadows store large amounts of organic carbon in both plant biomass and underlying sediments, making them key players in long-term coastal carbon storage (Duarte et al. 2013; Fourqurean et al. 2012). Efforts focused on conserving and restoring seagrass ecosystems are increasingly valued as nature-based solutions that help mitigate climate change while also boosting coastal biodiversity, fisheries productivity, and ecosystem resilience (Unsworth et al. 2019; Macreadie et al. 2017).

Various restoration methods have been developed to help the recovery of degraded seagrass habitats. Among these, transplanting vegetative shoots or sods from donor meadows has historically been one of the most commonly used techniques, especially for species that spread through rhizome growth (Orth et al. 2006; Fonseca et al. 1998). The success of vegetative transplantation mainly depends on environmental factors like sediment stability, water clarity, and hydrodynamic conditions, which influence the survival and growth of transplanted shoots (van Katwijk et al. 2016).

In Southeast Asia, restoration research has been vital in developing seagrass transplantation methods and improving ecological understanding of meadow recovery. Early restoration efforts in the Philippines demonstrated the possibility of reestablishing tropical seagrass species in disturbed coastal areas (Fortes et al. 2018; Fortes 1990). In Indonesia, studies by Kiswara and Rappe further advanced restoration techniques by evaluating transplantation methods and community-based programs aimed at restoring seagrass in degraded coastal ecosystems (Rappe et al. 2013; Kiswara 2004). These regional efforts have helped create practical restoration strategies suited to tropical coastal environments.

Recently, seed-based restoration methods have gained more attention as alternative strategies for seagrass rehabilitation. Unlike vegetative transplantation, seedling-based restoration can enhance genetic diversity while reducing pressure on donor meadows. Studies in Malaysia have shown that transplanting seedlings of tropical species such as *Enhalus acoroides* can successfully support meadow recovery under suitable environmental conditions. Long-term monitoring in the Sungai Pulai estuary has revealed that seedling transplantation helps establish stable seagrass patches and aids sediment stabilization in disturbed coastal habitats (Zakaria et al. 2025, Fig. 5). These results suggest that seed-based approaches could be a promising option for restoring large tropical seagrass species that produce viable seeds and seedlings.

Despite advances in restoration techniques, conserving existing seagrass ecosystems remains the most effective way to protect blue carbon stocks. Mature seagrass meadows store organic carbon in

sediments for long periods, and disturbance or removal of these habitats can release this stored carbon into the environment (Macreadie et al. 2017; Pendleton et al. 2012).

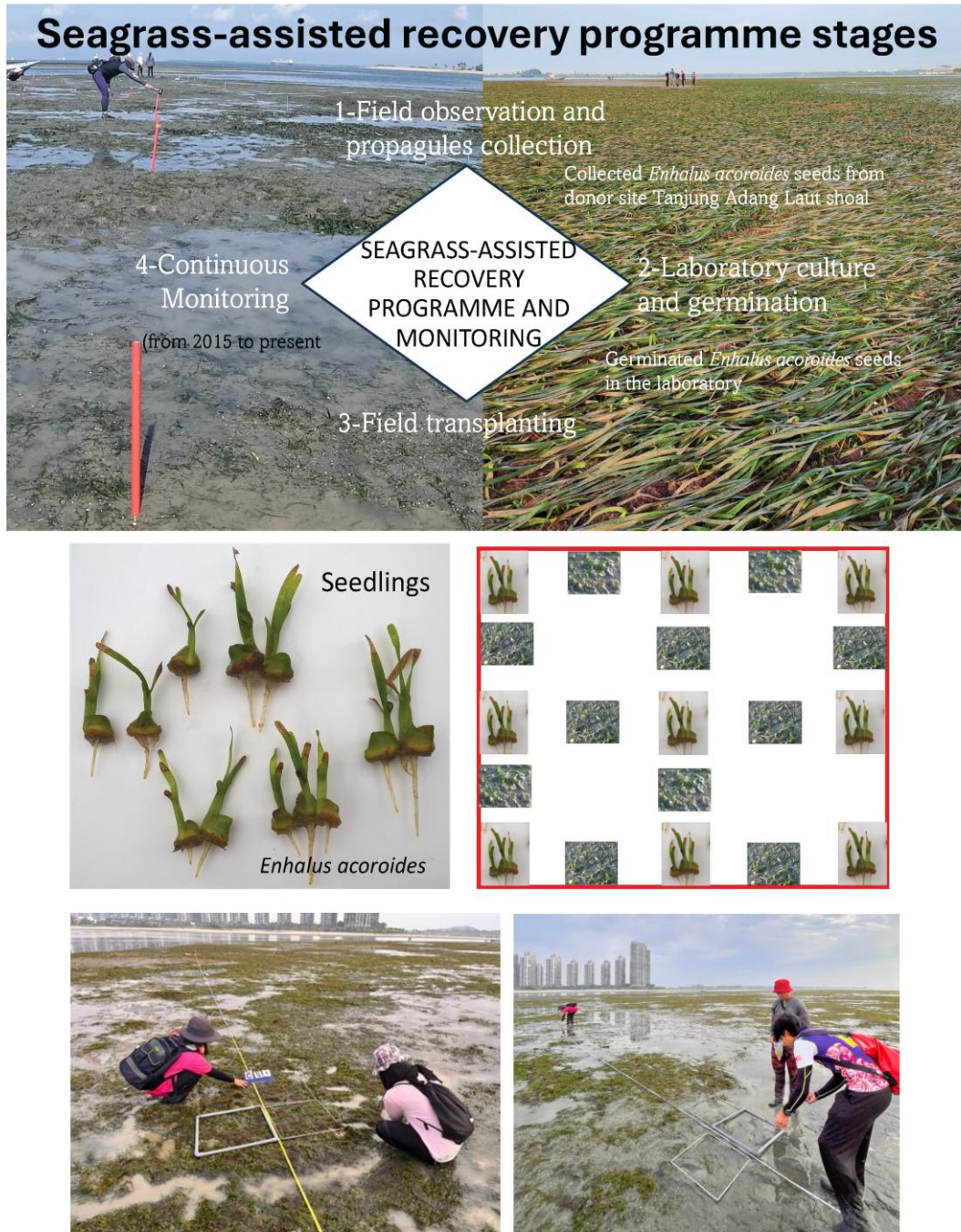


Figure 5: Long-term monitoring in the Sungai Pulai estuary has shown that seedlings of *Enhalus acoroides* and mixed transplants with *Halophila ovalis*/*H. major*/*H. spinulosa*

Therefore, protecting healthy seagrass habitats through marine protected areas, integrated coastal management, and enhanced environmental monitoring is crucial for maintaining their long-term carbon storage capacity (Unsworth et al. 2019).

Given the rapid coastal development across Southeast Asia, enhancing conservation and restoration efforts will be crucial for maintaining the ecological functions of seagrass ecosystems. Integrating seagrass conservation and restoration into blue carbon management and coastal planning strategies can provide valuable opportunities to boost climate mitigation while maintaining coastal ecosystem resilience.

KNOWLEDGE GAPS AND FUTURE RESEARCH DIRECTIONS

Although there is growing recognition of the ecological and climate-regulating importance of seagrass ecosystems, many knowledge gaps still exist in understanding their role in global blue carbon dynamics. While significant progress has been made in quantifying carbon stocks in temperate seagrass ecosystems, data from tropical regions, especially Southeast Asia, remains limited (Miyajima et al. 2015; Fourqurean et al. 2012). Since Southeast Asia has one of the highest diversities of seagrass species and expansive shallow coastal habitats, improving regional carbon stock assessments is essential for developing more accurate global blue carbon estimates (Unsworth et al. 2019; Fortes et al. 2018).

Another significant research gap involves the impact of species-specific traits and habitat variability on carbon sequestration potential. Seagrass species vary greatly in morphology, growth strategies, and biomass allocation patterns, which can affect sediment stabilization and organic carbon accumulation (Duarte et al. 2013; Hemminga and Duarte 2000). However, comparative studies examining how morphological plasticity and habitat adaptation influence carbon storage remain limited, particularly for tropical species. Understanding these connections is crucial for identifying species and habitats with the highest carbon sequestration potential and for enhancing restoration efforts.

Furthermore, the role of external carbon sources in seagrass sediment carbon pools needs further research. While past studies indicate that a large portion of sediment carbon in seagrass meadows may come from mangroves, phytoplankton, or terrestrial sources, the contributions of these sources can vary greatly across regions and environments (Duarte and Krause-Jensen 2017; Kennedy et al. 2010). Understanding of how carbon is transferred between mangroves, seagrasses, and nearby coastal habitats is crucial for improving blue carbon accounting methods.

Another emerging field of research involves combining genetic and ecological studies to better understand the resilience and adaptive capacity of seagrass populations. Genetic diversity affects the ability of seagrass populations to respond to environmental stressors, including climate change, coastal development, and habitat fragmentation (Unsworth et al. 2019; Orth et al. 2006). However, studies linking genetic variation to habitat characteristics and ecosystem functioning remain limited, particularly for tropical seagrass species.

Finally, although restoration efforts have increased in recent years, many projects still have limited spatial scope and lack long-term monitoring. Better assessment of restoration outcomes, including survival, meadow growth, and carbon accumulation, is essential to evaluate the effectiveness of different restoration methods (Macreadie et al. 2017; van Katwijk et al. 2016). Integrating long-term ecological monitoring with blue carbon assessments is essential for measuring how restoration programs contribute to climate mitigation and ecosystem recovery.

Addressing these research gaps is vital for improving our understanding of seagrass ecosystem functions and highlighting the significance of seagrass meadows in global blue carbon efforts. Future research should emphasize interdisciplinary approaches that combine ecological, biogeochemical, and genetic insights to better understand the resilience and carbon storage potential of seagrass ecosystems.

CONCLUSION

Seagrass ecosystems are among the most vital coastal habitats for supporting biodiversity, stabilizing sediments, and regulating carbon processes in marine environments. As a crucial part of global blue carbon systems, seagrass meadows play an important role in capturing and storing atmospheric carbon dioxide in both plant biomass and sediments below. Their ability to function as long-term carbon sinks depends on various interacting factors, including species composition, plant morphology, sediment properties, water movement, and the degree to which the landscape is connected to neighboring coastal habitats. In Southeast Asia, seagrass meadows exist across diverse coastal environments and significantly contribute to regional ecological productivity and coastal resilience. However, these ecosystems face increasing threats from coastal development, sediment accumulation, eutrophication, and climate-related disruptions. These threats not only endanger seagrass biodiversity and ecosystem functions but may also disrupt long-term sediment carbon storage, potentially transforming seagrass meadows from carbon sinks into sources of greenhouse gases.

Restoration and conservation efforts are crucial for preserving the ecological and climate-regulating functions of seagrass ecosystems. Recent studies show that both vegetative transplantation and seedling-based restoration can help recover degraded seagrass habitats when environmental conditions are appropriate. Specifically, restoration projects involving tropical species like *Enhalus acoroides* demonstrate the potential of assisted recovery techniques to enhance sediment stabilization and improve long-term ecosystem resilience.

Despite growing scientific interest, several research gaps remain in understanding the carbon dynamics and ecological roles of tropical seagrass ecosystems. Future studies should focus on improving regional carbon stock assessments, examining how species traits and habitat variability influence carbon sequestration, and utilizing ecological, genetic, and biogeochemical methods to better evaluate seagrass resilience and restoration success.

Strengthening conservation policies, increasing restoration efforts, and expanding scientific research are essential for protecting seagrass ecosystems and maintaining their vital role in coastal climate mitigation strategies. Protecting and restoring seagrass beds will not only preserve biodiversity and ecosystem services but also contribute significantly to global efforts to fight climate change and ensure coastal ecosystems remain healthy.

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Report from ISSAAS Secretariat

ISSAAS Board of Directors Meeting 2025

Date: 5 November 2025 (Fri), 17:30 –19:30

Venue: Dong Do Meeting Room, 2nd Floor, Thang Long Opera Hotel, Hanoi
Vietnam

AGENDA

(Presided by ISSAAS Secretary General Hironobu Shiwachi)

1. Greetings from ISSAAS President
Prof. Dr. Pham Van Cuong (VNUA)
2. Activities Report 2025 (October 2024-September 2025)
 - (a) ISSAAS International Congress 2024
Date: 9-11 November 2024
Venue: Tokyo University of Agriculture, Tokyo, Japan
Theme : *ISSAAS in 2024 and Beyond: Agricultural Sciences for Sustainable Development in Southeast Asia*
Notes: Celebrating 30 years of ISSAAS, the congress saw a strong turnout of 477 participants, including 397 international participants, representing 17 countries. In total, 273 oral and 78 poster presentations were delivered.
 - (b) Board of Directors Meeting
Date: 8 November 2024, 17:00 – 19:00
Venue: Conference Room, International Center,
Tokyo University of Agriculture, Tokyo, Japan
Decisions made:
 - a. Revision to the Bylaw of the ISSAAS Award
The following provision will be incorporated into the Bylaws:
“There shall be only one recipient of Matsuda Award every year.”
 - b. Constitution Revision
The constitution will be amended to officially recognize the Cambodia Chapter, which was established in 2024. Furthermore, effective from 2024, the membership fee for all full members – including those in the Japan Chapter - will be adjusted to US\$30. Student membership fee will remain at US\$15, maintaining a rate exactly 50% of a full membership.

Report:

a. Journal of ISSAAS

As approved during the previous Executive Board Meeting, a new page charge scheme and mandatory submission of a Turnitin Similarity Test Report were implemented starting with the ISSAAS 30(2) December 2024 Issue. Additionally, J. ISSAAS 30(2), and J. ISSAAS 31(1) were also published on schedule.

b. International Congress and General Meeting

The host chapters for the upcoming three years have been designated as Malaysia (2026), Thailand (2027), Indonesia (2028).

(c) Board of Directors Meeting

Agenda: Call for ISSAAS Award Recipients

Date: 25 June 2025

Venue: Email Conference

Status: The society received a total of two nominations for the ISSAAS Matsuda Award, submitted by the Malaysia and Vietnam Chapters and one nomination for the ISSAAS Young Scientist Award from the Japan Chapter.

(d) Board of Directors Meeting

Agenda: Granting of ISSAAS Award

Date: 19 September 2025

Venue: Email Conference

Status: In accordance with the recommendation from the Award Screening Committee, the Members of the Executive Board approved the granting of the following awards:

ISSAAS Matsuda Award

Prof. Dr. Tran Duc Vien (Vietnam) in recognition of his distinguished contributions to the advancement of science, research, and trainings on agriculture and rural development in Vietnam. The plaque will be presented during the ISSAAS General Assembly 2025 to be held at Center Hall, Vietnam National University of Agriculture on 6 November 2025.

ISSAAS Young Scientist Award

Asst. Prof. Dr. Riskina Juwita (Japan) in recognition of her distinguished contributions to research on agribusiness development of spice and herb commodities as a strategy for rural development in Indonesia, as well as her significant contribution to the growth and development of ISSAAS since 2015. The certificate will be presented during the ISSAAS General Assembly 2025 to be held at Center Hall, Vietnam National University of Agriculture on 6 November 2025.

- (e) Board of Directors Meeting
 - Agenda: Confirmation of ISSAAS Officers to be invited by SAEDA
 - Date: 19 July 2025
 - Venue: Email Conference

- (f) Publications of Journal
 - Vol.30, No.2: Published in December 2024
 - Available online (SCOPUS; <http://issaasphil.org/issaas-journals/>)

 - Vol.31, No.1: Published in June 2025
 - Available online (SCOPUS; <http://issaasphil.org/issaas-journals/>)

According to the Editorial Team, all chapters are highly active; however, some submitted papers were rejected to maintain publication standards. This included one identified case of “salami publication.” The team has also noted an increase in submissions from graduate students. Consequently, mentoring has become a unique and essential form of support provided by J. ISSAAS technical editors to help graduate students develop their academic writing skills and understand research ethics. Additionally, in recent years, the team has implemented a requirement for all authors to sign an Authorship Declaration to further ensure original and ethical reporting.

- 3. Financial Report 2025: Approved
- 4. Auditors’ Report for 2025: Approved
- 5. Business Plan for 2026 (October 2025-September 2026)
 - (a) Board of Directors Meeting
 - Date: 5 November 2024, 17:30 – 19:30
 - Venue: Dong Do Meeting Room, 2nd Floor, Thang Long Opera Hotel, Hanoi, Vietnam

 - (b) International Congress 2025
 - Date: 6-8 November 2025
 - Venue: Vietnam National University of Agriculture, Hanoi, Vietnam
 - Theme: *Development of Agriculture with Low Carbon Emission in Asia*
 - Notes: In this year, we celebrated the 31 years of ISSAAS with a total of 477 participants, including 397 international participants from 17 countries. There were also 273 oral and 78 poster presentations.

 - (c) Publications of Journal of ISSAAS
 - Vol.31, No.2: To be published in December 2025
 - Vol.32, No.1: To be published in June 2026

According to the Editorial Team, approximately 30–35 papers are processed annually. Currently, ten papers have been finalized for uploading to issaaphil.org website for the December issue. To maintain Scopus indexing standards, the team uploads content to issaasphil.org where J ISSAAS is housed, twice per year, specifically during the first weeks of December and June.

6. Budget 2025: Approved

7. ISSAAS Awards

ISSAAS Matsuda Award: Prof. Dr. Tran Duc Vien (Vietnam)

ISSAAS Young Scientist Award: Asst. Prof. Dr. Riskina Juwita (Japan)

8. Letter of Appreciation: No Issuance

9. Donations: No donation received

10. Activities Report for 2025 by Each Chapter

Indonesia	Prof. Dr. Suryo Wiyono (Chapter President; ISSAAS VP)
Japan	Prof. Dr. Kenji Yokota (Chapter President; ISSAAS VP)
Malaysia	Prof. Dr. Teck Chwen Loh (Chapter President; ISSAAS VP)
Philippines	Prof. Dr. Fernando Sanchez, Jr. (Chapter President; ISSAAS VP)
Thailand	Prof. Dr. Sukanya Rattanatabtimtong (Regional Secretary)
Vietnam	Prof. Dr. Pham Van Cuong (Chapter President; ISSAAS VP)
Cambodia	Prof. Dr. Buntong Borarin (Regional Secretary) – <i>not present</i>

11. Plan for 2026 International Congress

Theme: *Regenerative Agriculture: Innovation, Biodiversity and Community Resilience*

Date: 12-14 November 2026

Venue: TM Digital Academy, Cyberjaya, Selangor, Malaysia

12. Others

- Establishment of a Unified ISSAAS Homepage
The board has approved the recommendation from the Philippine Chapter regarding the necessity of establishing a unified ISSAAS homepage and its financial budget. However, the specific details concerning the website's content framework will require further deliberation in future discussions.
- Availability of JSTA Membership Application
- Invitation to 32nd International Horticultural Congress in Kyoto, Japan (August 23-28, 2026)

ISSAAS General Meeting 2025

Date: 6 November 2025, 11:00-12:00

Venue: Center Hall, Vietnam National University of Agriculture

AGENDA

1. Greetings from ISSAAS President
Prof. Dr. Pham Van Cuong (Vietnam National University of Agriculture)
2. Greetings from ISSAAS Central Secretariat
Prof. Dr. Hironobu Shiwachi
3. ISSAAS Organization and International Congress
Presented by Prof. Dr. Hironobu Shiwachi
5. Journal of ISSAAS
Presented by Prof. Dr. Hironobu Shiwachi
As approved during the 2024 Executive Board Meeting, a new page charge scheme and mandatory submission of a Turnitin Similarity Test Report were implemented starting with the ISSAAS 30(2) December 2024 Issue. J. ISSAAS 30(2) and J. ISSAAS 31(1) were also published on schedule.
6. Others
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Indonesia	Prof. Dr. Suryo Wiyono (Chapter President; ISSAAS VP)
Japan	Prof. Dr. Kenji Yokota (Chapter President; ISSAAS VP)
Malaysia	Prof. Dr. Teck Chwen Loh (Chapter President; ISSAAS VP)
Philippines.	Prof. Dr. Fernando C. Sanchez, Jr. (Chapter President; ISSAAS VP)
Thailand.	Prof. Dr. Sukanya Rattanatabtimong (Regional Secretary)
Vietnam	Prof. Dr. Nguyen Thi Bich Thuy (Regional Secretary)
Cambodia ^(New)	Prof. Dr. Buntong Borarin (Regional Secretary) - <i>absent</i>
8. ISSAAS Awards

Presented by Dr. Fernando C. Sanchez, Jr., Award Screening Committee Chair.

ISSAAS Matsuda Award to Prof. Dr. Tran Duc Vien (Vietnam) in recognition of his distinguished contribution to the advancement of science, research, and trainings on agriculture and rural development in Vietnam.

ISSAAS Young Scientist Award to Asst. Prof. Dr. Riskina Juwita (Japan) in recognition of her distinguished contribution to research on agribusiness development of spice and herb commodities as a strategy for rural development in Indonesia, and significant contribution to the growth and development of ISSAAS since 2015.

SAVE THE DATE

International Congress and General Meeting 2026

Theme: *Regenerative Agriculture: Innovation, Biodiversity and Community Resilience*

Date: 12-14 November 2026

Venue: TM Digital Academy, Cyberjaya, Selangor, Malaysia

Schedule:

November 11 (Wednesday) Arrival of Participants; Executive Board Meeting

November 12 (Thursday) Opening Ceremony, General Meeting, Plenary Sessions
Individual Presentations

November 13 (Friday) Individual Presentations, Closing Ceremony

November 14 (Saturday) Congress Tour

November 15 (Sunday) Departure of Participants

FIRST ANNOUNCEMENT

Organised by: **ISSAAS** Malaysia Chapter

Powered by: Telekom Malaysia **TM**

Regenerative Agriculture:
Innovation, Biodiversity
and
Community Resilience

ISSAAS
International
Congress 2026

Date: 12-14 November 2026

CALL FOR PAPERS

Venue: TM Digital Academy
Cyberjaya, Selangor, MALAYSIA 

Sub-themes:

- Aquatic Science
- Agro-forestry and Natural Resource Management
- Plants, Animal and Aquatic Production
- Agricultural Extension
- Agribusiness & Agricultural Economics
- Digital & Smart Technology In Agriculture
- Biodiversity of plants and animals
- Weed, pest and disease management

Registration Fees:

- ISSAAS Member: USD150
- Malaysian ISSAAS Member: RM600
- Non-Member: USD200
- International Student: USD120
- Malaysian Student: RM480
- Accompanying Person: USD100
- Congress Tour (Optional): USD35

Important Deadlines:

- Abstract Submission: 31/07/2026
- Letter of Acceptance: 31/08/2026
- Registration Payment: 15/09/2026

 **SCAN HERE**
TO REGISTER

 [Link https://bit.ly/4stFBDT](https://bit.ly/4stFBDT)

CONTACT US:
issaas2026.upm@gmail.com

Further details available at:

-  ISSAAS Malaysia-Chapter
-  <https://issaasmalaysia.org>





The International Society for Southeast Asian Agricultural Sciences

Journal of ISSAAS

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