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2987-1 Onoji Machida-shi, Tokyo 195-0064, Japan
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E-mail: iserd.secretariat@gmail.com
Webpage: www.iserd.net

in Collaboration with

Association of Environmental and Rural Development (AERD)

93/64 Moo.3, Sinsab Village 2, Bungyeetho Sub-District, Thanyaburi District,
Pathum Thani 12130, Thailand
Tel/Fax: +66-2957-8064
E-mail: iserd.secretariat@gmail.com
Webpage: www.iserd.net

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2987-1 Onoji Machida-shi, Tokyo 195-0064, Japan
Tel/Fax: +81-42736-8972
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Profitability and Economic Viability of Upscaled Mussel Hatchery Operations

TAN REYNOLD D.*

*Department of Accounting,
College of Management, and Technology Transfer and Business Development Office (TTBDO)
University of the Philippines Visayas, Iloilo City, Philippines
Email: rdtan1@up.edu.ph*

HIBALLES, RYAN PIO VINCENT

*Department of Accounting, College of Management
University of the Philippines Visayas, Iloilo City, Philippines*

AMAR, MARY JANE APINES

*College of Fisheries and Ocean Sciences,
University of the Philippines Visayas, Miagao, Iloilo, Philippines*

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Abstract Mussels are bivalve species with established ecological and economic importance. They are known to provide essential supporting services such as nutrient recycling and storage, structural habitat, substrate, and food web modification, and are also used as environmental monitors; regulating services such as water purification (biofiltration); and provisioning and cultural services, including their use as a food source, for making tools and jewelry, and for spiritual enhancement. Mussel hatcheries are crucial for ensuring a stable supply of mussel seeds, supporting the growing global demand, and contributing to sustainable aquaculture practices. This study evaluated the profitability and economic viability of an upscaled mussel hatchery in Miagao, Iloilo, Philippines. Primary and secondary data were used to analyze the project profitability and financial viability. Six business revenue models were considered in the study: (1) invest in housing and produce 1-mm spats, (2) invest in housing and produce 1-cm spats, (3) invest in housing and grow 1 mm-spats until 1 cm, (4) no investment in housing - produce until 1-mm, (5) no investment in housing - produce until 1 cm, and (6) no housing—produce 1 cm-spats from the until 1 mm. The indicators used include total revenue, net profit, gross profit margin, net profit margin, return on investment, net present value, internal rate of return, breakeven volume and price, and payback period. The results showed that the upgraded mussel hatchery requires an investment of approximately PhP. 3 million. The most profitable business model involves producing mussel spats of up to 1 mm. Investment in mussel hatchery is capital intensive. In the short run, existing or unused hatcheries owned by State Universities and Colleges (SUCs) and government institutions can be rehabilitated to increase production. Meanwhile, to increase profitability, existing R&D efforts can be extended to improve survival rates, particularly at the pediveliger to early spats and 1-mm to 1-cm stages.

Keywords mussel hatchery, economic viability, profitability analysis, upscaling, sustainable aquaculture

INTRODUCTION

Mussels are bivalve species with established ecological and economic importance. They are known to provide essential supporting services such as nutrient recycling and storage, structural habitat, substrate, and food web modification, and they are also used as environmental monitors; regulating services such as water purification (biofiltration); and provisioning and cultural services including their use as a food source, in the creation of tools and jewelry, and for spiritual enhancement

(Vaughn, 2018). Mussel farming has been found to enhance nutrient regeneration in coastal lagoons (Jansen, et al., 2019), and their role in cycling and storage of nutrients in the Oligo-, Meso-, and Cultivation areas has been extensively reviewed (Jansen et al., 2019). Mussels also support biodiversity, serve as a food source for various species, and help maintain the balance of aquatic ecosystems by controlling phytoplankton biomass (Dolmer & Frandsen, 2002).

Mussels are ecologically and economically important. Mussel farming is a sustainable practice that supports local economies by providing food and employment opportunities (Shumway et al., 2003). Globally, aquaculture's role in meeting the global demand for fish has increased (Tran et al., 2022), and the demand for mussels is rising (Market Research Future, 2024); (Global Information, Inc., 2024); (Global Marketing Insights, 2024); (Global Information, Inc., 2024); (Global Marketing Insights, 2024). The continuously growing demand is attributed to the rising interest in healthy and sustainable food choices (Global Information, Inc., 2024), increasing popularity of value-added mussel products offering a unique profile to consumers (Global Information, Inc., 2024), and their applications in indirect consumption, processed foods, animal feeds, and nutraceuticals (Global Marketing Insights, 2024).

While mussels are vital for ecosystem health and economic sustainability, their populations are declining, necessitating conservation efforts to maintain their ecological and economic roles in the ecosystem. Mussel Philippines (2017) reported that production has been declining due to the following factors: low product value, limited market demand, poor sanitary quality, occurrence of red tides, and unpredictable supply. Hatcheries eliminate variability and uncertainty associated with environmental factors and overexploitation of natural seeds (Helm et al., 2004), support industry expansion by producing seeds all year round, thus facilitating greater flexibility in production cycles (Salomon and Holm, 2013), and enable controlled breeding programs focusing on selected traits such as faster growth rates, disease resistance, and tolerance to environmental stressors (Vu et al., 2020). Hence, they are essential for improving the performance of bivalve species in aquaculture (Gjedrem and Rye, 2018) and support sustainable aquaculture practices by promoting responsible resource management and minimizing negative environmental impacts (Nascimento-Schulze et al., 2021). Thus, upscaling hatchery operations is essential to ensure a consistent supply, improve product quality, and reduce reliance on wild seed collection.

OBJECTIVE

The main objective of this study was to determine the viability of scaling up mussel hatchery operations. Specifically, it aims to determine the investment requirements and the financial and economic viability of scaling up green mussel hatchery operations.

METHODOLOGY

This study used a quantitative analysis involving financial modeling and economic evaluation of the upgraded hatchery design and operations. The results represent a case study of an upscaled mussel hatchery funded by the Philippine Council for Agriculture, Aquatic, and Natural Resources Research and Development (PCAARRD).

Primary data were collected from a scaled-up mussel hatchery established at the University of the Philippines Visayas. Production data were gathered from the scaled-up production runs. Secondary data were obtained from published reports, production data from existing UPV hatcheries, and market price data for mussels.

Six business revenue models were considered: (1) invest in housing and produce 1-mm spats, (2) invest in housing and produce 1-cm spats, (3) invest in housing and grow 1 mm-spats until 1-cm, (4) no investment in housing - produce until 1-mm, (5) no investment in housing - produce until 1 cm, and (6) no housing - grow 1 mm spats to 1 cm.

RESULTS AND DISCUSSION

Cost Structure Analysis

Operating a green mussel hatchery requires a capital of approximately Php 3 million. Of this Php 3-M capitalization, 16% was allocated to working capital, while the remaining 84% was dedicated to fixed capital investments. The capital assets in this nursery business are hatchery tanks, structures, and facilities. The most significant capital investment in green mussels was the purchase of hatchery facilities (approximately 46%). Hatchery housing comprises 40% of the total investment cost, hatchery tanks account for 12%, and the remaining 4% is allocated to broodstock facilities and breeders.

Table 2 Budgetary requirement for the construction of a green mussel hatchery, 2024

Particulars	Quantity	Unit cost (PhP)	Total cost (PhP)
Hatchery tanks			
Broodstock tanks (250-L)	1	10,000.00	10,000.00
Spawning tanks	1	15,000.00	15,000.00
Larval rearing tanks			
1 ton	3	11,800.00	35,400.00
500-L	1	15,000.00	15,000.00
250-L	14	8,000.00	112,000.00
100-L	30	3,800.00	114,000.00
Total cost for hatchery tanks			301,400.00
Hatchery structures			1,000,000.00
Total cost of hatchery structures			1,000,000.00
Hatchery facilities			
General	10	67,493.00	674,930.00
Algal culture	10	9,201.50	92,015.00
Basic laboratory equipment	10	31,800.00	318,000.00
Laboratory reagents	10	6,520.00	65,200.00
Total cost of hatchery facilities			1,150,145.00
Broodstock facilities and breeders			
Aeration blower	1	25,000.00	25,000.00
Water pump	1	2,750.00	2,750.00
Aeration system (Aeration pipeline)		21,048.00	21,048.00
Water system (Installation of water pipeline)		56,288.00	56,288.00
Breeders	15	100.00	1,500.00
Water heater (1.8L)	3	800.00	2,400.00
Total cost of broodstock facilities and breeders			108,986.00
Total investment			2,560,531.00
Operating cost during the first year of operation			479,470.00
Total capital requirement to start the operation			3,040,001.00

Revenue Projections

Attachment 1 (provided on the last page) presents the revenue projections for each revenue model. Other profitability and economic indicators used to assess the viability of each revenue model are also included. Profitability is computed as the difference between revenues and the cost of selling goods. Total revenue was derived as the product of the quantity sold and the price per unit.

The fixed costs of mussel hatchery operations include water, electricity, and other utilities. Variable costs, on the other hand, include breeders, spat (if the revenue model is nursery operations), algal starter feeds, hatchery supplies, and direct labor.

The highest-cost item across all revenue models was labor. The highly technical nature of running a mussel hatchery necessitates hiring workers with advanced degrees and commands relatively higher remuneration. Among the fixed costs, the depreciation of capital assets is a major expense, attributed to the high capital expenditure required to establish a hatchery.

Revenue and Net Profits

From Attachment 1, running a hatchery and producing spat until 1 mm generates the highest revenue (Options 1 and 4). In addition to the relatively higher spat price, turnover is high at six cycles per annum when these revenue models are adopted. Nursery operations (buying 1-mm spat and growing them to 1 cm) yielded the lowest revenue (Options 3 and 6). This is explained by the limited maximum production capacity, as the number of spat that can be sold is constrained by the nursery capacity in which an investor invests.

Net profit is highest when producing 1-mm spat without housing investment. Examples include the use of existing hatcheries or facilities operated by research institutions, government agencies, and local government units. Gross profit is highest for Model 1 (housing until 1- mm spat production) and Model 4 (no housing until 1 mm production). Consequently, Revenue Model 4 yields the highest net profit. Although the costs are the same as those in Revenue Model 1, Model 4 does not incur depreciation expenses.

Profitability Ratios

The profitability ratios of the different green mussel hatchery technology revenue models were analyzed using the gross profit margin and net profit margin. The gross profit margin is highest for Revenue Models 1 and 4, at 56.09%, and lowest for revenue options 3 (with housing nursery operations from 1 mm to 1 cm) and 6 (no housing nursery operations from 1 mm to 1 cm).

To be acceptable, the gross profit margin must be between 50% and 70%, which is considered healthy for industries such as retail, manufacturing, and goods production. Other industries, such as financial institutions, have higher benchmarks for healthy gross profit margins. The net profit margin was highest for Option 4 (housing nursery operations from 1 mm to 1 cm) at 48.09%. This is because depreciation was not included in the cost. This model is most applicable to research institutions, local government units (LGUs), and state universities and colleges (SUCs) that have existing or underutilized multispecies hatcheries.

Financial Viability

To determine the ability of the enterprise to generate the required cash flow to meet ongoing operational costs and debt repayments, the investment was subjected to the following standard capital budgeting tools: return on investment (ROI), net present value (NPV), internal rate of return (IRR), and breakeven volume and price. ROI calculates the profits generated by an investment relative to the total cost of the investment. Using ROI as the criterion, all revenue models except Model 3 (nursery operations with investment in housing) are considered to be good investment alternatives.

NPV explains how much an investment is worth throughout its lifetime, discounted to today's value. Comparing the financial viability of the six models based on the NPV criterion, all except the nursery operation, with and without investment in housing (options 4 and 6), yielded positive results. Revenue Models 4 and 6 fail the NPV test because of the volume limitations imposed by nursery-rearing capacities. A hurdle rate of 6% was used to discount the present net value, which is close to the risk-free rate of return. The project duration used in the NPV calculation was 10 years with annual cash flows.

The IRR is the discount rate that makes the NPV equal to zero, serving as a benchmark for comparison against the cost of capital. Investments are acceptable if the IRR is greater than or equal to the cost of the capital. With 10% as the hurdle rate (the current approximate commercial banking rate), Revenue Models 1 (housing until 1-mm spat), 4 (no housing until 1-mm spat), and 5 (no housing until 1-cm spat) are considered sound investment options.

Investing in housing and operating a nursery (1 mm to 1 cm) remains the least viable Model because the IRR was computed to be -8%. This result implies that cash flows from the investment are insufficient to cover the initial investment costs.

The payback period is the time required to recover the investment. Based on the projected income of all six revenue models, potential investors can recover their costs most quickly by exclusively producing 1-mm spat using the old multi-species hatcheries. In this scenario, the

investment recovers in one year and four months. In contrast, it would take 35 years to recover the investment in producing 1-mm to 1-cm spat with housing.

CONCLUSION

Profitability varies across the business models. Spat production up to 1 mm in size demonstrated positive profitability, with both housing and no housing factored in the overall project cost. Profitability was highest in the model that produced 1-mm spats without housing. This is understandable, as no depreciation associated with investment in housing was incorporated into the overall cost.

Investment in a mussel hatchery is capital-intensive. In the short run, existing or unused hatcheries owned by State Universities and Colleges (SUCs) and government institutions can be rehabilitated to increase production. Meanwhile, existing R&D efforts can be extended to increase survival rates, particularly during the pediveliger to early spat stages and from 1-mm- to 1-cm.

The profitability performance observed may not be applicable universally to all regions or hatchery systems. Farmers and investors may gain practical insights into the financial feasibility of expanding hatchery operations. On the other hand, policymakers may benefit from the study's findings by formulating policies and incentives to promote hatchery upscaling and sustainable growth in aquaculture.

Several practical and policy recommendations can be drawn from this study. From this mussel hatchery upscaling profitability study, strategies for optimizing production costs can be explored in the future. Furthermore, it is recommended that the government support mussel hatchery operations. Potential entry points would include subsidies, low-interest loans, and the provision of technical assistance. Finally, research on technological innovations aimed at improving hatchery efficiency, increasing survival rates, and reducing costs is recommended.

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Attachment 1 Proforma income statement and profitability and economic analysis for the six-business model opti

	Housing until 1- mm spats production (1)	Housing until 1 cm spats (2)	With housing 1mm to 1 cm (250,000 spat capacity)	No housing until 1 mm production (4)	No housing until 1 cm production (5)	No housing 1 mm- 1 cm production (6)
			-3			
Income						
Income from sale of mussel spats	2,183,792.28		1,574,977.46	2,183,792.28	1,574,977.46	1,190,000.00
Cost of goods sold						
Direct materials- breeders	4,800.00		4,800.00	4,800.00	4,800.00	4,800.00
Direct Materials- 1mm spats						
Algal feeds starters	2,000.00		2,000.00	2,000.00	2,000.00	2,000.00
Fertilizers	6,000.00		6,000.00	6,000.00	6,000.00	6,000.00
Hatchery supplies (Chlorine, detergent, filters, etc.)	12,000.00		12,000.00	12,000.00	12,000.00	12,000.00
Direct Labor	743,520.00		743,520.00	743,520.00	743,520.00	743,520.00
Utilities						
Water	4,800.00		4,800.00	4,800.00	4,800.00	4,800.00
Electricity	185,820.00		185,820.00	185,820.00	185,820.00	185,820.00
Total cost of goods sold	958,940.00		958,940.00	958,940.00	958,940.00	958,940.00
Gross income	1,224,852.28		616,037.46	1,224,852.28	616,037.46	231,060.00
Less: Administrative and Selling Expenses						
Depreciation	256,053.10		256,053.10	156,053.10	156,053.10	41,038.60
Repair of equipment and facilities	5,000.00		5,000.00	5,000.00	5,000.00	5,000.00
Permits and licenses	8,530.00		8,530.00	8,530.00	8,530.00	8,530.00
Miscellaneous	5,000.00		5,000.00	5,000.00	5,000.00	5,000.00
Total administrative expense	274,583.10		274,583.10	174,583.10	174,583.10	59,568.60
Net farm income	950,269.18		341,454.36	1,050,269.18	441,454.36	171,491.40
Net profit margin (%)	43.51		21.68	6.01	48.09	14.41
No. of cycles per year	6		4	8	6	4
Financial viability						
ROI (%)	37.11		13.34	2.92	74.47	11.81
Payback period (years)	2.69		7.5	34.29	1.34	8.46
Initial investment requirement (PhP)	2,560,531.00		2,560,531.00	2,451,545.00	1,410,386.00	1,451,545.00
NVP (PhP @ 6% hurdle rate)	4,437,079.30		209,786.79	-1,572,710.76	6,102,152.23	1,748,136.98
IRR (%)	36%		8%	-8%	74%	26%
Breakeven volume	890,100		392,261.21	290,124.25	565,935.74	249,404.07
Breakeven price	0.31		0.47	0.56	0.29	0.43
Selling Price of spats (PhP/piece)	0.55		0.7	0.55	0.55	0.7
Average selling price of mussel (PhP/piece)- 27 pcs. per kg	3.7		3.7	3.7	3.7	3.7



Contribution of Local Protected Areas to the Protection of Natural Resources and the Livelihood of Community Members in Northern part of Cambodia

CHUN NIMUL*

*Faculty of Agriculture, Svay Rieng University, Svay Rieng Province, Cambodia
Email: chun_nimul@hotmail.com*

HONG CHHUN

Faculty of Agriculture, Svay Rieng University, Svay Rieng Province, Cambodia

TUON SOMPHORSDAVIN

Independent Researcher

TUM SARAVUTH

Svay Rieng University, Svay Rieng Province, Cambodia

SAN SOKUNTHEA

Graduate School, Royal University of Agriculture, Phnom Penh, Cambodia

ROS VANCHEAY

Faculty of Agriculture, Svay Rieng University, Svay Rieng Province, Cambodia

OR CHANTHAN

Faculty of Business Administration, Svay Rieng University, Svay Rieng Province, Cambodia

CHHUON SOKLANG

RECOFTC, Regional Office, Bangkok, Thailand

Received 16 December 2024 Accepted 3 May 2025 (*Corresponding Author)

Abstract This study explores the economic benefits of locally managed protected areas (LPA), the role of natural resources in local livelihoods, and the future existence of natural resources in connection with community-based natural resource management. The study selected eight Local Protected Areas (LPAs): three Community Forestry (CF) areas in Kampong Thom province and five Community Protected Areas (CPA) in Siem Reap provinces, Cambodia. The study interviewed 320 households that are members of the eight LPAs. In addition, a total of 17 key informant interviews (KIIs) were conducted with relevant stakeholders and eight group interviews with the eight LPA committee members. The study revealed that agriculture, forest-related activities, and labor are major sources of income, with forest-related income contributing an average of 23%. Livelihood changes are linked to income sources, the perceived importance of LPAs, and participation in natural resource (NR) protection. Despite conservation efforts, challenges such as deforestation and limited financial support persist. Women significantly contribute to livelihood activities but are less involved in NR management activities. A perception gap exists between the poor and non-poor regarding NR benefits. NR persistence was influenced by the benefits people received and their participation in protective activities. Therefore, enhancing community awareness, especially among the poor, along with financial and technical support, is crucial for sustaining NR use. Awareness-raising programs, government financial support, and external assistance to address challenges and seize opportunities are recommended.

Keyword community forestry, protected area, natural resources management, natural livelihood

INTRODUCTION

Cambodia's forest cover was 46.86% in 2018 (MoE, 2018), with 70% of all households in Cambodia having their income-related activities with natural resources (MoP, 2020). As of 2022, 57% of Cambodian households were engaged in agriculture (MoP, 2022), which contributed 22.2% to the country's gross domestic product (GDP) (The World Bank, 2025). The sustainability and productivity of this sector are closely linked to forest resources (APFNet, 2020). At the national level, forestry management in Cambodia is overseen by two key institutions: the Ministry of Environment (MoE) and the Ministry of Agriculture, Forestry and Fisheries (MAFF), whereas at the community level, local protected areas are managed by the community. Community Protected Areas (CPA) and Community Forestry (CF) are terms used by the MoE and MAFF, respectively.

Currently, 648 CFs and 193 CPAs have been established in 21 and 15 provinces, respectively (FA, 2023; MoE, 2023). Forestry resources are critical to the livelihoods of rural Cambodian communities. Chou (2017) highlighted the roles of Non-Timber Forest Products (NTFPs) in livelihoods and ecosystem services within a protected area in Cambodia, noting that the importance of these resources is often overlooked due to their non-monetary value. Ehara et al. (2016) reported an inverse relationship between household wealth and NTFP dependence, indicating that as households become wealthier, they rely less on forest resources. Socioeconomic development has drastically impacted natural resources, particularly forest cover, which declined from 10.7 million hectares in 2002 to 7.9 million hectares in 2021, with the most significant decline occurring between 2010 and 2013 (MoE, 2020). This accelerated reduction has adversely affected rural livelihoods, contributing to internal and external migrations (Oudry et al., 2016).

OBJECTIVES

This study aims to understand the contribution of natural resources within local protected areas (LPA), specifically CF and CPA, to LPA members within the Kampong Thom and Siem Reap provinces. This study seeks to provide insights into how changes in forestry resources affect economic benefits, community roles, and perceptions regarding natural resource protection and management.

METHODOLOGY

Study Area and Samples

There is a total of eight Local Protected Areas (LPAs), three Community Forestry (CF) and 5 Community Protected Areas (CPAs), located in Kampong Thom and Siem Reap provinces, in the northeastern part of Cambodia, that were included in the study (Fig. 1). This study employed both qualitative and quantitative methods to explore the economic benefits of LPAs in response to community members' needs.

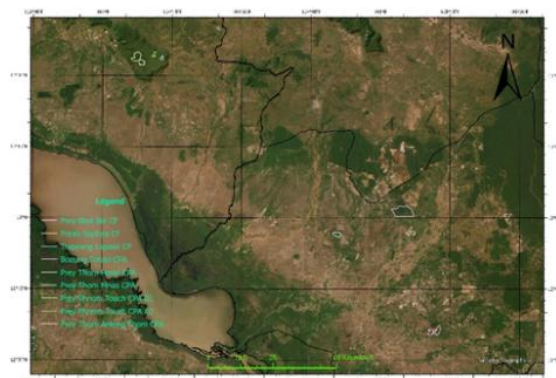


Fig. 1 Map showing location of the study area

The sample for the study was calculated from the 1,719 member households of the selected eight LPAs. Using Cochran's sample formula with a 95% confidence interval, 5% margin of error, and 50% proportional response, the number of households to be interviewed was determined to be 315. The final number of samples included in the survey was 320 households across eight LPAs. Of the 320 respondents, 252 were women. A structured questionnaire was used for the household interviews after completing the questionnaire testing. In addition to the quantitative survey, the study utilized qualitative interviews with 17 key informants: three (3) from natural resource protection Non-Governmental Organizations (NGOs), two (2) officials from the Provincial Department of Environment, four (4) commune leaders, and eight (8) village leaders. Additionally, eight (8) group interviews were conducted with eight (8) community-based protection committee members representing each LPA, as shown in Table 1.

Table 1 Demographic and samples of the study

No.	Community	Total Area (ha)	Total HH Members	Total People	Female	Sampled HHs	Female Respondents
1	Boeung Toteul CPA	772	402	1,889	957	41	40
2	Trapeang Lapeak CF	325	300	400	180	42	23
3	Preah Sophea CF	384	293	1,393	720	38	31
4	Prey Kbal Bei CF	2,587	62	152	82	41	34
5	Prey Thom Anlong Thom CPA	798	308	1,186	624	37	20
6	Prey Phnom Moneas CPA	113	109	463	233	41	40
7	Prey Phnom Kduoch CPA	92	141	656	335	40	35
8	Prey Thom Popel CPA	365	104	410	204	40	29
Total		5,436	1,719	6,549	3,335	320	252

To measure the respondents' perception, a five-point rating scale was applied and considered an interval scale for the analysis of the data.

Data Analysis and Interpretation

Descriptive statistics were used to describe the respondents' general responses. Additionally, Pearson product-moment correlation (Pearson's r), multiple regression analysis, and binary logistic regression were employed to determine the correlation and predictability of factors influencing the socioeconomic situation of LPA members. Qualitative data were analyzed using narrative and content analysis to understand the actual situation and how the community received support, as well as their mechanisms for responding to challenges to ensure the longevity of the natural resources. Qualitative data were used to triangulate the reviewed documents and quantitative data.

RESULTS AND DISCUSSION

Contribution of Natural Resources to the Livelihood of the Community

The analysis indicated that dependence on natural resources remains highly significant for members of community-based natural resource management, with natural resources being one of the three major income sources: agriculture (82%), forest-related activities (66%) – slightly below the report of MoP (2020) at 70%—and laborers/workers (48%). Moreover, the average share of income from forest-related sources within the households among the surveyed respondents was 23%, following agriculture (61%) and laborers/workers (41%) income. This portion reflects a strong connection with natural resources. The findings suggest a significant change in the role of natural resources in the livelihoods of the poor, with the proportion of income from forest-related sources decreasing to 23% from 41%, as reported by McKenney et al. (2004). To understand the changes in community members' livelihoods, correlation and multiple regression analyses were conducted. As shown in Table 2, the results showed that livelihood changes were significantly associated with eight factors: income from forest-related sources, income from non-forest-related sources, perceived importance

of locally protected areas (LPAs), current importance of natural resources, benefits received after joining LPAs, changes in pest and disease prevalence, current severity of pest and disease changes, and the number of natural resource protection activities.

Table 2 Livelihood activities of the membered household

No.	Sources of Income	Total	Percent	Percent Share	SRP	Percent	Percent Share	KPT	Percent	Percent Share
1	Agriculture	261	82%	61%	129	82%	59%	132	81%	63%
2	Forest related	211	66%	23%	110	70%	25%	101	62%	21%
3	Laborers or workers	155	48%	41%	93	59%	43%	62	38%	38%
4	Vendors/business	31	10%	55%	15	9%	57%	16	10%	53%
5	Wage workers	20	6%	47%	3	2%	37%	17	10%	49%
6	Migration	5	2%	26%	1	1%	50%	4	2%	20%
7	Vendors at tourism site	3	1%	40%	2	1%	50%	1	1%	20%
8	Government salary	4	1%	50%	2	1%	40%	2	1%	60%
9	Others	56	18%	29%	9	6%	14%	47	29%	32%
Total		320	100%	100%	158	100%	100%	162	100%	100%

However, stepwise multiple regression analysis indicated that only three factors—income from forest-related sources, income from non-forest-related sources, and the number of natural resource protection activities—were predictors of livelihood changes among the members, with a prediction level of 30%. These results highlight the critical importance of participation in natural resource protection, suggesting that participants possess the necessary knowledge, courage, sacrifice, and commitment to both natural resource and livelihood development. This confirms that although natural resources have changed their contribution to the country's GDP from 8.3% in 1995 to 1.9% in 2017, and only 0.8% in 2021 (The World Bank, 2025), the contribution of the NR to rural households is still highly important.

Roles of Locally Protected Areas in the Protection of Natural Resources

Locally protected areas (LPAs) have been prominent players in protecting natural resources, supported by various organizations. The government has recognized the importance of these communities and allowed their establishment. Interviews with committee members confirmed the significant contribution of these communities to managing and protecting natural resources, with some suggesting that natural resources might not exist without community involvement. Four of the eight interviewed communities reported significant forest loss adjacent to the LPAs. Qualitative data also indicated that the existence of LPAs is closely tied to the livelihoods of community members, and without direct benefits, their role in protection diminishes. Multiple regression analysis showed that the existence of natural resources depends on two key factors: the level of poverty and the perceived importance of LPAs by community members, suggesting that protection improves as living conditions and community acknowledgment of LPAs' importance increase.

Despite positive conservation and protection activities, challenges remain, including the continuous degradation of natural resources, limited law enforcement (e.g., land grabbing, deforestation, illegal logging, and fishing), insufficient financial and technical support, limited knowledge, lack of environmental responsibility, and difficulties in dealing with powerful land grabbers. The capacity of the committees to sustain LPAs without external support is a concern. However, opportunities such as promoting sustainable agriculture, eco-tourism linked to cultural and natural resources, advancing non-timber forest products (NTFPs) processing and marketing, and developing financial sustainability models have been identified. These opportunities require technical and financial support to be realized.

Roles of Women in Natural Resources Management

Key informant interviews confirmed that women play crucial roles in livelihood activities, including savings, handicrafts, and agricultural production, across all locally protected areas (LPAs) related to

natural resources. However, their involvement in the management and conservation of natural resources, particularly in planning and patrolling activities, is limited due to household responsibilities and safety concerns, as patrolling and a number of conservation activities occur in forest areas where women find it challenging to participate. Despite this, women are the most affected group if natural resources vanish. Several anecdotal evidence has reported the positive contribution of women to the improvement of effectiveness and efficiency in conservation efforts. However, systematic and scientific research on the roles of women in natural resource management for local protected areas in Cambodia is not available to confirm this finding.

Awareness and Perception Regarding the Importance of Natural Resources

A comparison of perceptions between the poor and non-poor regarding natural resources revealed that out of 20 variables tested, only one showed a significant difference: the perceived benefits received from natural resources. The poor perceived these benefits as being lower than the non-poor. In contrast, the income contribution from forest resources was 25% for the poor and 23% for the non-poor, a difference that was statistically insignificant. This figure somehow suggests that the poor value natural resources less than the non-poor, possibly due to limited knowledge and understanding of their importance for livelihood. This is aligned with the findings of Qamruzzaman (2024), where the association between natural resources and financial benefits contains both negative and positive aspects, indicating the complexity in managing natural resources, which needs a proper understanding of the actual context, especially those involving conservation activities.

Qualitative interviews further confirmed that committee members of locally protected areas (LPAs) have a better grasp of the importance of natural resources. They are more aware of both the short- and long-term benefits to their community. In contrast, community members typically focus on immediate physical and financial benefits rather than broader, more abstract advantages, such as biodiversity and ecosystem services.

Predicting the Future Existence of Natural Resources

Logistic regression analysis was conducted to predict the future existence of natural resources (NR). The results suggest that halting the destruction of NR is likely dependent on the benefits that individuals can derive from these resources. Correlation analysis indicates that preventing NR destruction is positively influenced by several factors: the perceived importance of the local protected area (LPA), the number of participants in NR protection activities, the shift in income sources away from forest-related occupations, and the frequency with which people currently benefit from NR. The likelihood of NR existence was positively estimated at 96%. UNDP (2019) reported that human resource development is negatively associated with a country's forest cover, which is the same as Ehara et al. (2016). Therefore, it can be concluded, based on the findings here, that improved human development is negatively associated with forest cover only applicable to the country overall, whereas the people who are located and directly benefited from the protected areas are in the opposite direction.

Additionally, the level of change in benefits from NR over the next 10 years is influenced by multiple factors, including changes in income sources, the importance of NR, benefits before and after joining LPAs, past and current severity of pests and diseases, and participation in NR protection. These factors were significantly associated with the level of impact expected over the next decade. Stepwise multiple regression analysis predicted the impact levels based on six key factors: participation in NR protection, benefits after joining the LPA, current severity of resource changes, current resource changes, current pest and disease changes, and changes in income sources from forest-related occupations. The prediction model estimated a 45% impact proportion.

CONCLUSION AND WAY FORWARD

At the local level, individuals and organized communities, including local organizations, play a crucial role in protecting natural resources. It has been confirmed that without their efforts, these resources would likely have vanished, as evidenced by the degradation of the nearby areas. Currently, natural resources continue to be vital for the livelihoods of community members, contributing significantly to household incomes and influencing livelihood stability. Local protected areas offer a positive outlook on the future preservation of these resources, with communities believing in the potential for significant conservation. However, the study also indicates that without community recognition of the importance and benefits of these resources, their condition would be worse than it is now. This contrasts with the perception of some leaders, who anticipate resource depletion due to changing economic conditions. Although government support is gradually improving, it remains limited in terms of finances. The poor exhibit a lower recognition of the NR's contribution to their livelihoods than the non-poor, which may contribute to resource degradation. The study also highlights that long-term changes in benefits significantly impact people's livelihoods with a high level of predictability. While challenges persist in community-managed areas, opportunities have also been reported.

The study suggests that special attention should be given to the poor and vulnerable in recognizing the benefits of natural resources and promoting their participation in the protection of natural resources. Awareness-raising efforts should focus on understanding the risks and threats to these resources, as community members' views often differ from those of their leaders. Simultaneously, promoting women's participation in grassroots-level management is crucial to ensure gender inclusiveness. In addition, different financial models are needed to grasp the opportunities for generating income for the protection of natural resources, such as the payment of ecosystem services, ecotourism, handicraft, and NTFP generation. This could be achieved if the government considers regular financial allocations to LPAs to support resource management. External and technical support are necessary to leverage opportunities and address challenges and threats. Lastly, further research on developing financial and management models of LPAs should be considered to protect NR and the role of women in protecting natural resources.

DATA STATEMENT

The Ministry of Environment's data on Community Protected Areas (CPA) statistics and Community Forestry statistics from the Forestry Administration are available only through direct access to the institution and are not officially available online. The authors can provide them upon request.

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Assessing Soil Carbon Sequestration in Salt-Affected Areas Managed with Vermicompost and Organic Waste Materials: A Geographic Information System Approach

SAHARATKARIN NAMSE

Faculty of Agriculture, Khon Kaen University, Khon Kaen, Thailand

PORNTIP PHONTUSANG

Faculty of Agriculture, Khon Kaen University, Khon Kaen, Thailand

TAKASHI KUME

Graduate School of Agriculture, Ehime University, Matsuyama, Japan

TADAO YAMAMOTO

Research Faculty of Agriculture, Hokkaido University, Sapporo, Japan

CHULEEMAS BOONTHAI IWAI*

Faculty of Agriculture, Khon Kaen University, Khon Kaen, Thailand

E-mail: chuleemas1@gmail.com

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Abstract Global warming is a significant challenge faced by many countries worldwide. It adversely affects the environment, climate, society, agriculture, and human life as a whole. The primary cause of global warming is the accumulation of greenhouse gases, which leads to issues such as droughts, decreased agricultural productivity, and climate change. Notably, soil and plants can store more carbon than the atmosphere can. Salt-affected soils are a prevalent issue in many regions worldwide. Therefore, monitoring and surveying soil carbon storage are essential. This study aimed to utilize geographic information systems (GIS) to assess organic carbon levels in salt-affected soils in an area where vermicomposting was applied with organic waste materials. The results showed that the saline soils treated with vermicompost, and organic waste had a higher SOC of 0.560% compared to the unmanaged areas, which had an SOC of 0.350%. Moreover, the soil electrical conductivity in the managed areas with vermicompost was lower (10.16 dSm⁻¹) than that in the unmanaged areas (13.69 dSm⁻¹), and the soil salinity levels during the rainy season were also reduced. The electrical conductivity (ECa) values at a depth of 0-0.75 m were higher than those at 0-1.5 m, indicating that soil with a high organic carbon content had a lower electrical conductivity. In contrast, soils with low organic carbon content exhibited higher conductivities. In conclusion, the experiment demonstrated that managing saline soil areas with vermicompost and organic waste materials effectively increased soil carbon sequestration and reduced soil electrical conductivity, with more benefits observed during the rainy season than during the dry season.

Keywords land use, carbon storage in soil, economic crops, climate change

INTRODUCTION

The long-term increase in the global average temperature is due to the accumulation of greenhouse gases in the atmosphere. These gases, such as carbon dioxide (CO₂), trap heat from the sun and prevent it from escaping into space, causing a gradual rise in global temperatures. This phenomenon is primarily caused by human activities, such as burning fossil fuels, industrial processes, deforestation, and agriculture, which release large amounts of greenhouse gases into the atmosphere.

The consequences of global warming include rising sea levels, more frequent and severe weather events, loss of biodiversity, and ecosystem disruption (Nazir et al., 2024). Salt-affected soils, or soils with high concentrations of soluble salts, include sodium (Na), calcium (Ca), magnesium (Mg), and potassium (K). Soil salinity can occur naturally in arid and semi-arid areas or be caused by human activities, such as saline irrigation or overuse of fertilizers. Soil salinity adversely affects plant growth and yield. High salt concentrations in soil disrupt the water absorption balance of plant roots and interfere with plant nutrient absorption, leading to nutrient deficiency in plants. Additionally, the presence of salt can affect soil structure and reduce soil fertility (Petmuenwai et al., 2024). Moreover, reducing soil organic carbon (SOC), an outcome of soil degradation and mismanagement, has intensified atmospheric CO₂ levels.

However, by implementing state-of-the-art land applications and contemporary management systems in agriculture, it is possible to slow the rate of CO₂ emissions (Nazir et al., 2024). The combination of vermicompost and organic fertilizers can improve the quality of salt-affected soil and yield in severely salt-affected areas, resulting in increased crop yields and plant nutritional value. This is a suitable and cost-effective approach. Vermicompost can increase the available potassium and, at the same time, reduce the exchangeable Na compared with non-salt-affected soil, indicating that vermicompost application can reduce soil salinity and increase plant nutrients (Petmuenwai et al., 2024). Generally, soil carbon storage assessments use laboratory methods such as dry combustion (Nelson et al., 2018) and wet oxidation (Walkley and Black, 1934). However, these methods are expensive to analyze. Currently, geographic information technology is used to assess soil carbon storage using geographic information system techniques and remote sensing data (Bilgili, 2013), which helps to identify the distribution of carbon storage in soil in the area efficiently. Therefore, this study aimed to assess soil carbon sequestration in salt-affected areas managed with vermicompost and organic waste materials using a Geographic Information System (GIS) approach.

OBJECTIVE

The objective is to assess soil carbon sequestration in salt-affected areas managed with vermicompost and organic waste materials applying a geographic information system approach.

METHODOLOGY

Fieldwork was conducted in June 2024 in Ban Phai, Khon Kaen Province in Northeast Thailand. Figure 1 shows an outline of the study area (plot). This plot (~16.125 rai (1 rai = 1,600 m²)) was abandoned because of excessive soil salinity. In 2019, drainage ditches and trenches were dug in the center and around the western part of the plot to remove salt by improving the drainage. After digging drainage ditches and trenches, vermicompost and organic fertilizers were applied to cultivate the salt-tolerant crops. After improving the drainage, we confirmed that these plants continued to grow until 2021.

Electrical Conductivity Measurement Method

The ECa at each depth range (V: 0-1.50 m, H: 0-0.75 m) was measured at 80 points in the field using an electromagnetic induction instrument (EM38-MK2, GEONICS Limited). Surface soil, ~3.0-cm thick, was sampled at 80 points, and pH and EC1:1 (three replicates) was measured after air drying. All measurement and sampling sites were located using GPS (GPSmap 60CX).

The soil salinity level was classified via ECe, as follows: non-saline: 0–2 dS/m; slightly saline: ≥2–4dS/m; moderately saline: >4–8dS/m; highly saline: >8–16dS/m; severely saline: >16dS/m. The soil salinity in this study was moderate to high.

Soil Organic Measurement Method

Soil organic carbon (SOC) was measured using the Walkley and Black method of wet oxidation (Walkley and Black, 1934). The classification of soil based on Soil Organic Carbon content is as follows: <1 = very low; $1.0-2.0$ = low; $2.0-4.3$ = medium; $4.3-6.0$ = high; >6 = very high. (Tan, 1986).

Spatial Mapping

The SOC and ECa maps were created by loading the ECa data with location information into ArcGIS and interpolating the ECa data using the Kriging method.

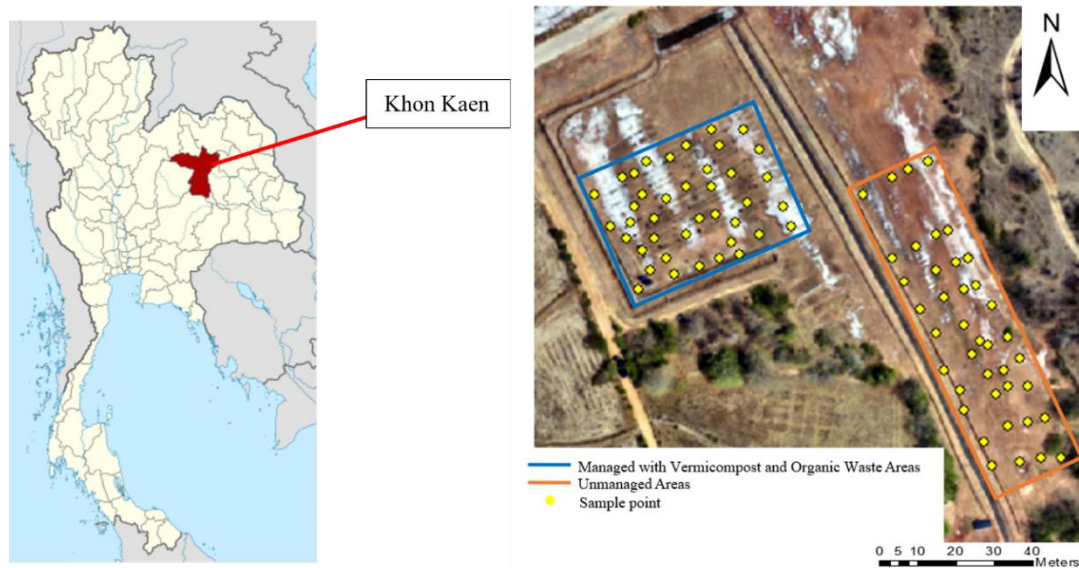


Fig. 1 Outline of the study area (field)

RESULTS AND DISCUSSION

The results of the study found that the organic carbon in the managed areas in the rainy season was low (SOC: 0.338%) and decreased to a very low level in the dry season (SOC: 0.192%), which was significantly different ($p < 0.001$). The saline soil area managed with vermicompost combined with organic waste had higher organic carbon (SOC: 0.560%) than the unmanaged area (SOC: 0.350%). In managed areas, there is low SOC in the dry season; in the rainy season, SOC is low in 50 percent of the area and very low in 50 percent. In unmanaged areas during the dry season, SOC was low in 50% of the area and very low in SOC 50%, and in the rainy season, SOC was very low (Fig. 2).

Figure 3 shows that the soil electrical conductivity in the managed area was lower (10.16 dSm⁻¹) than that in the unmanaged area (13.69 dSm⁻¹), and the soil salinity level in the rainy season was already lower.

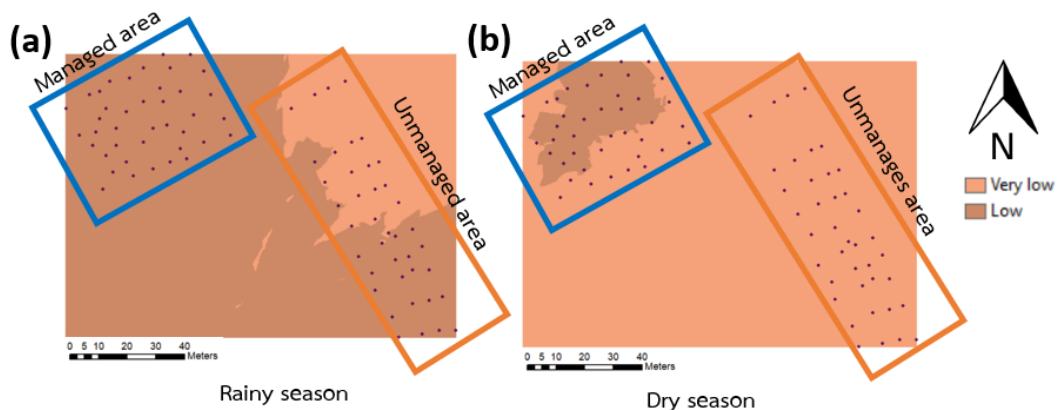


Fig. 2 SOC% surface soil (~3 cm) during rainy season (a) and dry season (b)

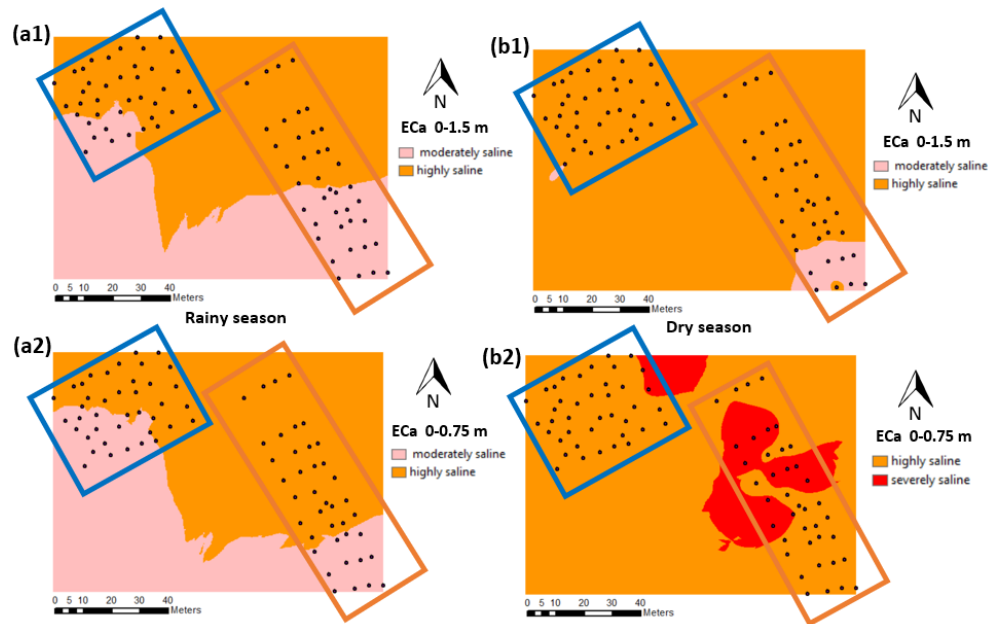


Fig. 3 ECa map in depth ranges during rainy season (a1 and a2) and dry season (b1 and b2)

The ECa value at a depth of 0-0.75 meters had higher soil electrical conductivity than at 0-1.5 meters. In the managed area, at ECa 0-1.5 m in the dry season, the soil was highly saline with shallow SOC in 70% of the area and moderately saline in 30%. At ECa 0-1.5 m during the rainy season, the soil was highly saline. At ECa 0-0.75 m, in the dry season, 50% of the area was highly saline, and 50% was moderately saline. At ECa 0-0.75 m in the rainy season, 95% of the area was highly saline and 5% was severely saline. In the unmanaged area, at ECa 0-1.5 m in the dry season, 50% of the area was highly saline, and 50% was moderately saline. At ECa 0-1.5 m in the rainy season, 80% of the area was highly saline and 20% was moderately saline. At ECa 0-0.75 m in the dry season, 50% of the area was highly saline and 50% was moderately saline. At ECa 0-0.75 m in the rainy season, 65% of the area was highly saline and 35% was severely saline. Some areas had highly saline (11.02 dSm^{-1}) and very low SOC (0.290%) soil. In areas with moderate salinity (6.10 dSm^{-1}), SOC was low (0.340%).

Vermicompost and organic materials enhance carbon sequestration efficiency by forming stable humic compounds, facilitating carbon binding with soil minerals through organomineral interactions, and reducing carbon loss in the gas form. Soil structure improvement by vermicomposting improves soil particle stability. Organic materials increase soil pore space for carbon accumulation and bind to soil particles (Xie et al., 2023). Soil carbon sequestration in salt-affected areas managed with vermicompost and organic waste materials results in long-term carbon sequestration, increasing the amount of stable organic carbon, reducing the rate of carbon loss from the soil, and extending the carbon retention time in the soil. It also adapts to the soil ecosystem, increases the tolerance of plants and microorganisms to salinity, restores the balance of the carbon cycle, and creates an environment suitable for plant growth.

CONCLUSION

The results of the experiment concluded that saline areas managed using vermicompost and organic waste helped increase carbon sequestration in the soil. They also reduced the soil electrical conductivity, with a more significant effect in the rainy season than in the dry season. Applying a Geographic Information System (GIS) to assess soil carbon sequestration in salt-affected areas significantly reduces the costs and resources required for soil sampling. GIS can analyze and predict soil properties across large areas using data from selected sampling points through spatial interpolation techniques, thereby eliminating the need for comprehensive soil sampling across every

location. This approach substantially saves time, labor, and laboratory analysis costs. Moreover, the data collected can be used for the long-term monitoring of soil carbon changes. This research will be helpful in policy development and planning to assist in the development of regional strategies for managing salt-affected soils.

ACKNOWLEDGEMENTS

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Sustainable Water Use from a Freshwater Lens in the Yumi-Hama Peninsula, Japan – Effects of Precipitation on Groundwater Levels

AOI NARITA

Graduate School of Sustainability Science, Tottori University, Tottori, Japan

YURI YAMAZAKI*

Faculty of Agriculture, Tottori University, Tottori, Japan

Email: y.yamazaki@tottori-u.ac.jp

KATSUYUKI SHIMIZU

Faculty of Agriculture, Tottori University, Tottori, Japan

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Abstract The formation of a freshwater lens, a distinctive lens-shaped body of underground freshwater, is a marvel in areas surrounded by saltwater, such as islands and peninsulas. Despite saltwater infiltration beneath underground freshwater, the density difference ensures that the freshwater floats on the saltwater and remains separate. This freshwater lens, replenished by rainwater infiltration and temporarily storing freshwater, is a precious water resource of immense significance. A freshwater lens has been used for agriculture in the Yumi-Hama Peninsula in Tottori, Japan. However, the limited number of studies on the availability of freshwater resources and their fluctuations in this area is a cause for concern for future sustainability. Moreover, droughts have occurred frequently. Therefore, unstable surface water, such as rivers, reinforces the importance of sustainable groundwater usage. This study investigated the effects of precipitation on groundwater levels using a cross-correlation analysis of the Antecedent Precipitation Index (API) and groundwater levels. The API is an indicator of precipitation involved in groundwater level fluctuations, which is calculated using an exponential function to describe underground infiltration and storage processes. We found positive correlations between the API and groundwater levels at some sites. However, the correlation coefficients were relatively low at sites close to canals, large-scale farms, and shorelines. Possible factors contributing to the low correlation coefficients were the effects of infiltration from canals, pumping for agricultural purposes, and tides. In addition, the time lags for rainwater to reach the groundwater table from the land surface were within 1 day at most sites. These can be explained by the high hydraulic conductivity of sandy soil in the study area.

Keywords freshwater resources, groundwater recharge, antecedent precipitation index, cross-correlation analysis, correlation coefficients, time lags

INTRODUCTION

A freshwater lens is a lens-shaped body of freshwater located underground (Fig. 1). This formation is a global phenomenon that occurs in land areas surrounded by saltwater, such as islands and peninsulas. Despite underground saltwater intrusion from the surrounding land, the water density difference ensures that recharged freshwater floats on saltwater and remains separate. The freshwater lens can temporarily store freshwater and serve as a valuable water resource.

Freshwater lenses are an important water resource internationally, and at the same time, are vulnerable to climate change (IPCC, 2022). Drought and rising sea levels lead to a reduction in water resources and salinization, threatening livelihoods. Therefore, this study is valuable for identifying the factors contributing to freshwater lens fluctuations.

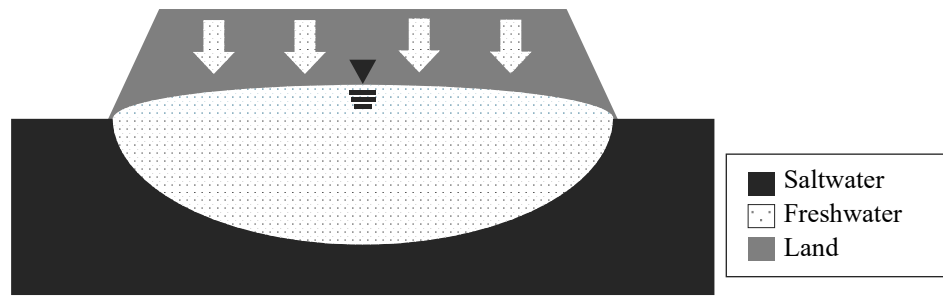
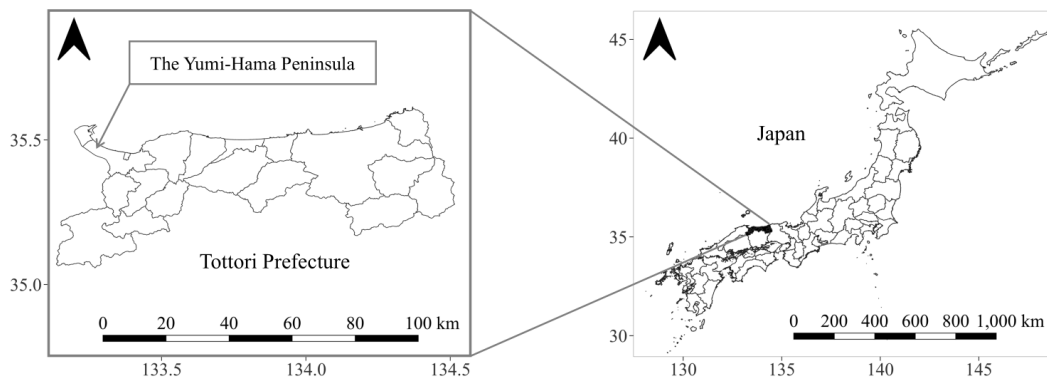


Fig. 1 Diagram of freshwater lens

The Yumi-Hama Peninsula, which is the study area, is located in the western part of Tottori Prefecture, Japan (Fig. 2). It is the first location where a freshwater lens was found in Japan, and the water has been used for agricultural purposes. However, a limited number of studies have examined the availability of freshwater resources and fluctuations in this area. This is a cause for concern regarding future sustainability.



(Created by editing the digital national land information (MLIT, 2024))

Fig. 2 Location of the Yumi-Hama Peninsula

The Yumi-Hama Peninsula has no natural rivers, although an artificial concrete canal, the Yone-Gawa River, exists. The water flowing in the canal is obtained from the Hino-Gawa River upstream, a class-A river in the Tottori Prefecture. The intake is regularly $7.77 \text{ m}^3/\text{s}$ during the irrigation season (April to September). Droughts have frequently occurred in the study area, decreasing river flow and leading to surface water instability. Surface water is the primary source of water for agricultural use. Therefore, unstable surface water reinforces the significance of the availability and sustainability of groundwater use. The Yone-Gawa River canal has a unique feature in that holes in the bottom of the canal are thought to recharge groundwater, and a yet-to-be-defined relationship between the flow rate of the canal and groundwater exists and should be studied.

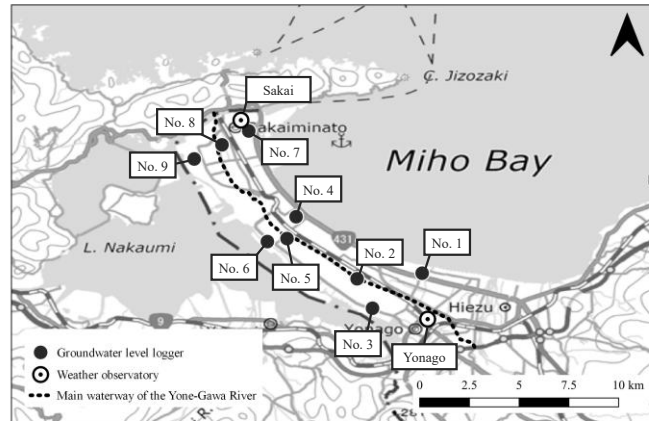
OBJECTIVE

The main objective of this study was to clarify the relationship between the availability of freshwater resources and the factors contributing to groundwater levels. This study focuses on the relationship between groundwater level fluctuations and precipitation.

METHODOLOGY

Data Acquisition

Two data points, groundwater level and precipitation, were collected at the sites, as shown in Figure 3.



(Created by editing the international map (Geospatial Information Authority of Japan, 2013))

Fig. 3 Sites measuring groundwater level and precipitation

Groundwater Levels: At the bottom of the wells, pressure-type water level loggers (HOBO U20-001-02, Onset) were installed to measure the absolute pressure and water temperature. Using the atmospheric pressure measured by another logger, the absolute pressure was converted into water level (the land surface was the standard level = 0.00 m) using Eq. (1). The density of the water used to calculate the water level was calculated using Eq. (2) (Kell, 1975). The measurement intervals were 30 min, and the period was from October 1, 2023, to September 30, 2024. Each site was numbered from 1-9.

$$WL = (P_{abs} - P_{atm}) / \rho g - h \quad (1)$$

Where, WL is the water level from the land surface (m), P_{abs} is the absolute pressure at the bottom of the well (kg/m/s^2), P_{atm} is the atmospheric pressure (kg/m/s^2), ρ is the density of the water (kg/m^3), g is the gravity acceleration (m/s^2), and h is the distance between the land surface and the elevation of the bottom of the well (m).

$$\rho = (999.83952 + 16.945176t - 7.9870401 \times 10^{-3} t^2 - 46.170461 \times 10^{-6} t^3 + 105.56302 \times 10^{-9} t^4 - 280.54253 \times 10^{-12} t^5) / (1 + 16.879850 \times 10^{-3} t) \quad (2)$$

Where ρ is the density of water (kg/m^3), and t is the water temperature ($^{\circ}\text{C}$).

Precipitation: Precipitation was measured by the Japan Meteorological Agency (JMA) at two sites: the Yonago and Sakai observatories. Data were collected from the Internet (JMA, 2024). The collection interval was 1 hr, and the period was from October 1, 2023, to September 30, 2024. Precipitation measured at the Yonago observatory was used to understand the relationship with groundwater levels at sites No. 1 to No. 6, and at the Sakai observatory, it was used from No. 7 to No. 9 because it was the closest observatory to each site.

Cross-correlation Analysis

This analysis calculated a correlation coefficient that indicated the similarity between the groundwater level and precipitation fluctuations, and the time lags taken for rainwater to reach the groundwater table from the land surface at each site.

Antecedent Precipitation Index

Before cross-correlation analysis, precipitation data were converted into the Antecedent Precipitation Index (API). The API is an indicator of precipitation involved in measuring groundwater level fluctuations, which is calculated using an exponential function to describe how wet or dry the soil is

based on previous and current precipitation, expressing the underground infiltration and storage processes. The API was calculated using Eq. (3) based on the concept defined by Kohler and Linsley (1951).

$$API = \sum_{i=0}^n 0.5^{(i/H)} \times P_i \quad (3)$$

Where *API* is the Antecedent Precipitation Index (mm/day), *n* is the accumulation period (days), *H* is the half-life period (days), and *P_i* is precipitation *i* days ago (mm/day). The accumulation period is how many past days of precipitation are used to calculate *API*. The half-life period is the time taken for the impact of one precipitation event on soil moisture to reduce by half.

The combination of *n*, *H*, and time lags was determined when the correlation coefficient was the highest, using data from October 1, 2023, to September 30, 2024. The parameter ranges were as follows: *n* and *H*, and ranged from 0 to 100 days. The time lags ranged from 0 to 10 days. In previous studies, there are limited examples of the application of the API to understand the variability of freshwater lenses, and parameter ranges were determined on a trial basis.

After determining the parameter combination, the data from the first 100 days were removed, and the correlation coefficient was calculated again using data from December 30, 2023, to September 30, 2024. This is because the first API could not express the effects of the previous precipitation.

RESULTS AND DISCUSSION

The parameters and correlation coefficients for each site are listed in Table 1.

Table 1 Parameters and correlation coefficient

Site no.	<i>n</i> (days)	<i>H</i> (days)	Time lags (days)	Correlation coefficient
1	48	15	1	0.60
2	100	100	10	0.37
3	38	5	0	0.70
4	51	10	1	0.85
5	100	19	0	0.84
6	28	11	0	0.26
7	54	26	1	0.87
8	56	20	0	0.45
9	100	100	10	-0.11

At sites No. 4, No. 5, and No. 7, the correlation coefficients were greater than 0.80. At these sites, the API primarily explained groundwater level fluctuations. For example, the graph of the groundwater level and API at No. 4 is presented in Figure 4.

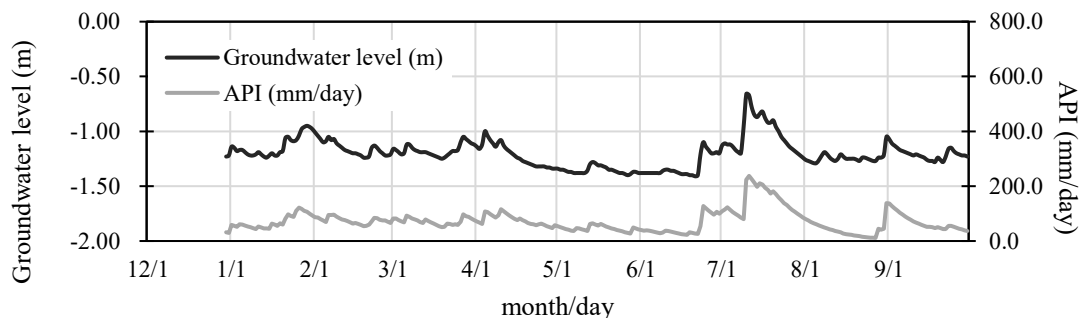


Fig. 4 Groundwater level and API at No. 4

However, at sites No.1, No. 2, No. 3, No. 6, No. 8, and No. 9, the correlation coefficient was less than 0.70. Possible factors for the low correlation coefficients were the low impact of precipitation, the high impact of other factors, and the need to adjust the parameter ranges. Other factors include infiltration from rivers, pumping, and tides. Site No. 2 was the closest to the canal. Therefore, infiltration from the canal could affect groundwater level fluctuations. A graph of the

groundwater level and API at site No. 2 is shown in Figure 5. A graph of the water level in the canal, as measured by the local Land Improvement District Office, is shown in Figure 6. The fluctuations in the groundwater level at site No. 2 and the water level in the canal were similar.

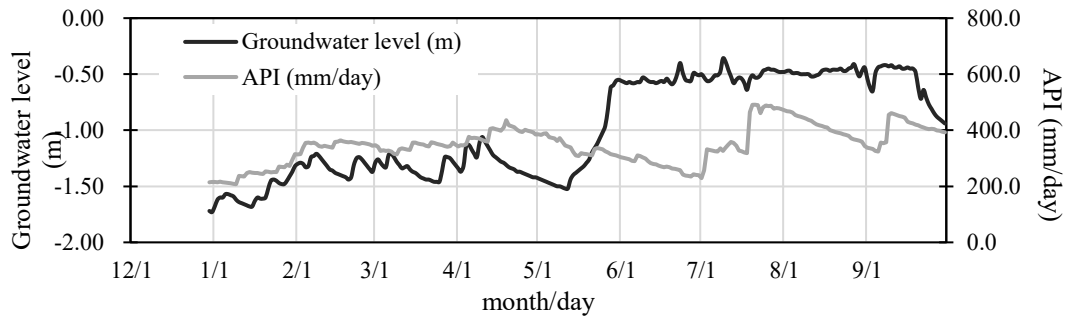


Fig. 5 Groundwater level and API at No. 2

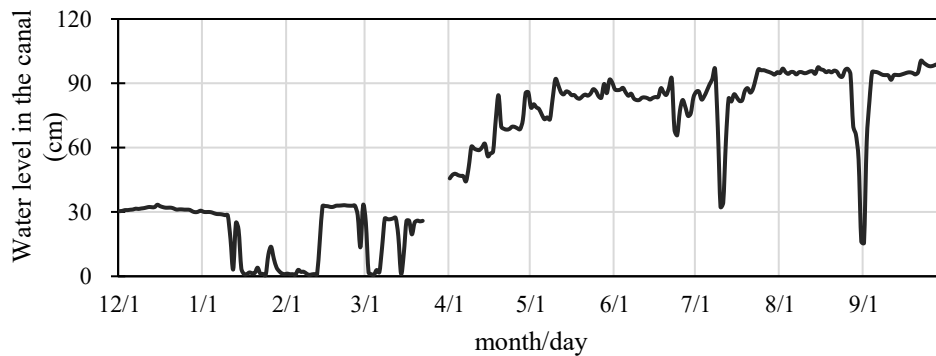


Fig. 6 Water level in the canal (missing from March 23 to 31, 2024)

Site No. 6 was the closest to a large-scale farm and shoreline. Therefore, pumping for agricultural purposes and tides could affect groundwater level fluctuations. A graph of the groundwater level and API at site No. 6 is shown in Fig. 7.

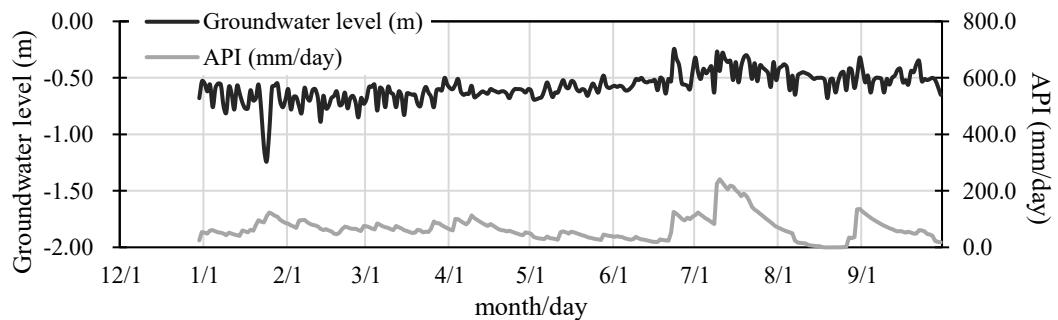


Fig. 7 Groundwater level and API at No. 6

In addition, the time lags were within one day at most sites. This can be explained by the high hydraulic conductivity of sandy soil. The Yumi-Hama Peninsula is largely composed of sand layers (Nakamura et al., 2001).

CONCLUSION

This study investigated the relationship between the groundwater level and API. As a result, some sites had high positive correlations with each other. However, the correlation coefficients were relatively low at the other sites. Possible factors contributing to this were the effects of infiltration from canals, pumping for agricultural purposes, and tides. In addition, the time lags were within one

day at most sites. These can be explained by the high hydraulic conductivity of sandy soil in the study area.

Two improvements were made to the model. The first is to prove correctness. In this study, we conducted only learning steps regarding groundwater levels, which are thought to have annual fluctuations and have not been validated. Second, the number of weather observatories should be increased. Only two observatories could cause a spatial bias. The solution is to interpolate or install new rain gauges in these areas.

As a future enhancement, to estimate the amount of water in the freshwater lens, the saltwater-freshwater boundary needs to be determined by methods including electrical conductivity and electromagnetic measurements. There is also a lack of data on the factors affecting fluctuations in the freshwater lens, which need to be collected. For example, in this study, pumping could influence groundwater levels, but there was a lack of quantitative pumping data. After these are clarified, predictions of freshwater lens fluctuations can be realized. The simulation allows for more efficient water use, making it easier and timelier to plan countermeasures against water shortages caused by climate change.

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Biomass Blending Approach: Availability and Potential of Agricultural Residues as an Energy Source in Thailand

WICHTRA SINGHIRUNNUSORN*

*Multidisciplinary Research Center for Environmental Sustainability (MRCES),
Faculty of Environment and Resource Studies, Mahasarakham University, Thailand
Email: swichitra@gmail.com*

PANNATAT LUESOPA

Provincial Energy Office of Nong Khai, Ministry of Energy, Thailand

Received 30 December 2024 Accepted 8 May 2025 (*Corresponding Author)

Abstract Blending different agricultural residues for pellet production can address the problem of seasonal availability of materials and improve biomass pellet quality and efficiency. With widely available agricultural residues in Thailand, our previous research took the blending approach to produce biomass pellets from five residue types, including Rice Stubble (RB), Rice Straw (RW), Sugarcane Leaves (SL), Cassava Leaves (CL), and Cassava Rhizome (CR). By combining high and low energy residues, it is possible to enhance the energy density, durability, and other desirable properties of the pellets. To gain a better understanding of agricultural residue availability, this study investigated farming practices and crop/residue characteristics by considering several factors, including the plantation process (site, area, growing crops, production, and harvesting), crop residue production, and crop residue utilization and the management. Using a sub-district in Mahasarakham Province as a case study, a questionnaire survey was conducted on 100 households to collect data on rice, sugarcane, and cassava crops and their associated residues. The Surplus Availability Factor (SAF) was estimated using survey data to assess the ratio of residues available for energy use to the total residue produced. This factor indicates the portion of the residue that can be collected for energy as a surplus after basic local usage. The study showed that RB and RW are the most commonly produced residues in Mahasarakham Province, but only RB has the greatest potential for energy use. SL and CR exhibited substantial volumes in the area despite the lower production of cassava and sugarcane. Regarding seasonal availability, RB and RW are available for a longer duration, whereas SL, CL, and CR are only available for four to five months. The results show that SL and CL were not used at all, and their SAFs were 1.00. Meanwhile, CR and RB had relatively lower SAF values (0.913 and 0.875, respectively). As rice straw may be sold and utilized for various applications, it had the lowest SAF (0.134). An estimated 5,509 tons of biomass pellets could be produced annually in Mahasarakham Province using the agricultural residues that are currently available. The biomass blending technique can offer an alternative use of agricultural waste to generate energy and value-added products. Using agricultural waste as an energy source has numerous environmental benefits, including minimizing harvesting burning, providing a carbon-neutral fuel supply, and encouraging the circular economy by using waste as an input for new products.

Keywords agricultural residues, biomass blending, renewable energy, energy potential, surplus availability factor

INTRODUCTION

Agricultural residues are an important source of renewable biomass energy because the process of using biomass feedstock can contribute to carbon neutrality. Approximately 5.5 billion metric tons of crop residues are produced annually. However, several activities use only a portion of the total production and require collection, bundling, and transportation (Shinde et al., 2022). Approximately

22.7 million hectares, or 42% of Thailand's total land area, are used for agriculture (NSO, 2023). The annual production of agricultural residues is 294.3 million tons. Approximately 136.5 million tons were used annually, whereas 159.8 million tons were either openly burned by farmers or left in the fields after harvest (DEDE, 2020).

The Alternative Energy Development Plan 2024-2037 (also known as AEDP 2024), currently under public hearing, aims to increase the share of renewable energy consumption in Thailand to 36% by 2037 (Kurovat, 2024). The Power Development Plan (also known as PDP 2024) complements this by targeting 50% renewable energy generation (electricity and heat) for the same year (EPPO, 2024). This represents a significant shift from the previous target of 36%. In these plans, biomass is targeted as the third-most important renewable energy source for power generation after hydropower and solar power. Agricultural residues are a significant biomass source, offering various opportunities for sustainable energy production and economic benefits for the agricultural sector. However, this has become a limitation for commercial production from agricultural residues because of the wide range of material properties, compositions, and seasonal availability.

Biomass blending has been proposed as a promising strategy for producing biomass fuel from agricultural residues (Hanaki and Portugal-Pereira, 2018; Anukam et al., 2016; Sasongko et al., 2017; Martinez et al., 2019). This strategy can mitigate the impact of seasonal availability-related material shortages and high costs. Additionally, blending can improve the energy efficiency of biomass feedstocks (Luesopa and Singhirunnusorn, 2023). It is difficult to control the use of agricultural residues throughout the year. It may be limited or available depending on the current alternative applications, such as animal feed, domestic use, and ecological uses (Daioglou et al., 2016). Therefore, it is necessary to evaluate the residue availability of various crops. Several studies have evaluated the potential and availability of agricultural residues using various methods, such as the residue-to-product ratio (RPR), Residue Recovery Factor (RRF), Surplus Availability Factor (SAF), and Residue Dryness Factor (RDF) (Aker et al., 2024). Furthermore, the potential of biomass as a source of energy production is also impacted by geological factors and site differences (Lozano-García et al., 2020; Zyadin et al., 2018). The SAF was used in this study to determine the crop residue potential for bioenergy. It is the ratio of residues available for energy purposes to the total number of residues produced. This factor indicates the portion of the residue that can be collected for energy as a surplus after basic usage.

OBJECTIVE

The purpose of this study is to assess the local potential for applying the biomass blending approach to manufacture biomass pellets from agricultural residues, including rice stubble (RB), rice straw (RW), sugarcane leaf (SL), cassava leaf (CL), and cassava rhizome (CR). The study investigates the farming practice and crop/ residue characteristics by considering a number of factors, including plantation process (sites, area, growing crops, production, and harvesting), crop residue production, and crop residue utilization and management.

METHODOLOGY

Case Study

All districts and subdistricts were clustered based on their similar growing crops. For this study, a sub-district with all three major crops—rice, sugarcane, and cassava—was chosen at random. The Tha Song Kon subdistrict area was randomly selected as the case study, and 100 households cultivating rice, sugarcane, and cassava were randomly sampled.

Questionnaire Survey

To examine the availability of crop residues after harvesting, this study conducted a questionnaire

survey with 100 household heads through in-person interviews. The sample comprised 56 rice-farming, 24 sugarcane-farming, and 20 cassava-farming households. The questions were grouped into three sections: 1) plantation process (sites, area, growing crops, production, and harvesting), 2) crop residue production, and 3). Crop residue utilization and management.

Surplus Availability Factor (SAF)

The Surplus Availability Factor (SAF) is an important factor used to estimate the bioenergy potential of crop residues. It is the ratio of residues available for energy purposes to the total residue produced. The SAF of five materials (RB, RW, SL, CL, and CR) was evaluated based on the surveyed data. The availability potential of crop residues for energy production or Volume of Agricultural Residues (VOR) was then calculated according to the following equation (Eq. 1):

$$\text{VOR} = \text{Cultivation Area (ha)} \times \text{Biomass Load (ton/ha)} \times \text{SAF} \quad (1)$$

Energy Potential

Energy potential of biomass pellet produced from the agricultural residues was calculated using the following Equations [Eqs. (2), (3), (4)].

$$\text{ENU} = \text{VOR} \times \text{RNU}_r \times \text{HHV} \quad (2)$$

where ENU: energy not used (10^{12} J), VOR: volume of agricultural residue (10^3 kg), RNU_r : residues not used ratio (%), HHV: higher heating value (MJ/kg).

$$\text{TOE} = \text{ENU} / (42.244 \times 10^9) \quad (3)$$

where TOE: tons of oil equivalents energy (10^3) and 1 TOE is 42.244×10^9 (J), ENU: energy not used (10^{12} J).

$$\text{POE} = (\text{ENU} \times \text{PE}_{\text{hour}}) / 3,600 \quad (4)$$

where POE: potential of energy (10^9 Wh), PE_{hour} : power of electric per hour (Wh).

RESULTS AND DISCUSSION

Availability Potential of Agricultural Residues

The 100 examined households included 56 rice, 24 sugarcane, and 20 cassava farming households. Because most of their agricultural land is outside government irrigation districts, they can only produce one crop each year. They usually use machines for planting and harvesting. Rice Stubbles (RB) and Rice Straw (RW) were the most commonly generated residues in the area. However, research revealed that 76.34% of RB was typically abandoned in the field without being used, 11.16% was burned before the following crop began, and only 12.5% was used to feed livestock. In contrast, RW was considered more valuable and adaptable. The majority of RW was used to feed animals (72.32%), whereas 14.29% was sold. Only 13.39% of the waste had the potential to be exploited as an energy source (Fig. 1).

Cassava and sugarcane were the second and third most productive crops in the area. They can also grow once a year. These crops were picked manually by hired workers. It was discovered that leaf leftovers from sugarcane fields have great potential for energy production. All sugarcane leaves were discarded. Farmers typically left sugarcane leaves in the fields (70.83%) without use, while another 29.17% were burned during or immediately after harvesting (Fig. 2). This also occurred with cassava leaves; farmers had not used the materials for any purpose. The majority of them (95%) were abandoned in the fields, with barely 5% being openly burned immediately after harvest. Only 8.75% of the cassava rhizome (root component) was used for traditional home fuel, with the remainder being left in the fields (53.75%) and burned (37.50%) (Fig. 3). Although cassava and sugarcane were

produced in significantly lower quantities than rice, their crop residues had a better potential for energy production than RB or RW.

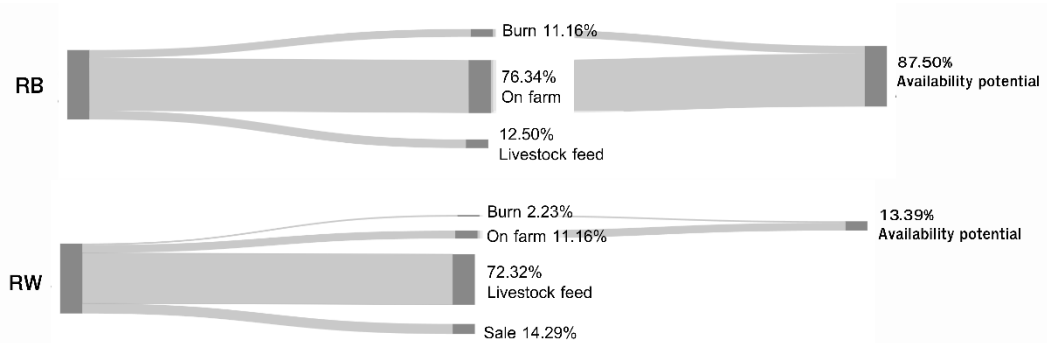


Fig. 1 Residue availability from rice cultivation

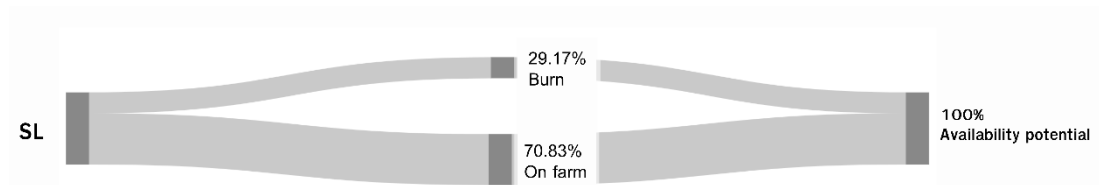


Fig. 2 Residue availability from sugarcane plantation

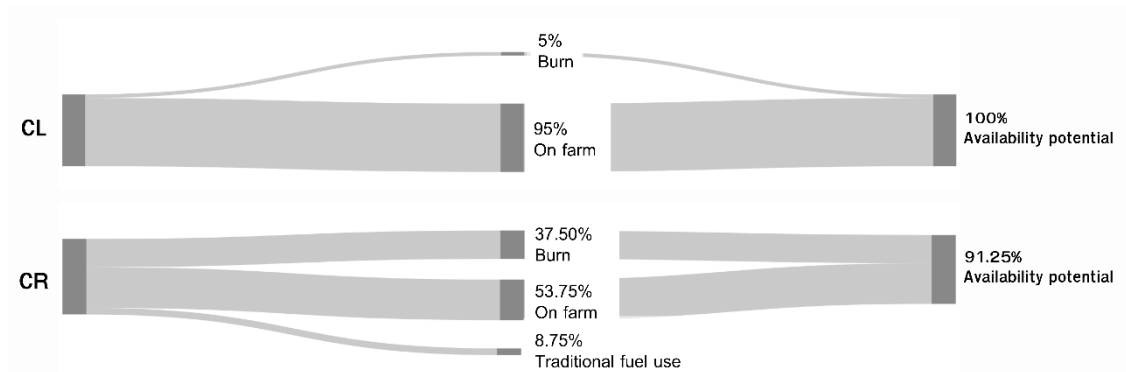


Fig. 3 Residue availability from cassava plantation

Table 1 Crop residue calendar of rice, sugarcane and cassava

Types	Residue production and availability											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Rice stubble (RB)												
Rice straw (RW)												
Sugarcane leaves (SL)												
Cassava leaves (CL)												
Cassava rhizome (CR)												

Crop Residue Calendar

Using agricultural residues as a source of energy production is quite complex. The quality and quantity of feedstock vary greatly, as does its seasonal availability. Table 1 depicts the periods of the year when various types of crop residues were produced and made available. Rice had traditionally been harvested between November and early December. RW was handled and stored for subsequent use and sales. Farmers normally leave RB in the fields until June, then burn or plow it into the soil before planting the next crop. SL, CL, and SR have been available for a shorter time of 4-5 months.

Farmers must burn or plow all remains before beginning the next crop rotation. This information is beneficial for residue-use planning and management.

Surplus Availability Factor (SAF)

The SAF is an important factor for estimating the bioenergy potential of crop residues. The residues produced are not only used for energy generation but also for other purposes. The study data showed that among the five crop residues, SL and CL had not been used at all, and their SAFs were 1.000. Meanwhile, CR and RB had relatively lower SAF values (0.913 and 0.875, respectively). Rice straw had the lowest SAF (0.134) because it can be sold and used for many purposes (Table 2).

Table 2 Surplus availability factor (SAF) of agricultural residues

Agricultural residues	Surplus availability factor (SAF)
Sugarcane leaves (SL)	1.000
Cassava leaves (CL)	1.000
Cassava rhizome (CR)	0.913
Rice stubble (RB)	0.875
Rice straw (RW)	0.134

To estimate the available potential of five crop residues in Mahasarakham Province, we used crop residue data estimated by the cultivation area from our previous work (Singhirunnusorn et al., 2017) and SAF values from this study. Table 3 demonstrates that RB has the highest potential for energy production, followed by SL and CR.

Table 3 Estimate crop residues available for energy production

Types	Cultivation area ^a (ha)	Crop residue ^b (ton/ha)	SAF	Potential availability (ton/year)
Rice stubble (RB)	3,530.16	0.75	0.875	2,316.67
Rice straw (RW)	3,530.16	1.25	0.134	591.30
Sugarcane leaves (SL)	81.04	15.44	1.000	1,251.26
Cassava leaves (CL)	480.87	0.5	1.000	240.44
Cassava rhizome (CR)	480.87	2.75	0.913	1,207.34

^a Data were adopted from the Land Development Department (2019), ^b Data adopted from Singhirunnusorn et al. (2017).

Pellet Heating Values

In our previous study (Luesopa and Singhirunnusorn, 2023), we employed a blending approach to produce pellets from RB, RW, SL, CL, and CR and investigated the heating values of the pellets. The data showed that CL, SL, and CR were among the biomasses with the highest Higher Heating Value (HHV) of 19.29, 17.49, and 16.92 MJ/kg, respectively. In contrast, RB and RW showed low HHVs of 14.20 MJ/kg and 14.31 MJ/kg, respectively, which are below the heat standard limit of biomass pellets. Blending techniques for biomass pellet manufacture have been suggested to improve the energy properties of pellets. The two-type blending technique revealed that the SL: RW ratio of 80:20 had the maximum heat value of 16.08 MJ/kg. Three-type blending revealed that SL:RW: RB in a 60:20:20 ratio had the maximum heat value (15.68 MJ/kg). Energy quality can be increased by using greater HHV as supplementary materials, such as CL and CR. For example, the RW: CL (50:50) ratio produced the greatest heat value of 16.25 MJ/kg (Luesopa and Singhirunnusorn, 2023).

Energy Potential

A blending strategy for biomass pellet manufacture was suggested in a previous study. The energy potential was calculated based on this scenario. The findings indicate that all available crop residues in Mahasarakham may be used to produce 5,509 tons of pellets each year, accounting for 2.5 Ktoe of biomass (Table 4). The utilization of pellets might generate approximately 5,910 MWh.

Table 4 Energy Potential from different scenarios

Production period	Biomass blending	Biofuel pellet production (Ton)	Energy Potential	
			TOE (Ktoe)	POE (MWh)
Jan- Mar	RB:SL (20:80)	1,173	0.49	1,157
	RB:CR (90:10)	843	0.32	741
	RW:CR (90:10)	235	0.09	209
	CL (100)	240	0.12	272
	CR (100)	1,100	0.48	1,113
April	RB:SL (20:80)	391	0.16	385
	RB:RW (20:80)	88	0.33	776
	RB (100)	235	0.09	209
May	RB:RW (20:80)	265	0.10	229
Nov - Dec	RB (100)	939	0.35	819
Annual Energy Potential		5,509	2.53	5,910

CONCLUSION

The study showed that in Mahasarakham Province, rice stubbles and straw are the most produced residues, but only rice stubbles show the highest availability potential for energy use. Although the production of cassava and sugarcane residues is low, sugarcane leaves and cassava rhizomes show high residue volumes in the area. In terms of seasonal availability, rice production residues are available for a longer period, whereas cassava and sugarcane residues are available for only four to five months. The biomass blending approach can provide a solution to the seasonal variation of materials proposed as an alternative use of agricultural residues to produce energy fuels and reduce material shortages and storage costs. Blending different agricultural residues for pellet production is a strategy to improve pellet quality and efficiency. This strategy allows for the efficient use of both high- and low-energy residues, potentially enhancing the overall energy density and other desirable properties of the pellets.

In the AEPD 20224 and PDP 2024 plans, biomass is targeted as the third-most important RE source for power generation, after hydropower and solar power. Agricultural residues are a significant source, offering various opportunities for sustainable energy production and economic benefit for the agricultural sector. The government's policies aim to utilize agricultural residues for multiple purposes by using them as a source of industrial energy, co-firing them with fossil fuels in power plants, generating renewable energy at the local level, and creating income opportunities for farmers through biomass collection and processing.

ACKNOWLEDGEMENTS

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Hydrochemical and Isotopic Characteristics of Irrigation Channel Water in Oil Palm Plantations, Kuala Selangor, Malaysia

MAYU OGIYA*

Faculty of Science, Shinshu University, Matsumoto, Japan

Faculty of Forestry and Environment, University Putra Malaysia, Serdang, Malaysia

Email: mayuogiya@gmail.com

CHEN ZHUO

Faculty of Forestry and Environment, University Putra Malaysia, Serdang, Malaysia

SITI NURHIDAYU

Faculty of Forestry and Environment, University Putra Malaysia, Serdang, Malaysia

YUSRA SHABIR

Faculty of Forestry and Environment, University Putra Malaysia, Serdang, Malaysia

TAKASHI NAKAMURA

Interdisciplinary Center for River Basin Environment, University of Yamanashi, Kofu, Japan

RORY WALSH

Department of Geography, Swansea University, Swansea, United Kingdom

KOICHI SAKAKIBARA

Faculty of Science, Shinshu University, Matsumoto, Japan

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Abstract The rapid expansion of oil palm plantation areas in Southeast Asia has brought economic benefits but has also led to substantial environmental challenges due to deforestation and excessive fertilizer use. This study examined the hydro-chemical and isotopic characteristics of water in irrigation channels in oil palm plantations in Kuala Selangor, Malaysia. Water samples demonstrated oxidative environments with pH ranging from 2.67–6.59, EC ranging from 7.27–138 mS/m and DO ranging from 0.46–4.83 mg/L. Channel waters in peatland areas were highly acidic (pH 3.25–3.67), probably because of the presence of humic acids. Isotopic analysis indicated that meteoric water was the primary source of water in the irrigation channels, with isotope fractionation due to water evaporation observed at specific points. The $\delta^{15}\text{N}$ and $\delta^{18}\text{O}$ values of NO_3^- suggest that the sources of nitrate were primarily ammonia fertilizers and atmospheric deposition. Overall, these findings imply that after precipitation enters the plantation irrigation water, subsequent evaporation and human activities modify water quality. These results highlight the need for sustainable oil palm management practices to safeguard water resources and mitigate the environmental impacts on surrounding ecosystems.

Keywords oil palm plantation, isotope tracer, water quality, irrigation channel, peatland

INTRODUCTION

Oil palm plantation areas are rapidly expanding in Southeast Asia because of their high productivity, commercial profitability at large scales among oil-producing plants, and rising palm oil demand (Sheil et al., 2009). However, intensive fertilizer use and land conversion have led to environmental concerns, such as eutrophication and water quality deterioration.

Several studies have reported higher electrical conductivity (EC), sulfate ion, and dissolved organic carbon (DOC) concentrations in river and drainage water in oil palm areas than in forest areas, attributing these differences to the use of fertilizers and herbicides (Itoh et al., 2023). High nitrate (NO_3^-) and ammonium (NH_4^+) concentrations have been detected in groundwater, river water, and irrigation channels (Muneoka et al., 2014), while several studies have recorded low NO_3^- concentrations, potentially due to denitrification or plant absorption (Fadhullah et al., 2020). These studies suggest that the water quality in oil palm plantation areas differs from that in forest areas. However, the factors contributing to these results are unclear. Nitrate-nitrogen and -oxygen isotope ratios ($\delta^{15}\text{N}$ and $\delta^{18}\text{O}$ of NO_3^-) can reveal the existence of denitrification and the source of NO_3^- in oil palm plantation areas (Nishina et al., 2023). Water isotope ratios ($\delta^2\text{H}$ and $\delta^{18}\text{O}$ of H_2O) provide information for understanding the hydrological cycle, such as identifying water sources and tracing phase changes (Itoh et al., 2023). Therefore, combining isotopic analyses ($\delta^{18}\text{O}$, $\delta^2\text{H}$, $\delta^{15}\text{N}$) with chemical tracers is a robust approach for understanding the hydrological cycle and its characteristics. Irrigation of oil palm areas can be a direct source of environmental pollution; however, studies on the characteristics and dynamics of irrigation water remain limited.

OBJECTIVES

The main objectives of this study were to assess and understand the hydro-chemical and isotopic characteristics of water in the irrigation channels within oil palm plantation areas in Kuala Selangor, Malaysia, and thereby help in assessing the environmental impact of oil palm plantations.

METHODOLOGY

Study Area

The study area is located between Kuala Selangor and Batang Berjuntai in the lowland section of the Selangor River Basin in Malaysia (Fig. 1). The major land uses along the river include oil palm and coconut plantations, orchards, villages, and peat swamp forests. Forest conversion to oil palm plantations has increased oil palm cover in the northern Selangor area from 249.3 km² in 1989 to 700.7 km² in 2016, whereas rainforest cover has decreased from 1455.7 km² to 880 km² (Charters et al., 2019).

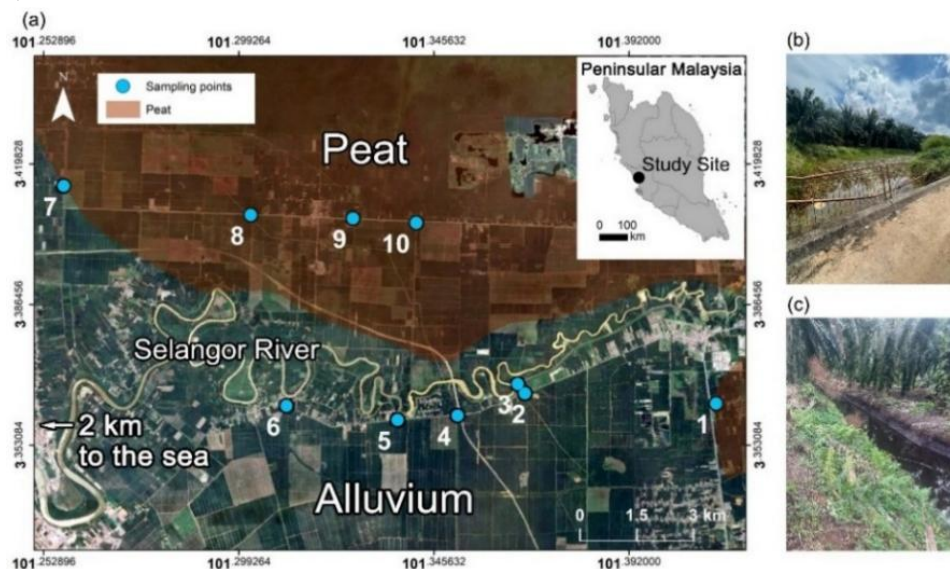


Fig. 1 Map of study area
 (a) Sampling locations and soil types in Kuala Selangor, Malaysia (Satellite imagery sourced from Google Earth),
 (b) Photograph of P5, and (c) Photograph of P8

Soil types in the study area are peat to the north of the river, Selangor-Kangkong (Alluvial Sediments), and Kranji (Acid Sulfate Soil) to the south of the river (Department of Agriculture Malaysia, 2023). The area is influenced by two monsoon seasons: the northeast (NE) monsoon from November to March and the southwest (SW) monsoon from April to October. The mean annual precipitation is 1572 mm (Department of Irrigation and Discharge Malaysia, 2002-2024).

Sampling and Analysis

An intensive field survey was conducted during the SW monsoon on July 7th and 8th, 2024. Water samples were collected from ten locations (P1–P10). Nine were landed in irrigation channels between the oil palm plantations and an access road, but P3 was taken from a drainage channel within plantation land a few meters before entering the Selangor River. At each sampling site, two water samples were filtered through a 0.45 μm Polyethersulfone (PES) filter and collected in 50 ml and 20 ml polypropylene (PP) bottles. Water temperature, pH, EC, oxidation-reduction potential (ORP), and dissolved oxygen (DO) were measured *in situ* using a digital thermometer (Testo104, testo), portable pH and conductivity meter (D-210PC-S, HORIBA), and portable DO and ORP meter (D-210PD-S, HORIBA). Water samples for ion concentration and water isotope analyses were refrigerated at 4°C, while those for $\delta^{15}\text{N}$ and $\delta^{18}\text{O}$ of NO_3^- were frozen at -18°C until analysis. The dissolved ion concentrations for F^- , Cl^- , NO_3^- , SO_4^{2-} , Na^+ , NH_4^+ , K^+ , Mg^{2+} , and Ca^{2+} were analyzed using ion chromatography (ICS-1500, ICS-2100, DIONEX). Bicarbonate concentration (HCO_3^-) was measured by titration to pH 4.8 using a 0.005 mol/L sulfuric acid solution. The $\delta^2\text{H}$ and $\delta^{18}\text{O}$ of H_2O were analyzed using wavelength-scanning cavity ring-down spectroscopy (L2130-i, PICARRO). The $\delta^{15}\text{N}$ and $\delta^{18}\text{O}$ of NO_3^- were analyzed using isotope ratio mass spectrometry (Hydra 20-20, SerCon) after NO_3^- was converted to nitrous oxide (N_2O) using the denitrifier method (Sigman et al., 2001). The stable isotope ratios of N, H, and O are defined by the following equation Eq. 1.

$$\delta_{\text{Sample}} (\text{‰}) = \{R_{\text{Sample}} / R_{\text{Standard}} - 1\} \times 1000 \quad (1)$$

Where R is the $^{15}\text{N} / ^{14}\text{N}$ or $^{18}\text{O} / ^{16}\text{O}$ ratio in NO_3^- and $^2\text{H} / ^1\text{H}$ or $^{18}\text{O} / ^{16}\text{O}$ ratios in the water of a sample or standard. The isotope values were calibrated using international standard materials (IAEA-N3, USGS34, USGS35, and V-SMOW: Vienna Standard Mean Ocean Water). The measurement accuracy (σ) was $\pm 0.025\text{‰}$ for $\delta^{18}\text{O}$ of H_2O , $\pm 0.1\text{‰}$ for $\delta^2\text{H}$ of H_2O (Sanyo Trading), $\pm 0.2\text{‰}$ for $\delta^{15}\text{N}$ of NO_3^- , and 0.3‰ for $\delta^{18}\text{O}$ of NO_3^- .

RESULTS AND DISCUSSION

Hydro Chemical Characteristics

Results of the selected water quality and isotopic analyses are summarized in Table 1. The pH ranged from 2.67 to 6.59, and the EC ranged from 7.27 to 138 mS/m. DO range from 0.46 to 4.83 mg/L and ORP from 125 to 520 mV, indicating an oxidative environment. At P4 and P6, the pH was particularly low (less than 3), with high EC and ORP. Irrigation channels in peatland areas (P7–P10), pH (3.25–3.67), and EC (7.23 –25.5 mS/m) showed low variability between samples. These findings might be due to the presence of natural organic matter, such as humic and fulvic acids in peatlands, which decrease pH (Qadafi et al., 2023). Peatlands are usually reductive environments, but the ORP of irrigation channel waters in peatlands indicates an oxidative environment. This suggests that oil palm

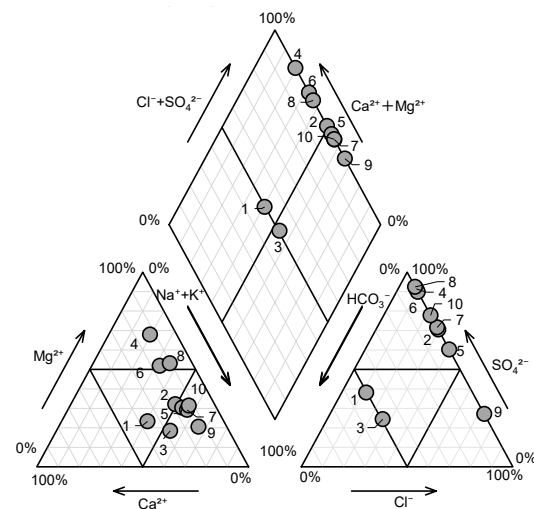


Fig. 2 Hydro-chemical composition of irrigation water

plantation activities expose peat to the atmosphere, leading to an oxidative environment. In contrast, P1 and P3 showed near-neutral pH, low EC, and low ORP values.

The dissolved ion results are shown in a Piper diagram (Fig. 2). Only P1 and P3 plots in the middle of the key diagram, indicating the dominance of Ca-HCO_3 compared to other samples. These samples showed near-neutral pH, low EC, and low ORP values. P3 is located near its inflow point to the river; therefore, there may have been some mixing with river water. Ca-HCO_3 can act as a buffer to achieve a neutral pH, which may explain the near-neutral pH of P1 and P5. The extremely low pH (2.7–3.3) noted at P4, P6, and P8 plots in the upper right of the key diagram are dominated by Mg^{2+} , SO_4^{2-} , and Cl^- . Other points (P2, P5, P7, P9, and P10) were dominated by Na^+ , Mg^{2+} , SO_4^{2-} , and Cl^- . There was a high positive correlation between NO_3^- and SO_4^{2-} ($r = 0.84$, $p < 0.01$), except for P3. Possible sources of SO_4^{2-} are fertilizers (such as kieserite and ammonium sulfate) and geological sources. However, the sources of NO_3^- include fertilizers, organic nitrogen in soil, and nitrification reactions. Since the primary common source for these two ions is fertilizer, the strong positive correlation observed between nitrate and sulfate indicates that both ions may have increased in the water due to fertilizer-runoff. Na^+ and Cl^- could be derived from aerosols evaporated from seawater and transported by precipitation, which is characteristic of coastal regions.

Table 1 Water quality and isotope analysis

ID	Water Temp	pH	EC	DO	ORP	Cl^-	NO_3^-	SO_4^{2-}	HCO_3^-	Na^+	NH_4^+	K^+	Mg^{2+}	Ca^{2+}	$\delta^{18}\text{O}$ - H_2O	$\delta^2\text{H}$ - H_2O	$\delta^{15}\text{N}$ - NO_3^-	$\delta^{18}\text{O}$ - NO_3^-
	°C		mS/m	mg/L	mV	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	‰	‰	‰	‰
P1	32.3	6.6	11.3	2.4	134	4.1	0.1	18.2	30.5	3.2	0.3	4.6	1.8	12.7	-5.1	-34.4	-2.4	7.4
P2	31.0	4.4	28.9	0.5	255	26.1	0.1	84.2	0.0	15.8	3.5	6.4	6.7	9.3	-5.9	-37.6	-7.4	29.4
P3	31.6	6.4	13.3	3.4	125	10.5	4.4	13.3	34.2	5.3	0.5	3.3	1.3	15.7	-6.3	-40.6	5.5	-1.6
P4	31.9	2.7	138.0	1.3	520	39.8	0.7	570.3	0.0	15.1	1.5	12.7	41.5	13.8	-6.3	-39.2	-1.4	25.6
P5	33.5	3.8	32.5	4.0	431	35.7	0.1	73.3	0.0	20.3	2.6	6.3	7.2	10.2	-6.0	-37.9	-10.2	3.8
P6	32.0	2.8	88.5	4.8	505	22.5	0.8	268	0.0	16.7	2.0	9.7	19.1	10.1	-5.8	-37.1	6.9	9.8
P7	28.6	3.7	15.0	2.1	369	4.2	0.2	14.3	0.0	4.7	0.1	1.2	1.5	1.2	-6.0	-37.3	-4.1	18.7
P8	28.8	3.3	25.5	3.4	435	3.1	0.2	51.7	0.0	3.8	0.1	1.1	3.4	2.6	-6.3	-38.1	0.6	26.3
P9	30.2	3.7	7.3	3.4	372	0.8	0.2	0.4	0.0	1.1	0.2	0.2	0.2	0.8	-6.7	-41.5	-1.9	8.4
P10	30.6	3.6	8.7	3.5	335	0.9	0.2	4.1	0.0	1.2	0.2	0.3	0.4	0.9	-6.7	-41.1	-0.4	3.7

Irrigation Water Dynamics

The δ -diagram of $\delta^2\text{H}$ and $\delta^{18}\text{O}$ of H_2O (Fig. 3a) shows that for irrigation channel water, $\delta^2\text{H}$ ranged from -6.7‰ to -5.1‰, and $\delta^{18}\text{O}$ from -41.5‰ to -34.4‰. Marryanna et al. (2017) found that the Local Meteoric Water Line (LMWL) in Peninsular Malaysia was $\delta^2\text{H} (\text{‰}) = 7.9 \delta^{18}\text{O} (\text{‰}) + 11.6$ ($r^2 = 0.98$) during the SW monsoon and $\delta^2\text{H} = 7.8 \delta^{18}\text{O} (\text{‰}) + 9.3$ ($r^2 = 0.99$) during the NE monsoon. Water samples for this study were collected in July 2024 during the SW monsoon season. Water collected in the peatland areas at P8, P9, and P10 were plotted on the SW LMWL, with results indicating that the source of peatland irrigation water was SW monsoon meteoric water. Water retained in peatland soil may comprise recent precipitation that has displaced old water from the NE monsoon.

The $\delta^2\text{H}$ and $\delta^{18}\text{O}$ of H_2O at P1, P2, P3, and P6 showed large deviations from the SW LMWL. The regression line slope for these four points was 3.95, which is much lower than the typical LMWL slope. This deviation suggests that the irrigation water was influenced by evaporation, which led to isotope fractionation. The regression line slopes of the δ -diagram are usually smaller when evaporation enrichment occurs because the lighter isotopes evaporate preferentially, whereas the heavier isotopes remain in the liquid phase. The slow flow in the irrigation channels of the study area may have caused water to stagnate for a long period, which in turn may have accelerated evaporation, resulting in isotopic enrichment of irrigation channel waters. If fertilizer input increases in the future, evaporation may lead to higher nitrate concentrations. However, in peatland areas, the groundwater table is high (Evans et al., 1999), and even small amounts of precipitation can saturate the peat, resulting in rapid surface water flushing. The effect of evaporation is considered to be small because

the water in the irrigation channels is easily flushed and does not tend to remain stagnant. It is also possible that isotopic ratios may have been diluted in the peatland areas due to the supply of groundwater to surface water.

Nitrate Sources of Irrigation Water

The $\delta^{15}\text{N}$ and $\delta^{18}\text{O}$ of NO_3^- vary depending on the source of nitrate in the environment and microbial activity (Kendall et al., 2007). Figure 3b illustrates the δ -diagram of the $\delta^{15}\text{N}$ and $\delta^{18}\text{O}$ of NO_3^- in the irrigation water in this study.

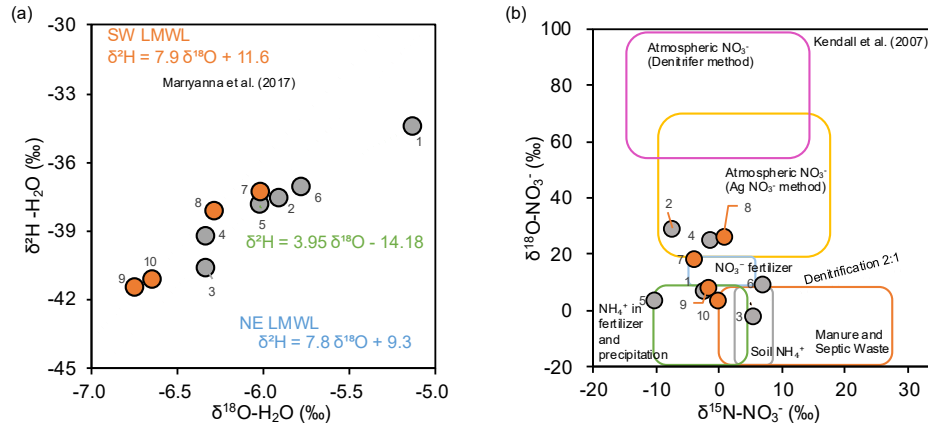


Fig. 3 The δ -diagram of irrigation water

orange dots: samples in peatland, gray dots: samples in alluvium (a) water isotopes, (b) nitrate nitrogen and oxygen isotopes

The typical ranges of $\delta^{15}\text{N}$ and $\delta^{18}\text{O}$ of NO_3^- for each source of nitrate were referenced from Kendall et al. (2007). The $\delta^{15}\text{N}$ of NO_3^- ranged from -6.7‰ to -5.1‰ and $\delta^{18}\text{O}$ of NO_3^- in irrigation water ranged from -41.5‰ to -34.4‰. These results indicate that the source of nitrate was dominated by ammonia nitrogen fertilizer and atmospheric deposition. Common fertilizers in Malaysia include urea, ammonium sulfate, ammonium nitrate, ammonium phosphate, and NPK compound fertilizer (FAO, 2004); however, nitrate fertilizer is not used in Malaysia. Thus, although some study sites were plotted in the nitrate fertilizer range, their source was not nitrate fertilizer. Fadhillah et al. (2020) reported that reservoir water in Malaysia has higher values of the $\delta^{18}\text{O}$ of NO_3^- than those derived from areas of nitrification and lower values than those from the atmosphere, and a similar pattern was observed in this study. This suggests that the mixing process of atmospheric nitrate with high values of $\delta^{18}\text{O}$ of NO_3^- and nitrate from other sources with low values of $\delta^{18}\text{O}$ of NO_3^- , such as fertilizer or soil. As mentioned earlier, this finding is consistent with water isotope evidence, which indicates that one source of nitrate is atmospheric precipitation. Thus, although the nitrate transported during the SW monsoon is considered to be derived primarily from fertilizers, some also derives from the mixing of marine aerosols and atmospheric pollutants.

NO_3^- concentrations were low (range: 0.09-0.84 mg/L) at all points except P3 (4.41 mg/L). Denitrification usually occurs in a reductive environment, such as below a DO of 2 mg/L. As several sampling points showed DO values greater than 3 mg/L, this reasoning cannot explain all the low NO_3^- values. Alternatively, when isotope data show a linear relationship with a $\delta^{18}\text{O}-\text{NO}_3^-$: $\delta^{15}\text{N}-\text{NO}_3^-$ ratio of approximately 1:2, it can be assumed that denitrification is occurring (Kendall et al., 2007). Although the ORP indicated an oxidative environment, nitrification was inhibited at pH values below 5.5 (Gieseke et al., 2015). Therefore, it is likely that nitrification did not occur at this location, which is consistent with the observed low NO_3^- concentrations.

CONCLUSION

This study investigated the water quality and isotopic characteristics of irrigation channels in an oil palm plantation area in Kuala Selangor. The results revealed that the hydrological cycle and geological conditions influence the water in irrigation channels in oil palm plantations. In the peatland area, the pH was lowered, likely due to the presence of humic and fulvic acids, and the main source of irrigation water was meteoric water. The $\delta^2\text{H}$ and $\delta^{18}\text{O}$ of H_2O results indicated that the main source of irrigation water was meteoric water, with isotopic fractionation due to evaporation observed at certain sites. The $\delta^{15}\text{N}$ and $\delta^{18}\text{O}$ of NO_3^- data showed that the main nitrate source in the water of the irrigation channel was nitrate from ammonia fertilizers and the atmosphere.

Overall, these results suggest that after precipitation enters the plantation area, factors such as evaporation, geological factors, and fertilization influence water quality. The natural nitrogen removal functions of peatlands and geology have thus far prevented serious pollution. However, if fertilizer application increases in the future, fertilizer runoff and evaporation in irrigation channels will lead to elevated nitrate concentrations; therefore, proper fertilizer application management is important. These findings highlight the importance of sustainable oil palm plantation management and water quality.

ACKNOWLEDGEMENTS

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Evaluation of Environmental Factors Influencing Revocation of Bauxite Mine Development in the Solomon Islands

BARRY N. NOLLER*

*The University of Queensland, Sustainable Minerals Institute,
St Lucia, Queensland 4072, Australia
Email: b.noller@uq.edu.au*

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Abstract Wagina Island, a small island within the Solomon Islands chain, is located in the South Pacific Ocean, 1700 km northeast of Australia. Wagina Island has an area of 110 km² with 60% of the island (48 km²) containing an economically viable quantity of bauxite. The Solomon Bauxite Limited (SBL) mining company was granted a prospective license over Wagina Island in 2011 and development consent in 2013. In 2018, the residents of Wagina opposed the development of the bauxite mine. In 2019, the Landowners Advocacy and Legal Support Unit (LALSU) within the Solomon Islands Public Solicitors Office (PSO) represented Wagina Island residents in 2018. The Solomon Islands Environment Advisory Committee (EAC) convened in 2018 for the first time since the 1998 introduction of the Environment Act 1998. All grounds presented by LALSU were upheld by the EAC, providing a historic defeat for the bauxite mine development. This study focuses on evaluating the environmental factors that influenced the revocation of the bauxite mine development. The EAC decision was based on: '(i) legislative procedures for public consultation and publication of the Environmental Impact Statement (EIS) were not followed; (ii) the EIS did not meet legislative and regulatory requirements; (iii) the decision to issue a development consent is inconsistent with the Convention on Biological Diversity and the Declaration on the Rights of Indigenous Peoples; and (iv) the unacceptable impacts to the environment, to the residents of Wagina and their livelihoods and on nearby islands and marine environment.' The decision was a win for the Wagina people and the environment of the Solomon Islands, incorporating an independent legal appeals process and building environmental law capacity in the Pacific region.

Keywords Bauxite, impacts, landowners, legislative procedures, environmental law

INTRODUCTION

The Solomon Islands are located in the South Pacific Ocean, 1700 km from Australia (Fig. 1). The Pacific Ocean's islands have 'evolved from a range of geophysical attributes and geological interactions observed in the Pacific linear chains of volcanic islands on the Nazca, Cocos, and Juan de Fuca (Gorda) Plates either by mantle plume or propagating fracture origin, atolls, uplifted coralline reefs, fragments of continental crust, obducted portions of adjoining lithospheric plates, and islands resulting from subduction along convergent plate margins' (Neall and Trewick, 2008).

The presence of bauxite in the Solomon Islands has been known since the 1940s. Prior exploration by Australian companies in the early 1970s identified extensive areas of bauxite mineralization in various Solomon Islands, which were proposed for the potential development of economic deposits (Pacific Bauxite, 2018). Interest in bauxite deposits has increased significantly due to the demand for the alumina industry in China and the Asia-Pacific region. Bauxite in the Solomon Islands is predominantly the preferred gibbsite (low-temperature trihydrate) type of mineralization and typically occurs as discontinuous pockets that fill depressions within the uneven karst surface of the uplifted Pleistocene coral limestone basement (Pacific Bauxite, 2018). The depth of bauxite deposits is variable because the surface above the deposits is uneven. Bauxite deposits are

distinguished from fern clearings by common tropical flora. These pockets are removed by mining and may prevent villagers from practicing alternative agriculture.

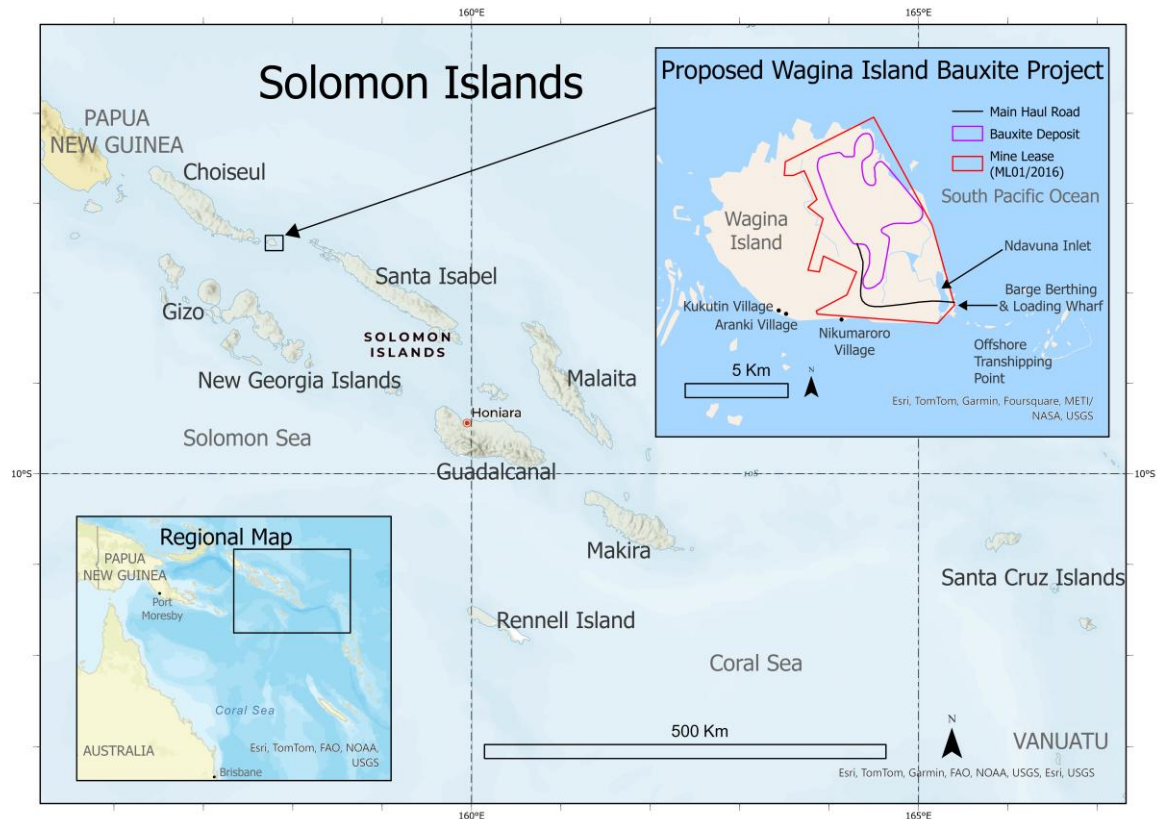


Fig. 1 Location of the Solomon Islands and the proposed Wagina Island bauxite project

The Noro Bauxite Project on New Georgia Island was identified as having substantial tonnages of material with grades of 40%–45% total aluminum oxide (Al_2O_3) and 5%–10% total silicon dioxide (SiO_2), and the grade is economically favorable (Pacific Bauxite, 2017). The Nendo Bauxite project on Santa Cruz Island has potentially high-grade bauxite mineralization with grades of 41.2%–45% total Al_2O_3 and 4.1% total SiO_2 (Pacific Bauxite, 2017). In addition, confirmation of grades planned to develop mining activity on the West Rennell Island Bauxite Project with resources of 30.1 million tons (Mt) at 46.9% Al_2O_3 and 3% total SiO_2 had received mining approval (Pacific Bauxite, 2017). The mining company Solomon Bauxite Limited (SBL) was granted a prospecting license for Wagina Island in 2011 and development consent in 2013 (EDO NSW, 2019).

The Solomon Islands *Environment Act* 1998 and Regulations of the Environment Regulations 2008 (National Parliament, 1998) provide the basis for issuing a decision for development consent and examination of the Environmental Impact Assessment (EIA). The EIA deals with pollution impacts from soil erosion, water pollution, marine pollution, loss of animals/plants, and social/cultural impacts, and is submitted to the Director of Environment and Conservation, Ministry of Environment, Brazil. The Minister holds a public meeting where people can attend and write letters of objection to the director. The Environmental Advisory Committee (EAC) considered any appeal matter for the minister.

In 2018, Wagina elder Tebukewa Mereki led an appeal by residents of Wagina Island opposed to developing the bauxite mine, coincident with the first stages of mining development (EDO NSW, 2019). The EAC considered the appeal matter for the Minister of Immigration. Tebukewa Mereki believed that the right of the people of Wagina to live peacefully on their island outweighed any promised economic or development benefits. When the mining company arrived at Wagina nearly a decade earlier with a proposal to mine 60% of the island, the former president of the Lauru Wagina Council of Women, Teuaia Sito, and a group physically stopped the machines that were landed on

site behind this island. They did not want mining on the island. In 2019, the Landowners Advocacy and Legal Support Unit (LALSU) within the Solomon Islands Public Solicitors Office (PSO) represented the Wagina Island residents' appeal in 2018. The EAC convened in 2018 for the first time since the 1998 introduction of the *Environment Act* 1998 (EDO NSW, 2019). The EAC case was between Tebukewa Mereki on behalf of the residents of Wagina (Appellant) and the Director of the Environment and Conservation Division (Respondent, with seven committee members). The Barrister for Appellant Trevor Wallwork, the Public Solicitors Office, Barrister-at-Law (Victorian Bar, an admitted legal practitioner in the Solomons), Solicitor for Appellant William Kadi, The Public Solicitors Office, and Solicitor for Respondent Daniel Damilea, Attorney General's Chamber (EDO NSW, 2019).

Enforcement under the *Environment Act* 1998 involves criminal offences. The Belo Belo case (2007) heard in the High Court (Hearing June 8, 2007; Date of Ruling 18 and June 27, 2007) is an example of action taken by the court (High Court of Solomon Islands, 2007). The Applicants were Nathan Kera, Ronald Kitu, and Agnes Lodge Limited, and the respondents were the Attorney-General representing the Director of Environment and Conservation, the Ministry of Environment, the Belo Belo tribe, Rupasi Murray, and CIP International. The case concerned logging on Belo Island, Roviana Lagoon, Western Province, within the New Georgia Islands (see Fig. 1). A 'Logging License' was issued in March 2006, but no Development Application was made to the Ministry of Environment under the Environment Act 1998 due to Legal Issues. The Court found that 'the responders were wholly obliged to comply with the provisions of the Act as it affects developers' and reflected that the parties were to consider both rights and responsibilities.

OBJECTIVE

This study evaluated the environmental factors that influenced the revocation of the bauxite mine development on Wagina Island and demonstrated the validity of the environmental and legal processes that were applied in the Solomon Islands.

METHODOLOGY

The small island of Wagina (Fig. 1), also referred to as 'Vaghena', is part of the Solomon Islands, located in the South Pacific Ocean, and has an area of 110 km² with 60% of the island (48 km²) (EDO NSW, 2019). The 2000 people of Wagina people originally came from their ancestral home, the Southern Gilbert Islands (now part of Kiribati). In the 1930s, the United Kingdom moved these people to the Phoenix Islands because of land shortages and overpopulation. In the early 1960s, the United Kingdom uprooted these people again and moved them over 3000 km to Wagina because of extensive droughts and British Nuclear testing in neighboring atolls. At Wagina, they began a new life and became seaweed harvesters for food, cosmetics, and fertilizers.

Wagina Island contains an economically significant quantity of bauxite. A proposed mining tenement would remove 2000 hectares (ha) of virgin forest and displace 2000 residents (EDO NSW, 2019). The removal of 150 truckloads of bauxite/day would continue for 20 years and have environmental impacts on water quality, air quality, ecology, and the marine environment. It could also affect residents who rely on the sea and land for their existence. This study focuses on evaluating the environmental factors that influenced the revocation of the bauxite mine development. Details of the '(i) legislative procedures for public consultation and publication of the Environmental Impact Statement (EIS) were examined; (ii) whether the EIS met legislative and regulatory requirements; (iii) if the decision to issue a development consent is inconsistent with the Convention on Biological Diversity and the Declaration on the Rights of Indigenous Peoples; and (iv) the unacceptable impacts to the environment, to the residents of Wagina and their livelihoods and on nearby islands and marine environment'. The residents were represented by a legal officer from LALSU, an Australian barrister, and four scientific experts.

RESULTS AND DISCUSSION

The appeal to the EAC by the residents of Wagina was related to the decision of the Director of the Environment and Conservation Division to grant development consent under Section 24 of the Environment Act to SBL on September 2, 2013. The Director's decision was inconsistent with the Act, and the Director did not comply with his obligations to provide notice of the development application before the 'Development Consent' was granted. The Environmental Impact Statement dated December 2012 (GREENPAC, 2012) and a Supplementary Report dated June 2013 ("Supplementary Report") were prepared on behalf of SBL, and together, these are the "EIS."

Expert advice was provided to the Wagina community (Vaghena Bauxite Project) on August 21, 2017, as follows (Noller, 2017):

A) Did the EIS contain sufficient information to adequately assess the environmental impacts of the Project, as it relates to any potential environmental contamination and associated impacts? Response 1 was that 'the EIS lists the key issues but appears to not follow the procedure required by the Government for proper submission of the EIS nor to provide sufficient detail on controlling issues to the point that the project can be considered to have the capacity to deliver adequate control to prevent impact from the mining operations'; and Response 2. 'Comparison with the Environment Act Section 23 requirements shows' in 22 items listed in Table 1 that many details were not included in the EIS.

B) What, if any, are the potential sources of contaminants from the project, and what, if any, is the risk of these contaminants impacting the local environment and the local community? Response 3 states that 'The source of contaminants is the bauxite and overburden from mining. This material is collectively soil or dirt, which can be dispersed as sediment if not retained on the mining lease or held in the ponds. Sediment may smother and affect biota such as macro-invertebrates and sea grasses by excluding light and oxygen, and Response 4 was 'However, the bauxite may also contain trace metals and arsenic, but the extent of these trace elements has not been established for this project in the EIS.' If sediment fines are held in still water ponds and become reduced (lack of oxygen), the trace elements may be released into the solution. If discharged, they may be taken up by biota. Response 5 states that 'Hydrocarbon spills and sewage leakage are also problems that commonly arise from such mining activities. These are difficult to avoid unless the project operation is sufficiently planned.

C) Does the Project, as approved, include all reasonable steps to minimize any risk of environmental harm from contamination? Response 6 that 'The EIS does not currently provide sufficient detail to minimize risk of environmental harm from contamination and needs to provide additional detail as indicated in (a) on controlling issues generated by the project operations to give confidence that adequate control to prevent impacts can be delivered'. And Response 7, that 'In addition, there are significant natural issues that the project needs to show can be dealt with. These are the effects of earthquakes on the stability of mine features, potential for longer-range volcanic activity, loss of topsoil from monsoon rain and cyclones, including ponds to retain sediment in the event of breaching, and the significance of annual rainfall of 3000 – 5000 mm. Bauxite contains approximately 35% moisture, which means that it is unlikely to dry completely (or not for very long). Wet sediment tends to stick to larger rocks and accumulates in waterways. Eroded sediments can be trapped by mangroves; therefore, any removal of mangroves will reduce the efficiency of sediment removal.

D) Provide any further observations or opinions that you consider relevant, considering the circumstances of this matter. Response 8 was 'The effect of sediment from bauxite mining on carrageenan seaweed production may be an issue for continuing farming on Wagina Island. Currently, there is insufficient detail available for local marine farmers to understand whether sediment from bauxite mining will restrict carrageenan seaweed growth.

The EAC decision was based on: (i) legislative procedures for public consultation and publication of the Environmental Impact Statement (EIS) were not followed; (ii) the EIS did not meet legislative and regulatory requirements; (iii) the decision to issue a development consent was inconsistent with the Convention on Biological Diversity and the Declaration on the Rights of Indigenous Peoples; and (iv) the unacceptable impacts to the environment, to the residents of Wagina and their livelihoods, and on nearby islands and the marine environment (EDO NSW, 2019).

Table 1 Comparison with Environment Act Section 23 requirements

(a) The EIS does not contain a full description of the objectives of the prescribed development. The EIS is set out like a proposal for such a project application without much supporting detail. There is very little background detail available to refer to in the EIS.
(b) There is no detailed analysis of the need for the prescribed development. There are predictions of the value of the bauxite planned to be mined.
(c) There is no indication in the EIS of the consequences of not carrying out the proposed development.
(d) The EIS does not include sufficient adequate information and technical data to allow assessment of the impact of the prescribed development on the environment.
(e) No reasonable alternatives to the prescribed development are described.
(f) The environment that is likely to be affected by the prescribed development or (alternatives) is not described because of the lack of currently available data.
(g) Following on from (f), there is little capacity to assess the actual or potential impact(s) on the environment.
(h) The reasons for the choice of the prescribed development are not given, apart from the established detail from earlier exploration work that the bauxite does not have undesirable minerals that complicate later extraction.
(i) The period of identified expected impacts is not given.
(j) The local geographical boundaries of the impacts of bauxite are not defined.
(k) Methods of predicting and assessing respective impacts through the lifetime of the project are not given.
(l) Justification of the prescribed development in terms of environmental, economic, cultural, and social Considerations are only partly given or not given at all.
(m) The likely impacts or consequences of implementing the prescribed development in the EIS, including for energy, it is not given.
(n) Measures to prevent or reduce significant adverse impacts and enhance beneficial effects, and an account of their likely success, with estimated costs are not given in the EIS.
(o) The residual impacts, which cannot be mitigated or can only be mitigated partially, are not described in the EIS.
(p) The proposed monitoring and reporting schemes, with estimated costs, are either not described or are not adequately described in the EIS.
(q) The safeguards or standards for the protection of the environment to be adopted or applied, including their implementation, monitoring, and reporting are proposed, but their cost-effectiveness is not described and assessed.
(r) An account of the impact on the environment of any of a series or programme of similar development (whether implemented or not) over a period is not given.
(s) The sources and references of information used during the preparation of the EIS are given to the extent that they are described.
(t) A site survey report concerning National Heritage items or traditional artefacts is given.
(u) It is not clear if further matters specified by the Director are addressed in the EIS.
(v) Based on a lack of details, a complete summary printed on a separate page is not given.

Source: Noller, B.N. 2017. *Expert Advice, Vaghena Project*. 21 August 2017

The residents were represented by a legal officer from LALSU, an Australian barrister, and four scientific experts who emphasized the ‘grave deficiencies of the environmental impact statement. The decision was a win for the Wagina people and the environment of the Solomon Islands, incorporating an independent legal appeals process and building environmental law capacity in the Pacific region (EDO NSW, 2019).

The immediate effect of mining bauxite is the effective removal of usable soil for any future agricultural activity, including tree recovery of bauxite deposits, which is variable, as the surface above the deposits is uneven. Bauxite deposits are distinguished from fern clearings by common tropical flora. These pockets are removed by mining and may prevent the development of alternative agricultural practices by villagers.

An additional issue related to environmental effects was identified earlier on water quality, air quality, ecology, and the marine environment. The *Environment Act* 1998 states that EIAs deal with pollution impacts from soil erosion, water pollution, marine pollution, loss of animals and plants, and social and cultural impacts in the Solomon Islands. Small island countries, such as the Solomon

Islands in the South Pacific Oceanic region, were identified as having common needs for regulatory and research requirements arising from limited economic resources. The Secretariat of the Pacific Regional Environment Program (SPREP), a regional organization established by the Governments and Administrations of the Pacific, was established in 1993. SPREP has 21 Pacific Island member countries and territories and five metropolitan ones. The strategic direction for SPREP is set out in its Strategic Plan (www.sprep.org). With the Solomon Islands, there are regular reports on country environmental issues and State of Environment Reports (SPREP, 2019). These reports provide a good picture of the current environmental status and conditions in the Solomon Islands.

CONCLUSION

This study evaluated the environmental factors that influenced the revocation of bauxite mine development. All grounds presented by LALSU were upheld by the EAC, providing a historic defeat for the bauxite mine development. The importance of the case was its implications beyond Wagina, providing a model for other rural communities that feel powerless against companies with government-issued mining or logging services.

ACKNOWLEDGEMENTS

I acknowledge the University of Queensland for providing funding and access to facilities. The residents of Wagina were represented by a legal officer from LALSU, an Australian barrister, and four scientific experts, including the author of this paper, who collectively emphasized ‘grave deficiencies of the environmental impact statement’. I thank Phil McKenna for preparing Fig. 1.

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Impact of Biochar Application on Andosol Soil pH and Electrical Conductivity Under *Avena sativa* Cultivation

SARVESH MASKEY*

Faculty of Regional Environment Science, Tokyo University of Agriculture, Tokyo, Japan
Email: smaskey27@gmail.com

KISEKI KURASHINA

Graduate School of Agro-Environmental Science, Tokyo University of Agriculture, Tokyo, Japan

HIROYUKI OSHIMA

Faculty of Applied Bioscience, Tokyo University of Agriculture, Tokyo, Japan

TAKU KATO

Faculty of Applied Bioscience, Tokyo University of Agriculture, Tokyo, Japan

HIROMU OKAZAWA

Faculty of Regional Environment Science, Tokyo University of Agriculture, Tokyo, Japan

Received 31 December 2024 Accepted 12 May 2025 (*Corresponding Author)

Abstract Biochar, a carbon-rich material derived from the pyrolysis of organic matter, has emerged as a promising soil amendment for enhancing soil properties. It has been shown to increase soil pH, boost microbial activity, improve nutrient retention, and enhance water-holding capacity. When applied to acidic soils, biochar neutralizes the pH and improves nutrient availability, creating a more favorable environment for crop growth. However, the effects of biochar vary significantly depending on the soil type, crop species, and biochar application rate. This study explored the impact of biochar application made from branches and twigs on soil pH and electrical conductivity (EC), under *Avena sativa* cultivation. Biochar was applied at rates of 0, 2, 4, and 8 tons per hectare, and soil pH and EC, and plant growth were monitored over two and a half months. The results demonstrated that biochar initially increased soil pH, with higher application rates of 4 and 8 t/ha, reaching mild alkaline levels favorable for leguminous crops. Biochar significantly increased pH and EC, particularly at higher rates, although the effects diminished over time. These findings highlight the potential of biochar as a short-term soil amendment for pH and nutrient enhancement in acidic soils. This study emphasizes the need for periodic applications or combined soil management strategies to sustain soil quality improvements. This study contributes to sustainable agriculture by offering insights into the role of biochar in enhancing soil health and productivity. Further research on the long-term effects of biochar and its interactions with other soil amendments could help optimize its use for sustainable crop production.

Keywords biochar, Andosol, soil pH, electrical conductivity, oat (*Avena sativa*), soil amendment

INTRODUCTION

Soil properties, such as pH and electrical conductivity (EC), are critical indicators of soil health, fertility, and suitability for agricultural production. pH influences nutrient availability, microbial activity, and the solubility of toxic elements, whereas EC is a measure of soil salinity and ion exchange capacity, reflecting the soil's ability to support crop growth (Brady and Weil, 2017). These parameters are particularly important in Andosols, a soil type derived from volcanic ash, known for its high porosity, organic matter content, and variable charge properties (Shoji et al., 1993). Biochar's

role as a soil amendment has been widely studied for its capacity to improve soil pH and EC. Its alkaline nature can neutralize soil acidity, creating a more favorable environment for nutrient uptake and microbial activity (Lehmann and Joseph, 2015). Furthermore, the porous structure and high surface area of biochar contribute to its ability to adsorb nutrients and water, thereby improving soil EC and overall fertility (Novak et al., 2012). The application of biochar to Andosols also influences its cation exchange capacity (CEC) and nutrient retention, with the potential to reduce phosphate fixation, which is a significant challenge in these soils (Agegnehu et al., 2016). These improvements are closely tied to the chemical properties of biochar, pyrolysis temperature, and feedstock material. Importantly, understanding the appropriate application rates of biochar is vital for achieving the desired soil enhancements without adverse effects. Over-application can lead to excessive EC, negatively impacting root function, whereas suboptimal rates may fail to provide meaningful improvements in soil properties. The optimal application rates of biochar are influenced by factors such as soil type, initial fertility status, crop requirements, and environmental conditions. In Andosols, studies have demonstrated that moderate application rates, e.g., 5-10 tons/hectare (t/ha), can effectively improve soil pH and nutrient availability while minimizing the risk of negative impacts. Furthermore, application rate optimization ensures cost-effectiveness and long-term sustainability, as excessive rates may lead to financial inefficiencies and ecological disturbances. Therefore, the objective of this study was to assess the effects and optimum application rates of biochar on Andosol soil pH and EC under *Avena sativa* cultivation.

METHODOLOGY

This study was conducted in an agricultural field in Sakura City, Chiba Prefecture, Japan (Fig. 1). A randomized block design was employed to evaluate the effects of biochar application at four treatment levels: 0 t/ha, 2 t/ha, 4 t/ha, and 8 t/ha, referred to as Control, Treatment 1, Treatment 2, and Treatment 3, respectively (Fig. 2). The soil type of this field was Andosol, which had a carbon-to-nitrogen (C/N) ratio of 13:1. Each treatment was replicated three times. The biochar used in this study was locally produced using traditional farmer techniques in a kiln, utilizing branches and twigs discarded from a nearby orchard. The initial pH and carbon content of the biochar used were 10.2 and 53.6%, respectively. No fertilizers were applied during the study, and all treatments relied solely on natural rainfall for irrigation purposes. Soil samples were collected to measure pH and EC, and crop parameters, including root length and height, were assessed. Statistical analysis was performed using R software, employing two-way ANOVA, followed by Tukey's post-hoc test to evaluate the significance of the results.



Fig. 1 Location of the field



Fig. 2 Random block design of the plots

RESULTS AND DISCUSSION

Effect of Biochar Application on Soil pH and EC

The results (Fig. 3) demonstrated that biochar significantly influenced soil pH dynamics, with a dose-dependent effect observed across the experimental treatments. At the time of application (day 0), the soil pH ranged from 6.0 to 6.5 across all treatments, reflecting uniform baseline conditions. By 42 days, a noticeable increase in soil pH was observed in the biochar-amended soils, with higher application rates (Treatments 2 and 3) showing more pronounced alkalinity. The increase in pH can be attributed to the release of alkaline cations, such as calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^+), and sodium (Na^+), present in biochar. These cations neutralize hydrogen ions (H^+) in acidic soils, thereby effectively increasing the pH (Yuan et al., 2011). Beyond 42 days, a decline in pH was observed across all treatments, which stabilized by 73 days. This trend likely reflects the leaching of soluble alkalinity from biochar, microbial oxidation of organic matter, and inherent acidification processes in the soil. However, soils treated with higher biochar rates maintained slightly higher pH levels than those treated with lower rates or the control. This residual effect indicates that biochar's buffering capacity is sustained over time, albeit diminishing gradually (Chintala et al., 2014). These results emphasize the importance of application rate in determining the effectiveness of biochar. In Treatment 3, biochar induced the most substantial and persistent pH increase, followed by Treatments 2, 1, and the control.

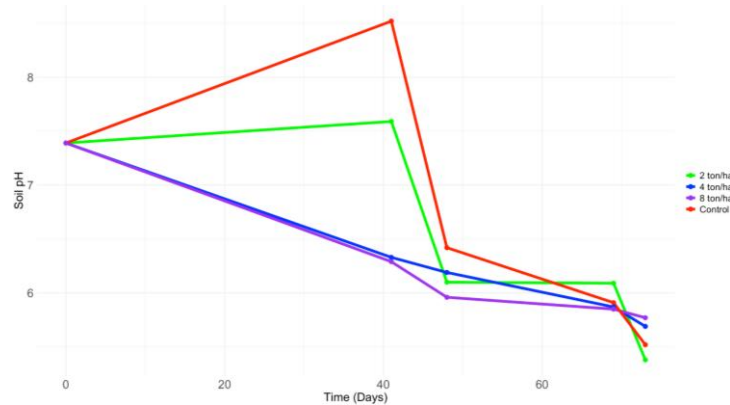


Fig. 3 Change in pH at varying treatments

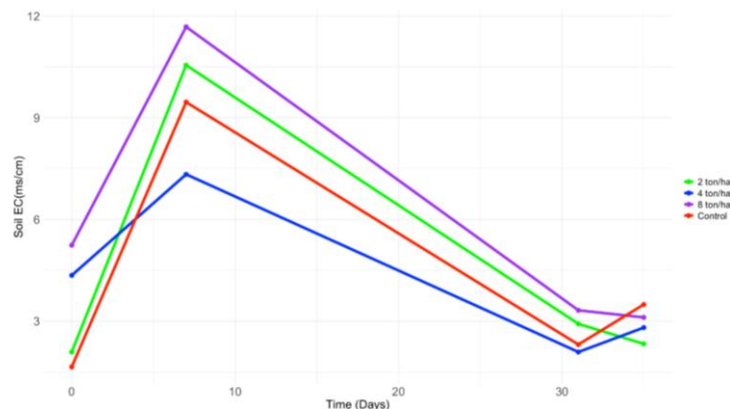


Fig. 4 Change in EC at varying treatments

These findings align with those of previous studies that have demonstrated the dose-dependent effects of biochar on soil pH (Lehmann and Joseph, 2015). While higher rates provide more immediate pH correction, their long-term benefits may depend on soil conditions, biochar stability, and environmental factors. Biochar's ability to raise and buffer soil pH has significant implications for improving acidic soils. By neutralizing acidity, biochar enhances nutrient availability, reduces aluminum toxicity, and fosters favorable conditions for microbial activity and plant growth (Van

Zwieten et al., 2010). Furthermore, the dose-dependent response suggests that while higher rates are more effective, lower rates may offer greater economic and environmental benefits over time.

The results (Fig. 4) indicate that EC increased with biochar application and varied over time. The EC peaked on day 46 for all treatments, with higher biochar application rates (treatment 3) resulting in the highest EC values. This initial spike was attributed to the release of soluble nutrients, such as potassium (K^+), calcium (Ca^{2+}), and magnesium (Mg^{2+}), from the biochar. Over time, the EC decreased significantly by 67 days and stabilized by 71 days, indicating nutrient uptake by plants, leaching, or immobilization within the soil matrix. These findings align with previous studies by Laird et al. (2010), which highlight biochar's nutrient release and subsequent stabilization. Biochar application significantly impacts soil EC due to its inherent properties and nutrient content.

The increase in EC shortly after biochar application demonstrates its role in enhancing short-term nutrient availability, particularly in soils with low fertility. Lehmann et al. (2006) reported that biochar's ash content provides essential nutrients and improves soil chemical properties. Additionally, biochar enhances soil CEC, enabling the retention of cations and reducing nutrient leaching over time (Laird et al., 2010). As biochar decomposes slowly, its effect on EC stabilizes, promoting long-term soil health without the risk of salinity buildup. The stabilization of EC observed in the study suggests biochar's potential as a sustainable amendment that balances immediate nutrient availability with long-term soil fertility. These results are consistent with the findings of Lehmann and Joseph (2009), who highlighted biochar's ability to maintain a steady nutrient supply over extended periods.

Effect of Biochar Application on Crop Height and Root Length

Figure 5 shows *Avena sativa* crop height under varying biochar applications, with no significant differences observed. The consistent height indicates that biochar had a minimal effect on growth, likely due to favorable soil conditions. The C/N ratio of the soil used in this study was 13:1, indicating high soil fertility. Research supports this, suggesting biochar improves soil properties but may not boost crop growth significantly in fertile soils. The benefits of biochar are more pronounced in degraded or nutrient-poor soils. Studies by Jeffery et al. (2011) and Liu et al. (2013) reinforce the context-dependent nature of biochar's effects. Similarly, biochar application at different rates had minimal impact on barley root length, with only a slight increase at the highest rate (Fig.6). The stable root length across treatments may indicate that biochar is not critical for enhancing barley root development in fertile soils. The slight increase at higher application rates suggests that biochar may have a minor positive effect on root growth under certain conditions. Studies on the effects of biochar on root systems support these findings, indicating that the effectiveness of biochar is influenced by soil conditions and crop type. Biochar enhances soil aeration, water retention, and nutrient availability, thereby supporting root growth, primarily in degraded soils. Under such conditions, soil structure and nutrient exchange capacity are improved (Cornelissen et al., 2013). However, in nutrient-rich soils, biochar has a neutral impact on root growth, as plants already have access to adequate resources (Liu et al., 2013; Agegehu et al., 2015).

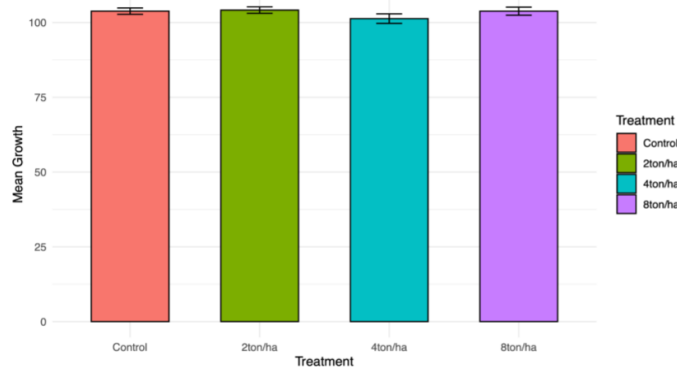


Fig. 5 Plant height at varying treatments

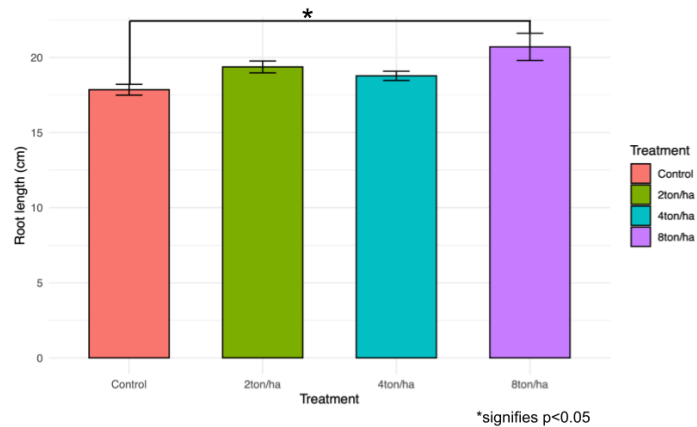


Fig. 6 Root length at varying treatments

CONCLUSION

The findings of this study underscore the significant role of biochar in enhancing soil properties, particularly soil pH and EC, in Andosols under oat (*Avena sativa*) cultivation. Biochar application demonstrated a dose-dependent impact, initially increasing soil pH and EC levels, with higher rates showing more pronounced effects than lower rates. These changes indicate improved nutrient availability and reduced soil acidity, creating favorable conditions for crop growth, particularly in acidic soils. However, the observed decline in pH and stabilization of EC over time highlights the transient nature of these benefits, emphasizing the need for periodic applications or integrated soil management strategies to sustain long-term soil health. The limited influence of biochar on crop height and root length further suggests that its benefits are more pronounced in degraded or nutrient-deficient soils than in inherently fertile conditions. This study provides valuable insights into the potential of biochar as a sustainable soil amendment, offering practical implications for improving soil quality and productivity in acidic soils. Future research should explore the long-term effects of biochar, its interactions with other soil amendments, and its application under diverse soil and crop conditions to optimize its utility for sustainable agriculture.

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Vulnerability Assessment of Communities to Climate Variabilities and Extremes: The Case of Cangaranan Watershed, Antique, Philippines

MELISSA R. SUGANOB*

University of Antique- Hamtic Campus, Guintas, Hamtic, Antique, Philippines
 Email: melissasuganob@antiquespride.edu.ph

JOSE ADONIS N. NACIONALES

University of Antique- Hamtic Campus, Guintas, Hamtic, Antique, Philippines

JOSE ARIEL A. TUTOR

West Visayas State University, Jayobo, Lambunao, Iloilo, Philippines

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Abstract This study assessed the vulnerability of households in the Cangaranan Watershed to climate variability and extremes and examined their adaptive strategies. Using a mixed-methods approach, data were collected through face-to-face interviews and focus group discussions across two municipalities in Antique Province, Philippines: Bugasong and Valderrama. The study involved 192 randomly selected respondents, complemented by socio-demographic data and development plans from municipal and provincial sources. A community-based vulnerability index was developed to identify the key factors contributing to this vulnerability. The findings revealed that the average respondent age was over 55 years, with a balanced gender distribution (54% women). Most respondents were married, had diverse educational backgrounds, and had an average monthly household income of PhP 12,434.00. Agriculture, particularly rice farming, is the primary livelihood in this area. The watershed has faced severe climate-related challenges over the past two decades, including numerous typhoons (e.g., Frank, Ondoy, Yolanda, Paeng, and Odette), prolonged droughts (notably during the 2009-2015 period), and recent El Niño events (2023-2024). These events have resulted in food shortages, water scarcity, and disruption of domestic water supply. Farmers employ various coping mechanisms, such as reducing consumption, taking out loans, and seeking assistance from social networks, NGOs, and government agencies. This study underscores the urgent need for effective and inclusive climate resilience strategies, emphasizing the importance of development planning that prioritizes the most vulnerable populations. Future research should focus on evaluating the long-term impact of adaptation measures and addressing socioeconomic barriers in marginalized communities.

Keywords climate variability, climate extremes, vulnerability assessment, climate change, adaptation practices

INTRODUCTION

Climate change is expected to create various weather patterns with significant and adverse effects. This causes intraseasonal and interannual variability in climate, extreme weather events such as typhoons, greater rainfall variability characterized by increased rainfall frequency and intensity, and prolonged dry spells. There have been many recent examples of floods and droughts in tropical Asia. According to the 2001 report of the Intergovernmental Panel on Climate Change (IPCC), the anticipated impacts of climate change, including global warming, may lead to an increased occurrence and intensity of extreme weather events in Asia. Significant changes in climate patterns have been documented in the Philippines, including an increase in the frequency of extreme weather events. These include an increase of 0.14°C in the mean, maximum, and minimum annual

temperatures from 1971 to 2000, and an increase in the annual mean rainfall since the 1980s (Cruz et al., 2007). Since the 1990s, there has been a noticeable trend in the number of rainy days and shifts in the onset of rainfall in the Philippines. The frequency of tropical cyclones entering the Philippine Area of Responsibility (PAR) has increased (Cruz et al., 2007), along with the occurrence of stronger ones. In 2024, the Philippine Atmospheric, Geophysical, and Astronomical Services Administration (PAGASA) released updated climate projections based on the Coupled Model Intercomparison Project Phase 6 (CMIP6). These projections indicate that the Philippines is expected to experience a significant increase in mean annual temperatures, ranging from 1.8°C to 2.2°C by 2050, affecting all regions of the country. An increase in rainfall is likely during the southwest monsoon in many areas of Luzon and Visayas. However, Mindanao is projected to experience a decreasing rainfall trend, particularly by 2050. Yusuf and Francisco (2009) stated that all regions of the Philippines are vulnerable to climate change. Maplecroft (2012) ranked the Philippines 10th among countries with an extreme climate change risk owing to the country's increasing exposure to extreme weather disturbances, growing population, and low adaptive capacity to combat the adverse impacts of climate change.

The watershed areas in the Philippines are believed to be adversely affected by climate change (CC). Watersheds are critical to a country's economic development and environmental protection and are therefore key to the pursuit of sustainable development. More than 70% of the total land area of the Philippines is located within watersheds. It is estimated that no less than 1.5 million hectares of agricultural land currently derives irrigation water from these watersheds (Pulhin et al., 2006). Moreover, approximately 20 to 24 million people, one-third of the country's total population, inhabit the uplands of many watersheds and are significantly dependent on them for resources and survival (Pulhin et al., 2006).

The Cangaranan River Basin in Antique Province is located west of Panay Island. The Department of Environment and Natural Resources (DENR) River Basin Control Office (RBCO) identified the Cangaranan Watershed as one of 421 river basins in the Philippines, with a drainage area of 294 km² and an estimated 374 million cubic meters of annual runoff. It is also one of the seven major river basins in Antique Province. The main stem of the basin, the Cangaranan River, passes through the Municipalities of Valderrama and Bugasong.

Previous studies on climate change in watershed areas have focused on biophysical aspects (Jose et al., 1996). Studies focusing on the human dimensions of climate change are lacking. Specific to the Cangaranan Watershed, there is minimal information on climate change and its impact on local communities. Of greater concern is the limited knowledge of the vulnerability of these communities to climate variability and extremes and their coping mechanisms to minimize the adverse impacts of these phenomena.

Most socioeconomic studies on climate variability and extremes have focused on a single event, such as El Niño, including those by David et al. (2007). Few studies have examined the impacts of other climate stressors, such as typhoons, La Niña, and early or late onset of the rainy season. Studies from other Southeast Asian contexts, such as Cambodia, also highlight the limited adaptive capacity of rural communities to face climate change, emphasizing the role of localized assessments in understanding vulnerability (Chun, 2016; Chhinh and Poch, 2012). Vulnerability assessments of communities have been conducted in various watersheds in Antique, such as the Sibalom Watershed (Saldajeno et al., 2012). However, the available literature and sources addressing the impact of climate variability and extremes on local communities within the Cangaranan Watershed remain limited. This pioneering study attempts to fill this gap.

OBJECTIVE

This study aimed to assess the communities in the Cangaranan Watershed, their vulnerability to climate variability and extremes, including related hazards, and their ability to respond to stress. Specifically, the study sought to answer multiple objectives, including **a.** identifying the socioeconomic profile of various communities within the watershed; **b.** identifying the climate variability and extremes experienced by the local communities over the last 20 years, including the

socioeconomic impacts; **c.** identifying which socioeconomic groups in the watershed experienced the most negative impacts; **d.** assessing the extent and nature of their vulnerability to climate variability and extremes; and **e.** identifying the adaptation practices of the local communities.

METHODOLOGY

Study Location

The Cangaranan Watershed is located in the Antique Province of the Philippines. It spans a considerable area, with the majority of the floodplain situated within the Bugasong and Valderrama municipalities, comprising four (4) barangays: Pandanan and Ubos in the Municipality of Valderrama and Igbalangao and Ilaures in the Municipality of Bugasong. Study site recommendations were gathered from the Office of the Municipal Agrarian and Municipal Environment and Natural Resources Office (MENRO). As cited by Paringit et al. (2017), the most devastating flooding event in the province occurred after Typhoon Frank landfall in 2008. The local population and officials claimed that the floodwater reached a height of 2 m in their communities.

Research Design and Instrumentation

This study used a mixed-methods approach that integrated qualitative and quantitative techniques. Qualitative analyses have focused on understanding the vulnerabilities of different socioeconomic groups. Quantitative analyses were employed to analyze household-level data using a vulnerability index developed based on household survey data, incorporating four key indicators: food, water, livelihood, and health. Drawing from Peras et al. (2008), this study relied solely on community-assigned weights for the indicators to ensure that local perspectives shaped the results. These indicators were further subdivided into relevant variables reflecting household sensitivity and coping capacity, following the framework of Moss et al. (2001). Focus group discussions (FGDs) in four barangays in Bugasong and Valderrama gathered community inputs to assign weights to the index components. The participants reached a consensus on these weights, ensuring that the index aligned with their experiences and priorities. This collaborative process highlighted variations in community perspectives and emphasized the importance of localized input in assessing vulnerability.

Sampling

Using Slovin's formula, a sample size of 192 respondents was computed. This sample size ensured a high level of accuracy, with a permissible error of 0.10 and a confidence interval of 90%. Respondents were selected through random sampling using barangay data.

Data Collection

This study used diverse methods to collect data effectively, addressing all research goals, including a household survey. A household survey was conducted through face-to-face interviews using structured questionnaires with 192 respondents across selected barangays within the Cangaranan Watershed from January to May of 2024. The structured questionnaires consisted of five distinct sections: Socio-Economic Profile of the Respondents, Perceived Impact and Benefits of Watershed Climate Variability and Extremes experienced over the last two decades and their impacts, and household vulnerability in terms of food availability, water supply, livelihood, health, and Adaptation Strategies. Enumerators were trained, and the tool was pretested to ensure clarity and appropriateness. Secondary data were collected from the following sources: Secondary data were gathered from municipal and provincial development plans, sociodemographic statistics from the National Statistics Office (NSO), maps from different agencies, the Department of Environment and Natural Resources (DENR), the Department of Agriculture, and Local Government Units. Comprehensive climatic data were obtained from agencies such as the Philippine Atmospheric, Geophysical and Astronomical

Services Administration (PAGASA). Participatory rural appraisal techniques were used. FGDs were conducted. Participants were selected through purposive sampling in coordination with barangay officials, ensuring representation from key vulnerable groups, such as farmers, women, and elders, with knowledge of past climate events in the watershed area. These discussions utilized a combination of participatory techniques, including timeline analysis and participatory vulnerability assessments. A timeline analysis was employed to identify significant natural events experienced by local communities in the watershed, reflecting climate variability and extremes from 2004 to the present day. In addition to assessing past and current vulnerability, the FGDs explored the vulnerability of different socioeconomic groups in the watershed to potentially harsher conditions in the future. Consistent with the participatory approach of the research, the FGDs also involved gathering communities' perspectives to determine the relative importance of different variables in developing a vulnerability index.

Data Analysis

Survey data were summarized using measures of central tendency (means, medians, and modes) and variability (standard deviations and ranges) to outline the socioeconomic characteristics and vulnerability levels. Qualitative data from FGDs were systematically categorized and analyzed for recurring themes and patterns, offering insights into the participants' experiences, perspectives, and adaptation strategies. A composite vulnerability index was developed by integrating quantitative and qualitative findings with weights assigned during the FGDs. This index captures the multidimensional nature of vulnerability and reflects both the statistical trends and community input.

RESULTS AND DISCUSSION

Respondents Socio-Economic Characteristics

The respondents' average age was 55 years, ranging from 23 to 85 years, highlighting their wide-ranging life experiences and familiarity with climatic variability and extremes in the watershed. Gender representation was balanced, with females accounting for 54% of respondents. Most respondents were married, with 39% having a secondary education, 21% having a tertiary education, and 10% lacking a formal education. Notably, 91% of the respondents were residents, reflecting their deep-rooted connections and understanding of the area's ecological and sociocultural dynamics.

Table 1 Demographic characteristics of the respondents

Category	Frequency	Percent %
The average age is 55 years old		
Gender distribution N=192		
- Male	89	46.40
- Female	103	53.60
Educational level N=190		
- None	10	5.20
- Primary	1	0.50
- Elementary	65	33.90
- High School	74	38.50
- College	40	20.80
Ethnic affiliation N=191		
- Native	174	90.60
- Migrants	17	8.90

The data reveal that the average monthly household income of respondents is PHP 12,434.00, which is only 3.35% above the national poverty threshold set by the Philippine Statistical Authority, indicating minimal financial security. Most households (61%) rely on crop cultivation as their primary income source, whereas others engage in small-scale businesses, fishing, and institutional

employment, emphasizing the watershed's critical role in sustaining diverse livelihood. Additionally, 67% of farmers are smallholders who manage less than one hectare of land. Among landowners, only 43% (82 192) hold formal land titles, limiting their ability to leverage land for financial gain. Furthermore, 37% of the respondents practiced monocropping, primarily by cultivating rice, highlighting the challenges of land tenure security and the need for agricultural diversification.

Table 2 Economic profile of the respondents

Category	Frequency	Percent %
Major sources of income (N= 186)		
Farming	138	71.80
Small enterprises (e.g., sari-sari store)	7	3.60
Employment	7	3.60
Fishing	8	4.20
Others (hired labor, driver, forest products gathering, etc.)	26	13.50
Average monthly income= PHP 12,434.00		
Farm sizes of cultivated land (N=166)		
<1 ha	129	67.20
1.1 – 2 ha	22	11.50
2.1 – 3 ha	9	4.70
3 ha and above	5	2.60
Tenure types of cultivated lands (N=164)		
Title	83	43.20
CSC/CLOA/NIA Agreement	3	1.60
Tax declaration	19	9.90
Others (agreement, right, amortization)	57	29.70
Agricultural/farm practices of farmers (N=159)		
Mono-cropping	71	37.00
Crop rotation	63	32.80
Agroforestry or mixed cropping	21	10.90
Crop diversification	4	2.10

Past Climate Variability and Extremes in the Cangaranan Watershed

Climate change significantly drives water scarcity, affecting communities that depend on limited drinking, sanitation, and agricultural resources (Gizaw, 2023). Household surveys and FGDs noted severe droughts in 2009 and 2015, coinciding with strong El Niño events recorded by the Oceanic Niño Index. Notably, the 2010 El Niño caused extensive drought across 977 ha and 208 ha in the Philippines, incurring \$580M in agricultural damage (Pulhin and Tapia, 2016). According to David et al. (2007), Panay, along with areas in Luzon and Mindanao, is highly vulnerable to El Niño. While respondents were unable to pinpoint the exact timing of past El Niño events, they vividly remembered an extreme El Niño episode that started in April 2023 and was expected to end by the end of May 2024, which brought an unusually prolonged and severe drought, far exceeding the typical three-month dry spells they had previously experienced. This recent event has significantly impacted their lives and livelihoods. Data from the PAG-ASA and Municipal Disaster Risk Reduction and Management Office (MDRRMO) from the Municipalities of Bugasong and Valderrama show that 67 typhoons hit the area from 2004 to 2024, with notable events including Typhoons Frank (2008), Ondoy (2009), Yolanda (2013), Paeng (2021), and Odette (2022), which caused profound and lasting impacts within the watershed community.

Communities' Perceived Benefits and Impacts from the Watershed

Watersheds are vital for water resource management and disaster risk reduction, particularly in countries vulnerable to typhoons (Pulhin et al., 2010). However, the interview results in Bugasong revealed that households perceived the watershed as a medium of destruction, citing massive flooding and sedimentation during heavy rains and typhoons, exacerbated by quarrying and

insufficient stone wall construction. In contrast, respondents in Valderrama recognized the watershed as critical for water supply for agriculture and domestic use. Pulhin et al. (2008) emphasized the importance of watersheds in sustaining agriculture, particularly by ensuring irrigation during dry seasons, which helps prevent water scarcity and supports rice production in the Philippines. Despite this, nearly half of the respondents did not recognize the value of watersheds, highlighting the need for educational campaigns and extension programs to promote conservation and maintain watershed ecological benefits.

Table 3 Benefits and impact of watershed

Benefits and impact of watershed	Bugasong		Valderrama		Total frequency
	frequency*	%	frequency*	%	
Destruction due to floods and sedimentation	82	88.17	61	61.61	143
Agricultural (for farming and livestock) use	32	34.40	59	59.60	91
Domestic use	19	20.43	67	67.67	86
Source of freshwater fishes	13	14.00	22	22.22	35
Sand and gravel for house construction	8	8.60	0	0.00	8

Note: *Multiple responses

Socio-economic Groups within the Watershed

Based on the FGDs, societal stratification in the Cangaranan Watershed revealed distinct vulnerability levels. Small farmers are the most vulnerable, facing hardships due to their low education, lack of land ownership, and limited capital, which makes them highly susceptible to climate variability. Findings from this study are comparable to the results of the study of Chhinh and Poch (2012), where small-scale farmers often face the greatest climate risks due to land tenure insecurity, low education, and poor access to financial resources. Those with moderate vulnerability include small-scale farmers with modest landholdings ranging from 0.5 to 2 hectares and local entrepreneurs who have slightly better access to resources but still face challenges in accessing them. Employees from different sectors and households with access to capital and technology are the least vulnerable, benefiting from higher education, substantial land, agricultural machinery, and diverse resources, which enable them to better adapt to climate impacts. These differences highlight the need for tailored climate-adaptation strategies that address the unique needs of each socioeconomic group.

Impact of Climate Variability and Extremes

This study assessed the impact of climate variability and extremes on communities in the Cangaranan Watershed, focusing on food, water, livelihoods, and health. The results highlighted several key issues: food shortages and rising costs due to extreme weather, with limited crop cultivation, affecting community sustainability. Water challenges are significant, particularly in Barangay Ilaures and Igbalangao, where outdated irrigation systems were damaged by Typhoon Undang in 1984. After the irrigation canal was destroyed, there was no further assistance from the government or other agencies that initiated the construction of an irrigation system in the study area. Consequently, most farmers in these areas are compelled to depend solely on rainwater to irrigate and cultivate their lands, highlighting their vulnerability to climatic irregularities and the need for resilient agricultural practices. Thus, the availability of domestic water in the barangays of Ilaures and Igbalangao is generally secure, as most households possess water pumps.

The study also noted the vulnerability of lowland communities, such as Ilaures and Igbalangao, to intense flooding during the typhoons. Farmers face challenges in terms of crop yield, with early rains benefiting crops, delayed rains, prolonged wet periods, and El Niño events causing significant damage to crops. Climate extremes, particularly typhoons, droughts, and floods, significantly disrupt farming, leading to crop loss and reduced income. Smallholder farmers, especially those without land, experience greater vulnerability and debt accumulation during extreme conditions, whereas wealthier

farmers with better resources have greater resilience to climate change.

This study revealed that health issues are closely associated with extreme climate. Respondents reported an increase in heat-related illnesses, such as hypertension, stroke, and migraines, during periods of extreme heat, whereas prolonged rainy seasons were linked to an increase in waterborne diseases, such as diarrhea and dengue. These findings are consistent with those of previous studies [insert references]. For instance, the World Weather Attribution (2024) reported that the April 2024 heatwave in the Philippines, with temperatures exceeding 40°C, would have been "virtually impossible" without human-induced climate change, leading to a spike in heat-related illnesses in the country. The World Health Organization (WHO) lists heat stress, cardiovascular strain, and worsening of pre-existing conditions (including hypertension and stroke) as health risks associated with extreme heat. Similarly, the Department of Health (as cited in Philippine Tribune, 2024) noted a significant increase in dengue cases during the same period, attributing this to warmer temperatures and heavy rainfall, which create ideal conditions for breeding mosquitoes.

Table 4 Impact of climate variability and extremes on food, water, livelihood, and health in Cangaranan watershed

Climate variability and extremes	Impacts	Frequency	Percent %
El Nino	• Shortage of food/ water (domestic/irrigation) supply	129	67.19
	• Misunderstanding among individuals stemming from water scarcity.	69	35.94
	• Zero/ decrease in income due to drought	152	79.17
	• A lesser number of crops	143	74.48
	• Rise in health issues (such as Hypertension, migraine, overfatigue, mild stroke, irritability)	85	44.27
Typhoon	• Destruction of homes	58	30.21
	• Overflowing/ Flooding of the watershed	81	42.19
	• Deposits of sediments in rice paddies result in damage to crops	74	38.54
	• Losses in crop production	124	64.58

Extent and Nature of People's Vulnerability to Climate Variability and Extremes

This study assessed community vulnerability to climate variability using a locally developed index that reflects residents' perceptions and experiences. The index, created through participatory FGDs, prioritizes four categories: food, water, livelihood, and health issues. Water scarcity was identified as the most critical issue, with the highest weight (40%), followed by food (25%), livelihood (20%), and health (15%).

Food vulnerability is linked to crop yield, which is heavily affected by climate extremes, leading to food shortages and malnutrition, especially among smallholder farmers. Water scarcity, exacerbated by climate extremes, has been recognized as the main concern, with limited irrigation and damaged infrastructure increasing the vulnerability. Despite adaptation efforts, communities felt that strategies often led to additional costs and conflicts that reduced their effectiveness.

Livelihood diversification has emerged as a key strategy for reducing vulnerability, with households seeking alternative income sources demonstrating greater resilience. Health problems, particularly during extreme weather, also contribute to vulnerability, with those experiencing health issues or lacking access to medical services ranking higher on the vulnerability index.

Adaptation Strategies and Practices

Local communities in the Cangaranan Watershed have developed various adaptation strategies to mitigate the effects of extreme climate. Strategies categorized as food, water, livelihood, and health aim to reduce the vulnerability and enhance resilience. Key practices include reducing food and water

consumption, improving storage, and shifting to alternative food sources such as sweet potatoes and bananas. Many also practice agroforestry and grow drought-resistant crops, such as root vegetables and legumes, to increase their resilience. Similar adaptive strategies have been documented in other rural areas of Southeast Asia, including improved food storage, shifting to drought-tolerant crops, and diversifying livelihoods. In Cambodia, households have adopted multiple coping mechanisms, including agroforestry and alternative income sources, to reduce climate-related risks (Chun, 2016; Chhinh and Poch, 2012).

Communities often rely on informal credit sources, such as family and neighbors, and turn to off-farm work, such as factory jobs or carpentry, during adverse conditions such as El Niño. Some seek support from local kinship networks and government or non-governmental organizations. Additionally, prayer is considered an adaptive strategy that offers comfort without any cost.

During calamities, asset disposal, such as selling livestock, is a common coping mechanism. Water security is addressed by channeling water from nearby streams, which is labor-intensive. Households also use herbal remedies to manage health issues. Despite these efforts, challenges persist in terms of long-term resilience, and research highlights the need for targeted interventions, such as improved access to climate information, financial support, and agricultural technologies to enhance adaptive capacity and sustainability.

Table 5 Adaptation practices employed by households in Cangaranan watershed during climate variability and extremes

Adaptation practices	Frequency N=192	Percent %
Reducing food and water consumption/ storage	154	80.21
Tree shade as relief from the intense temperature	136	70.83
Secure loans/ credit	94	48.96
Support from relatives/ family ties	68	35.42
Praying	52	27.08
Off-farm work/ alternative employment from farming	49	25.52
Rely on Assistance from the government/ NGOs	46	23.96
Asset disposal	32	16.67
Find other sources of water	13	6.77
Use herbal medicines	30	15.63
Affected but do nothing	21	10.94

CONCLUSION

Over the two-decade span from 2004 to 2024, the Cangaranan watershed was affected by numerous typhoons. Severe droughts occurred in 2009 and 2015, respectively. Between April 2023 and May 2024, the El Niño phenomenon compounded the difficulties of this year, presenting an extended period of intense drought and causing substantial disruptions. Watershed communities are deeply intertwined with agriculture, and vulnerability to climate variability and extremes varies significantly across socioeconomic groups.

The survey results revealed that a significant number of respondents, particularly in the Municipality of Bugasong, perceived the watershed as a source of destruction (e.g., flooding) rather than as a provider of ecosystem services. This indicates a gap in the understanding of watershed functions. To address this, there is a need for sustained extension of Information, Education, and Communication (IEC) initiatives to raise awareness of the importance of watershed management and how it contributes to reducing community vulnerability to climate extremes.

The prevailing droughts have presented new challenges for affected communities, emphasizing the escalating severity of climate-induced phenomena and the increasing need for effective coping and adaptive strategies to mitigate their impacts on the livelihoods of those dependent on agriculture in the region. Considering the adaptive strategies mentioned by the respondents, the development of water-harvesting systems, improved irrigation infrastructure, and efficient water-use practices are key adaptation measures that help mitigate the effects of climate extremes on agriculture and water

supplies. Although communities adopt various coping strategies to address these challenges, an examination of community knowledge and perceptions of the watershed, as well as the effectiveness of coping strategies in dealing with climate variability and extremes, is necessary. This deeper understanding is crucial for developing effective and context-specific policies and programs that address unique challenges and opportunities within the watershed.

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Institutional Innovation for Youth-Appealing Farming in Japan: An Overview of How European Countries Attract Youth to Agriculture

RIVAL VALCIN*

*Department of Agribusiness Management, Tokyo University of Agriculture, Japan
Email: rivalcing7@gmail.com / vr208925@nodai.ac.jp*

TOMOHIRO UCHIYAMA

Faculty of International Agriculture and Food Studies, Tokyo University of Agriculture, Japan

BÉNÉDIQUE PAUL

Faculty of Agriculture and Environmental Sciences, Quisqueya University, Haiti

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Abstract The agricultural sector in several countries in the Western world faces a two-sided problem: the aging of farmers and the shifting of the younger generation toward other sectors. In Japan, this issue is accentuated by the shrinking of the agricultural workforce, as the number of young new farmers has been declining significantly since 2016. Farming is, above all, an entrepreneurial activity, as it requires investment, risk-taking, and management skills. Over the years, Japan has consistently ranked low in terms of youth entrepreneurial intentions. This study suggests that the lack of attractiveness of farming activities to the younger generation is tied to the generally low entrepreneurial orientation of youth in Japan. Considering that European countries succeed in attracting and retaining more youth as agricultural entrepreneurs and workers, this study answers three questions: What are the characteristics of young professionals evolving in agriculture in European countries? What strategies have these countries implemented to attract younger generations to farming? What assets can a country like Japan mobilize to make farming more appealing to its youth? We analyzed the policies and farm business environments in selected European countries where youth are increasingly represented in agriculture. To this end, we followed the PSALSAR methodology to search, appraise, synthesize, analyze, and report the results. Countries included in the overview were France, Germany, Finland, Austria, and Poland. Ultimately, this study discusses how Japan can concretely address this issue to guarantee its future competitiveness and improve its self-sufficiency by attracting young professionals in agriculture. By analyzing the European Common Agricultural Policy (2023-27) and national institutional innovations of selected countries, the review finds that incentives are more effective than financial grants in attracting and retaining young people in farming.

Keywords policy, young farmers, rural areas, internship

INTRODUCTION

In Japan, the depopulation of rural areas caused by the aging population, the youth migration toward big cities, and the low birthrate have been an important socio-economic issue for several decades; however, the Japanese government has always implemented various countermeasures (Dan, 2024). These governmental actions, sometimes supported by private and non-governmental initiatives, have brought significant results, as the country has experienced several significant urban-to-rural in-migrations since 1990 (Mao et al., 2022; Zollet and Qu, 2023). For example, the number of new farmers had tripled by 2015; in 2012, the number of people joining agriculture was 50,800 people in total, according to the Ministry of Agriculture, Forestry and Fisheries (MAFF) of Japan, including 20 percent of those younger than 39 years old (Kurochkina, 2015).

Scholars from different fields, such as anthropology, rural sociology, and agriculture, within Japan and abroad have conducted a growing number of studies related to “What motivates people (particularly young) to move to rural areas? are also trying to understand their new lifestyle upon settlement in the countryside” (Dan, 2024; Mao et al., 2022; Rosenberger, 2027; Sasaki, 2018, 2017; Zollet and Qu, 2023). People decide to move to rural areas for different reasons, sometimes personal and sometimes circumstantial. Circumstantial reasons include natural disasters, financial crises and pandemics. The most substantial relocations observed in Japan were after the Global Financial Crisis of 2008, the Eastern Japan Earthquake (Fukushima Daiichi nuclear disaster) in 2011, and, more recently, the COVID-19 pandemic (Ji, 2024; Zollet and Qu, 2023). In addition, a long list of personal reasons may stimulate the decision to resettle in rural areas. These generally include a quest for freedom, living out of the common pressure in urban places (a more straightforward and slower life), being able to be their own bosses, growing their own food, and raising their children properly while experiencing nature (Zollet and Qu, 2023). People moving from urban to rural areas are usually classified into four categories: those returning to their home countryside (identified as U-turns), those resettling in another rural area close to their original home where they have no connection (J-turns), those who originated from urban places that are new to rural life (I-turns), and the grandchild’s turn, which refers to those born in cities who decide to go back to their parents origin (Dan, 2024; Kurochkina, 2015). However, all these movements appear to be a constant “in-out” flow as people come and leave; therefore, they cannot sustain life in rural areas (Miserka, 2020). In addition, since 2016, the number of youth (below 49 years old) becoming farmers has been declining significantly, falling below 20,000 for the first time in 2018, with a drop of 7% compared to 2017 (MAFF, 2019). After 2019, post-COVID-19 pandemic, a positive shift has been observed in the number of newly employed farmers and new entries; however, the number of new self-employed farmers continues to decrease significantly along with the total number of newcomers aged 49 years and younger (MAFF, 2023). “Newly employed farmers” are workers hired by farm companies. “New entries” or “new entrants” are people who become farmers on their own; they might take over a family farm, change careers to farming, or use their own money and land to start farming (MAFF, 2005). The main difference is how they start farming: by working for others or by starting their own farm.

Urban-to-rural in-migration led to a new peasantry, (Hisano et al., 2018) described as “what happened in Europe in 2008” based on (Van der Ploeg, 2012) description. Nevertheless, many European countries have succeeded in maintaining their farming workforce in a better shape, particularly the share of youth in the agricultural sector (Van der Ploeg, 2012). Countries such as France, Germany, Finland, Austria, and Poland are remarkably well positioned in terms of the percentage of youth evolving in agriculture, while several other countries from the twenty-seven states of the European Union (EU) have succeeded in increasing their youth’s share over the years (Rovný, 2016). What are the characteristics of young professionals evolving in agriculture in these European countries? What strategies have these countries implemented to attract and retain younger generations in farming? What assets can a country like Japan mobilize to make farming more appealing to youth, and what strategies can be used to retain them? These are the questions we propose to answer in this study. As one of the world's top ten agricultural countries, the agricultural sector is crucial to Japan's economy. Therefore, as stated by (MAFF, 2022), “In order for Japanese agriculture to develop sustainably, in addition to needing to secure and retain farmers from younger age groups, each farmer will need to play a larger role.” Through an analysis of what has been done in some selected European countries, this paper provides insights into what could be done in Japan as institutional innovation to bring more engaging young farmers into the sector.

OBJECTIVE

The main aim of this study is to propose a framework that Japan can implement to attract and retain more young people in farming. Specifically, the study aims to 1) identify key policies implemented by countries in the EU to attract and retain more youth in farming, 2) determine what Japan can learn from the EU experience, and 3) design and provide a strategy through which Japan can effectively address issues related to farming in rural areas.

Conceptual Framework

This study demonstrates how Japan can innovate in the internship system to enhancing youth interest in farming and rural areas. We hypothesize that better knowledge of rural life and more experience in farming will result in a stronger intention to work or do business in agriculture due to a greater perception of behavioral control and a better attitude toward evolving in farming. The theory of planned behavior, suggested by (Ajzen, 1991), supports this prediction. This approach is illustrated in Fig. 1.

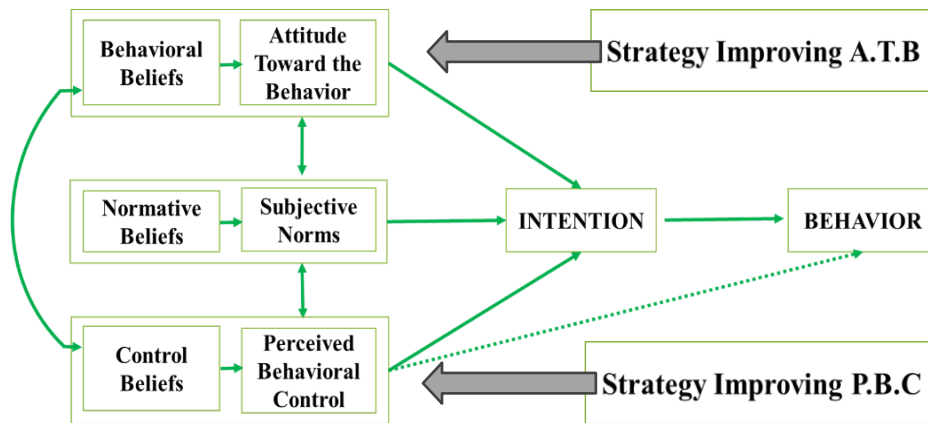


Fig. 1 Framework of the planned behavior theory (Source: Adapted from Ajzen, 1991)

METHODOLOGY

This overview examines the literature on Japanese rural evolution and points out key policies implemented in selected countries of the EU in the framework of the European Common Agricultural Policy (CAP/2023-27, 2023) to support young farmers and make rural areas more attractive. By comparison, we then show all the similarities between related Japanese policies while highlighting what is yet to be done in Japan to have a better impact on the rural world. These EU countries were selected because they succeeded in maintaining or increasing the share of young farmers between 2000 and 2020 (Rovný, 2016). Regarding data selection, a literature survey was performed using trustworthy scientific databases, such as ScienceDirect, Google Scholar, Scopus, and MDPI. We used literature published in French, English, and Japanese.

RESULTS AND DISCUSSION

The review revealed that Japan has implemented many policies and programs to make farming and rural areas more appealing to youth (Dan, 2024). However, compared to what is going on in the EU, there is still room for alternative exploration to bring Japan closer to its rural revitalization goal. Table 1 summarizes the key policies, programs, and structures implemented in the EU and describes whether they have been implemented in Japan. These actions are divided into youth support, rural development, and general structures. EU countries are referred to by the following codes: France (FR), Germany (GE), Finland (FI), Austria (AU), and Poland (PO). In addition, key policy points from the EU are extracted from the approved CAP (2023-2027).

The review shows that the Japanese government has done a lot in terms of incentives (subsidies, assistance, and training programs), even more than the EU. The EU and Japan still need to make further adjustments to make rural areas more attractive. Nevertheless, some EU countries currently perform better than Japan. Japan usually considers young farmers until 49 years old and younger; however, in the EU, it is bound to be 39 years old. Based on the latter, youth in Japan account for

only 4.9% of the agricultural workforce (MAFF, 2023), while some EU countries, such as Austria and Poland, account for 10% and 14%, respectively (Rovný, 2016).

Table 1 Strategy for farming and rural development in the EU and in Japan

Policy/Program in the EU	Japanese case	Remarks	Author
Help youth purchasing farmland. Ex: FR. Income support by direct payments to young famer.	Highly performed in Japan	Since 2012, over 43,500 people under 45 have joined the "Young Farmer's Fund." They receive monthly payments totaling about USD 15,000 each year (MAFF, 2017; McGreevy et al., 2018).	(Dan, 2024)
“Provide training and knowledge specifically to young famers in support of generational renewal.” Ex: PO	“Support for relocation and financial assistance. paid training programs to learn how to be a farmer for two years.”	“Subsidies for childcare, renovation and for house renovation.”	(Ji, 2024)
Create off-farm Job in rural areas of all the EU	Limited job opportunities in rural areas.	Less than 40% Japanese young farmers have off- farm job.	(Karahan, 2023)
Vow to improve “essential services such as transportation, communication, healthcare, and education. Ensuring 100% access to fast broadband internet in rural areas.”	“Inadequate transportation, and concerns over social integration and educational standards.”	For that, some people are passionate about rural areas, but don’t want to move there.	(Mao, 2022)
Internship (often long-term) is mandatory in many UE’s countries. In FR, GE, FI, AU, and PO it should be performed to have right to a certain degree or diploma.	In Japan, internship is conducted for educational purpose (on a university viewpoint) or for recruitment purpose (on an industry viewpoint).	It’s generally not mandatory.	(Kameno, 2023)

In Poland, where the share of youth exceeded 20% in 2020 (WASAW, 2021), making it easier to buy farmland or acquire a farm and facilitating businesses related to agriculture were the most common factors attracting youth to agriculture in 2023 (Statista, 2023). However, the same survey shows that prior to these two factors comes a solid knowledge of the rural world and existing opportunities. Career orientation for teenagers, mandatory internships for students, and exchange programs (Poland-Texas) for young farmers (Agronomist, 2023) are among the structures contributing to boosting the intention of the younger generation toward a farming career.

On-Farm Long-term Internship (OFLI): As a strategy to attract young people to the land, OFLI is a remarkable tool that can be implemented in Japan on a compulsory or even on a mandatory basis, because existing internship runs only for about a week and it is not compulsory. The following are the reasons why it will make a difference in many ways.

Only some students choose to work in rural areas upon graduation, as life there is unknown to them. Traditionally, employment in Japan has been a lifelong commitment. First-starting graduates will only try rural areas with all their stereotypes if they are sure of what awaits them. An internship of 6 to 12 months after graduation will give them the opportunity to make a well-informed decision.

There will be a midterm and a final evaluation of both the apprentice and the farm or firm, with the possibility for the student to try another farm to obtain a complete view. Ultimately, the student may decide to settle in rural areas, either to keep evolving on the same farm as a worker or associate or to start their own agribusiness. Students are also free to move to another kind of job anywhere else. Job hunting consumes a significant amount of time in the final year of many students, to the point that it affects the quality of their research dissertation or even prevents them from graduating. Students will be able to do their job hunting during their internship time, which would be counted as work experience in the future. The apprentice will be paid properly and receive appropriate support for accommodation. Internships have the potential to foster a high level of professional awareness while promoting understanding and attractiveness in certain work environments (Kameno, 2023). As reported by the Kawaijuku (2017) survey, more than hundred thousand students joined agricultural universities in 2017, while the total number of newcomers to agriculture four years later fell by 2.7% (52,000 in 2021) (MAFF, 2023).

Lastly, international students in Japan also represent an important asset to this structure. More than 4,000 international students major in agriculture in Japan (JASSO, 2020). Our ongoing survey on this matter reveals that one out of ten international students would accept a one-year on-farm internship after graduating from a Japanese university.

This program (OFLI) will have a direct impact on perceived behavioral control by enhancing knowledge and understanding of rural life and agriculture. It will challenge subjective norms by fostering a new perspective among the younger generation regarding rural life. Ultimately, it will guide their attitudes toward working and investing in rural areas.

CONCLUSION

This review compares EU countries and Japan's strategies for revitalizing rural areas and attracting young people to the agricultural sector. In terms of age category, young farmer in Japan is not categorized exactly as it is in the EU countries. The results show some similarities between the basic policies implemented to attract and retain youth in agriculture. However, some institutional innovations to make the young generation aware of opportunities and life in rural areas prior to their decision-making will prove more effective than financial grants in attracting and retaining young people in farming. Unlike EU countries, most internships in Japan do not exceed one week, and very few reach three months (Kameno, 2023). The results of this review argue that long-term on-farm internships have the potential to address the generational renewal problem, which is crucial for sustainable food production and competitiveness (Pechova, 2017; CAP/2023–2027, 2023; Borda et al., 2023; Lollini, 2021). Nevertheless, considering that the education system in Japan differs from that in European countries regarding how and when students should decide on their future careers, additional studies are needed to determine the propensity of young Japanese people to welcome such institutional novelties.

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A Critical Analysis of Digital Agricultural Information Dissemination Systems in Tamil Nadu, India

DIVYA SURESH*

Keio University, Fujisawa, Kanagawa Prefecture, Japan

Email: divyas@keio.jp

RAJIB SHAW

Keio University, Fujisawa, Kanagawa Prefecture, Japan

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Abstract Agricultural information dissemination systems play a key role in farmers' decision-making. Recently, much emphasis has been placed on agricultural modernization facilitated by digitizing agricultural information services in Tamil Nadu's agricultural sector. Studies point to various facilitating and limiting factors related to the availability, accessibility, and adoption and use of digital agricultural information dissemination systems, including the provision of information related to extension and advisory services, weather-based agricultural advisory services, and market-based agricultural advisory services. The Uzhavan application (app), a key digital agricultural information dissemination system developed by the Tamil Nadu government in 2018, provides comprehensive market prices, subsidy schemes, and weather forecasts. However, it has had poor uptake and utilization, and only 18% of Tamil Nadu farmers have registered on the Uzhavan app. To address this, we examined the evolution and institutional frameworks of agricultural information dissemination systems (extension and advisory services, weather-based, and market-based agricultural advisory services), we analysed facilitating and hindering factors of different digital agricultural information dissemination systems, and we identified challenges facing the farmers in the study area. Primary data were collected through semi-structured interviews with 30 farmers in the Chengalpattu district of Tamil Nadu. We also obtained relevant secondary data from the literature for this study. The results showed a lack of ideal institutional design for disseminating digital agricultural information in equitable and affordable ways. Lack of awareness, lack of institutional trust, gender and socioeconomic gaps in access, lack of contextualized content, and costs of access were identified as challenges to accessing digital agricultural information. Therefore, in the future, it is necessary to identify and incorporate factors responsible for the equitable and affordable dissemination of digital agricultural information.

Keywords digital agriculture, information dissemination, tamil nadu, effectiveness, challenges

INTRODUCTION

Agricultural information is central to farmers' decision-making, from sowing to harvesting and selling. Agricultural information dissemination is the process of delivering research-based information grounded in scientific innovation through the various stages of the agricultural life cycle, such as information on high-yielding seeds, farming practices, and the timing of inputs. It was originally targeted to improve agricultural productivity and rural development in the country. (Krishna and Naik, 2020) Recently, objectives such as adaptation and mitigation have been added. Inefficient information dissemination decreased access to, or poor adoption and use of agricultural information may decrease agricultural productivity, affecting farmers' income. Information and Communication Technology (ICT) plays a vital role in disseminating information. The adoption of mobile internet technology has proved to increase agricultural productivity. (Karanasios and Slavova, 2018) However, the advantages of ICT are yet to be reaped to full benefit in the agricultural sector

of the Indian economy. In this context, this study aims to analyze the agricultural information dissemination systems and infrastructure in Tamil Nadu's agricultural sector.

Previous studies have identified enabling and constraining factors for farmers' adoption of digital agricultural information in the study area. Farm characteristics, including land ownership, farm size, and farm succession; operator characteristics, including age, education, income, farming as a main occupation, general ICT possession and usage, self-reliance, farming experience, knowledge and capacity; and type and level of interactions, including group communication, frequent contact with extension agents, and information-seeking behavior, were the key independent variables in these studies. (Kumar and Chandrasekaran, 2020; Kumar and Karthikeyan, 2020; Nandhini and Rohini, 2022) Some of the important constraining factors mentioned in the studies are a shortage of extension agents noted by a 1:1834 ratio of assistant agricultural officers to farmers, far exceeding the FAO recommended range of 1:500 (Blum and Szonyi, 2015). This shortage reflects the limitations of the reach, frequency, and effectiveness of agricultural advisory services. In addition, infrastructural issues such as low digital penetration or lack of ICT infrastructure, pilot project syndrome (short-term, donor-driven initiatives that lack sustainability), gender gap in accessing information, and provision of generic information limit the equity, scalability, and effectiveness of agricultural information delivery. (Saravanan, 2012; Kumar et al., 2020; Mathuabirami et al., 2019; Vincent and Raj, 2022) Technological and psychological attributes were not explored per our review. Other studies have focused on the impact assessment of digital agricultural information systems. The findings revealed that illiterate farmers benefit from advisories delivered in audio or visual formats, leading to a significantly higher adoption of recommended agricultural technologies (Rani et al., 2020; Prabha et al., 2017; Prasad et al., 2020).

OBJECTIVE

Therefore, the objectives of this study were to 1) analyze the facilitating and hindering factors for different digital agricultural information dissemination systems specific to extension and advisory services, weather-based agricultural advisory services, and market-based agricultural advisory services, and 2) identify the challenges facing farmers in the study area.

METHODOLOGY

Regarding objective 1, secondary data were collected by reviewing the literature, articles, and reports. The identified qualitative datasets were analyzed through a comparative analysis of digital agricultural information systems in Tamil Nadu, focusing on effectiveness, capacity gaps, and scope for improvement. For objective 3, no formal quantitative data were collected for this study, as the primary focus was on qualitative insights obtained through semi-structured interviews with 30 farmers.

Primary data were collected from a random sample of 30 farmers selected from the Kollammedu, Pin padhar kootam, and Pon vilaintha kalathur villages located in the Chengalpattu district of Tamil Nadu. The Chengalpattu district is expected to fall under high-risk agriculture in the near future (CCCDM Anna University, 2024). This district was purposefully selected for an in-depth understanding of the barriers that may be common across regions but may be likely to increase due to high-risk zones. The district has approximately 600 villages under its jurisdiction, which is a subset of the approximately 15,000 villages in Tamil Nadu (Village Survey, 2022). Ten farmers from each village were selected, targeting a representative subset of the population and minimizing selection bias. While all participants were engaged in farming, notable differences existed in their gender roles, digital literacy levels, and access to agricultural support systems.

The Uzhavan mobile application, a bilingual platform (English and Tamil) developed by the Tamil Nadu Department of Agriculture, is a key service promoted by the state government and a comprehensive digital agricultural information system. It exemplifies a centralized effort to deliver diverse agricultural services digitally and was chosen for this study. The app is freely available on Google Play and Apple App Store.

Face-to-face, semi-structured interviews were used to collect perceptions of the accessibility of digital agricultural information and the limiting factors for its usage. The data analysis focused on qualitative and thematic insights of the data. The first author conducted a thematic analysis to identify recurring patterns, and efforts were made to ensure reliability through iterative reviews. Thematic analysis was performed using a six-step approach, which includes familiarization with interview responses (initial notes and responses), coding (extracting from interview data), generating themes (translating codes into themes), reviewing themes (rechecking the themes for accuracy), naming themes (formulating easily understandable names), and finally distilling the results. (Braun and Clarke, 2006).

RESULTS AND DISCUSSION

Extension and Advisory Services

The agricultural extension system in Tamil Nadu evolved from community-based development in the 1950s to a technology-driven approach in the 21st century. Key changes include the introduction of the Intensive Agricultural Area Program during the Green Revolution in the 1960s, Integrated Crop Management and the Training and Visit system in the 1980s, and ICT-based interventions such as AGRISNET and Uzhavan in 2018. While the government has led many initiatives, private companies now play a significant role in providing customized agricultural advisory services using technology.

Agricultural Extension and Advisory services in Tamil Nadu, which encompass different techniques, such as ICT-based advisory interventions, participatory farm extension, and agribusiness modes of reinventing farm enterprises, have resulted in a lower success ratio than expected. The effectiveness and countermeasures from the literature are synthesized in Table 1.

Table 1 Summary of ICT-enabled extension and advisory services in Tamil Nadu

ICT intervention (initiating authority)	Features	Facilitating factor	Effectiveness	Barrier	Further action needed
Uzhavan App (TN Government)	One stop solution providing information on market prices, subsidy schemes, weather forecasts etc.	Mobile based application for farmer self-service in local language	Algorithm led AI has reduced information searching time, increased the accessibility to agricultural officers and awareness about government schemes	Adoption depends on farmers smartphone literacy	Increase publicity to attract non-users Provision of timely updated information
TNAUAgriTech (TN Government)	Web portal developed by Tamil Nadu agricultural university	Credibility and scientific rigor of information	Problem diagnosis through video conferencing	Limited digital access and literacy farmers in remote areas	Mobile optimization for wider outreach
Agrisnet (Central Government)	Web based information gathering and analytics mechanism mainly for extension workers	Departmental interface, life cycle-based crop planning and advisories	Generation of customizable report	Digital illiteracy limited farmers direct engagement with the platform	Capacity building of extension workers

Table 1 Continued...

ICT intervention (initiating authority)	Features	Facilitating factor	Effectiveness	Barrier	Further action needed
e-Velanmai (Central Government)	ICT based demand driven and participatory technology transfer model	Sustainable paid membership model (50 to 150 rupee based on land size)	Clarifies problem based and decision-based inquiries of the farmers	Limited awareness among beneficiaries	Increase field coordinators and improve to provide more comprehensive information
ATMA (Central Government)	Extension reforms	Institutional support (Tamil Nadu Agricultural universities, Krishi vigyan Kendras, etc) for implementation	259978 beneficiaries reached through exposure visit, training, demonstration, Kisan mela, and Farm schools	Repetition in choosing the beneficiaries	Improve inclusiveness by diversifying beneficiary selection.

Weather-based Agricultural Advisory Services

Climate change is affecting agriculture in Tamil Nadu, with rising temperatures and unpredictable rainfall patterns affecting crop production. This necessitates climate-smart agricultural practices, such as the use of climate-tolerant crops, improved water management, and accurate weather forecasting. The Agro Climate Research Centre at the Tamil Nadu Agricultural University provides essential weather forecasts and research to support these practices. The effectiveness and countermeasures of agrometeorological advisory systems from the literature have been synthesized for weather-based agricultural advisory services, as shown in Table 2.

Table 2 Summary of ICT-enabled weather-based agricultural advisory services in Tamil Nadu

ICT intervention (initiating authority)	Features	Facilitating factor	Effectiveness	Barrier	Further action needed
Gramin Krishi Mausam Sewa (Central Government & Indian meteorological department)	Weather forecasts, crop advisories, alerts on pests/diseases, rainfall, wind, humidity through SMS, web, radio and TV	Backed by IMD, wide dissemination networks	Provision of weather based agricultural advisories at block level	Generic, no voice support, low awareness	Promote the Gramin Krishi Mausam Sewa system, and also contextualization of information
Kisan (Central Government & Indian meteorological department)	SMS/voice advisories in regional languages (Tamil)	Centralized data system	Localized weather-based advisories	Only for farmers who register	Support increasing farmer registration
TNAU-AAS App (Tamil Nadu agricultural University)	Mobile app, SMS, web portal based advisory	Backed by TNAU; local weather data from 385 AWSs	Provision of location, time, stage specific advisories based on ten important weather parameters	Digital literacy and application complexity challenges	Increase coverage of advisories for different crops

Market-based Agricultural Advisory Services

A significant point in the evolution of the Agricultural Marketing Department is the establishment of the Domestic and Export Market Intelligence Cell (DEMIC) at TNAU in 2004. The objective of DEMIC is to disseminate timely information on the prices of agricultural commodities to support the decision-making of various stakeholders, such as farmers, traders, researchers, policymakers, and firms. The different media through which information is disseminated are radio, TV, newspapers, and the Agmarknet website.

The effectiveness and countermeasures from the literature have been synthesized for agri-marketing advisory services, as shown in Table 3.

Table 3 Summary of ICT-enabled agri-marketing services in Tamil Nadu

ICT intervention (initiating authority)	Features	Facilitating factor	Effectiveness	Barrier	Further action needed
Market led extension (e-NAM) (Central Government)	Online trading platform, access to inter- state trading	Digital payments and logistics integration support	Integrated with Agricultural Produce Market Committee to enable transparent price discovery	Digital literacy issues	Improve connectivity of mandi, onboarding of FPO
Agmarknet (Central Government)	Provides daily market prices	Helps farmers make informed crop marketing decisions	Trends for commodities across Indian markets	Lack awareness, rely on middlemen to these platforms	Increase promotion and training in using these system

Limiting Factors for the Usage of the Uzhavan App in the Chengalpattu District, Tamil Nadu

This section examines the challenges faced by farmers in the study area. Since the Uzhavan app was launched in May 2018 as a key platform for digital agricultural information, only 18% of Tamil Nadu farmers registered for it by August 2024. Chengalpattu district has one of the lowest numbers of farmer registrations compared to other districts in Tamil Nadu. Through semi-structured interviews with 30 farmers in the Chengalpattu district, factors limiting farmers from using the Uzhavan app were identified through thematic analysis, as shown in Table 4 and Figure 1.

The main themes identified from the interview analysis included barriers to digital information access, such as accessibility issues (lack of device availability, low digital literacy, and inability to afford), availability issues (lack of localized content, lack of awareness, and training programs), socio-cultural barriers (gender norms and caste-based exclusion), and lack of trust in extension and institutional support (infrequent contact with extension agents and increased reliance on fellow farmers). The study's findings cannot be representative or generalizable to the district or state, which is a limitation.

The interview results showed that over 80% of farmers felt that there were no effective subsidy selection mechanisms, and the same farmers were repeatedly chosen to receive subsidies, training, and other benefits, leading to disparities. However, this may be due to farmers' limited awareness or less promotional efforts by the government for the Uzhavan App. Subsidies, financial support, and other programs play key roles in making digital agricultural information more accessible, which can increase adoption. (Beach et al., 2025)

The Uzhavan app offers detailed information on subsidy schemes for various agricultural inputs and the subsidy amount, depending on whether farmers are small, marginal, or large-scale.

Table 4 Challenges in accessing the Uzhavan mobile app: farmer voices and thematic insights

Theme	Sub-theme	Representative quotes	Insight
Accessibility issue	Lack of device availability	“I don’t have a smartphone.” “My children use, and we rely on them if needed.”	Farmers lack personal devices, and generational technology gaps exist. Feature phones remain prevalent among farmers.
	Low digital literacy	“I don’t know how to use the app.” “I am afraid if I will do something else while using unknowingly.” “I feel it is complex”.	
	Inability to afford	“I can’t afford to buy an android phone.” “I use basic phone which is enough for my needs”.	
Availability issue	Lack of localized content	“I feel advisories are not specific to my farm”. “I feel advisories are not specific to the crop/stage”.	Generic information, lack of applicability to real time farming. Also, many farmers have no knowledge on the availability of such digital agricultural information system.
	Lack of awareness and training programs	“I think I have heard about Uzhavan app”. “I am not sure in what way it can be useful for a farmer.”	
Socio-cultural barriers	Gender norms	“Only men in my house go for training”. “Only my husband owns smartphone as I don’t know to use”.	Deep-rooted social norms limit participation of women and marginalized caste groups in accessing digital agricultural information.
	Caste-based exclusion	“We feel certain privileged farmers in the community are repeatedly selected for training and other programs”.	
Lack of trust in extension and institutional support	Infrequent contact to Extension Agents	“We hardly see them”. “They don’t visit us”. “They visit us may be once in a month”. “They do not have time to hear to our queries”.	Total number of extension agent to farmer ratio is 1:1834. It depends on the knowledge from the community.
	Increased reliance on fellow farmers	“We rely on fellow farmers the most trusted source of our information”. “I benefit from the advice of my neighbor farmer”.	

The subsidy selection process is based on a priority registration system, where farmers are given preference on a first-come, first-served basis. (Kungumaselvan et al., 2021) Also, in the study area, it was found that women farmers had less or no access to digital agricultural information, reflecting broader accessibility issues. NSSO (2021) data reveal the existence of a digital divide, with only 14.9% of rural households able to access a computer with Internet access, compared to 42% of urban households. Amidst this scenario, a further gender divide in mobile ownership exists, with 51.6% of rural women not owning mobile phones.

The lack of contextualized information (block-level information is provided) and the requirement to use an Android mobile phone (Uzhavan mobile app installation compatible) were other key barriers. Approximately 67% of farmers widely own older-feature (basic) mobile phones and use SMS and audio calls (Prabha and Arunachalam, 2021). The lack of contextualized information is also due to the difficulty in conducting adaptive research, caused by a shortage of extension manpower and vast diversity in agro-climatic zones, soils, cropping systems, and individual farmer profiles (Krishna and Naik, 2020). More than 90% of the farmers interviewed felt that they rarely met an extension agent, and even if they had, some felt that fellow farmers were more reliable sources of agricultural information. Extension agents are considered the key implementers of agricultural technology adoption in general and digital services in particular, creating awareness of different programs and providing a supporting role to farmers. These findings point to the lack of an ideal institutional design for disseminating digital agricultural information in affordable and equitable ways. An ideal institutional design emphasizes decentralization, increased autonomy, and contracting extension services to the private sector, community-based organizations, and non-governmental organizations (NGOs) (Birner and Anderson, 2007).

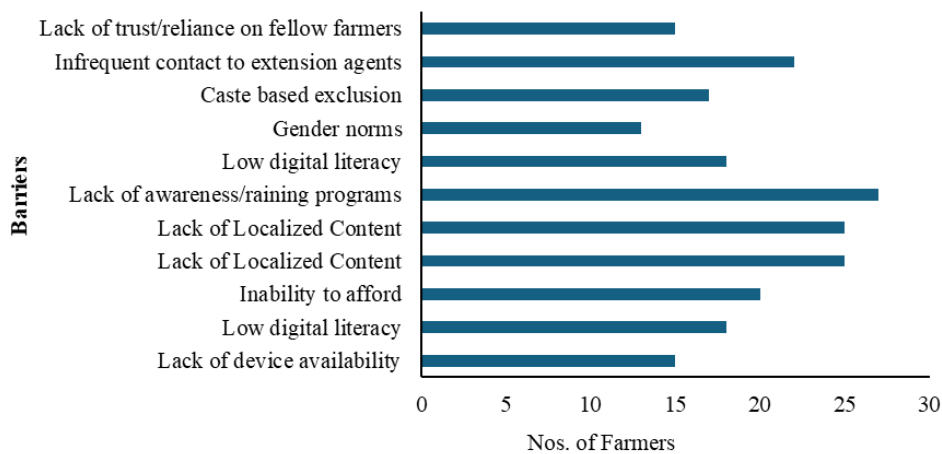


Fig. 1 Factors limiting access to digital agricultural information

CONCLUSION

This study provided a critical lens into the facilitating and hindering factors regarding farmers' access to digital agricultural information across extension, weather-based, and market advisory systems. It identified specific challenges that farmers faced in the study area, such as limited accessibility, lack of availability of contextual or localized information, sociocultural barriers, and a lack of trust in the extension system and institutional support. The reach and impact of Uzhavan applications have been limited by low farmer awareness, limited digital literacy, and infrastructural constraints such as the absence of offline functionality (access to information only with internet connectivity) and inaccessibility to farmers who rely on feature phones, reinforcing the digital divide. (Kumar et al., 2020) The findings emphasize the need for better contextualization of agricultural information. A unified agricultural data platform, such as the Agri-stack, has the potential to provide contextual local information through geo-tagged statistics (location-based data on farms and farmers), supporting the provision of farm-level agricultural advisories, and contributing to increased precision and relevance in the information delivered to farmers. However, technology alone cannot address deep-rooted structural gaps.

Importantly, this study highlights the absence of an inclusive institutional design that can ensure equitable, affordable, and trusted access to digital resources across the farming community. Addressing these multilayered challenges calls for policy interventions aimed at strengthening institutional trust, promoting user education, and designing content that aligns with the localized needs of farmers. Moving forward, research should focus on creating a robust and adaptive framework that supports inclusive and sustainable digital transformation in agriculture.

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Efficiency Assessment of Digital and ‘Phygital’ Food Retailers through Data Envelopment Analysis

MOZELLE M. RAMOS*

*Graduate School of International Food and Agricultural Studies,
Tokyo University of Agriculture, Tokyo, Japan
Email: 13823002@nodai.ac.jp*

TOMOHIRO UCHIYAMA

*Faculty of International Food and Agricultural Studies, Tokyo University of Agriculture,
Tokyo, Japan*

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Abstract The food retail landscape has undergone significant transformation in recent years, driven by the rapid expansion of online shopping and shifts in internal and external environments. This change has catalyzed the growth of pure-play digital food retailers and the adoption of a ‘phygital’ (physical and digital) approach by modern retailers. Using Data Envelopment Analysis (DEA) and Tobit model, this study evaluated the efficiency of digital (n=17) and phygital (n=42) food retailers across different regions and the key factors contributing to their efficiency. Digital food retailers were slightly more efficient than their phygital counterparts. Financial, structural, and macroenvironmental variables influence online retail efficiency, with farmer partnerships emerging as a critical factor for enhancing performance. Structural and financial factors showed the importance of experience, strong supplier relationships, and cost-control strategies in creating more efficient retail systems. Interestingly, macroenvironmental factors, such as high internet penetration rates, impeded efficiency, while a nation's overall network readiness showed no significant influence.

Keywords e-commerce, online retail, omnichannel, efficiency

INTRODUCTION

The food retail industry has undergone a dramatic transformation in recent years, particularly following the pandemic, which accelerated the shift toward online shopping. As consumer behavior has evolved, online food retailing has become increasingly competitive, with companies striving to meet the demand for convenience, variety, and speed. The rapid rise of e-commerce in the food sector has pushed retailers to focus on operational efficiency and reconsider their structural strategies to remain competitive. This shift has highlighted the importance of integrating both digital and physical channels, known as omnichannel or phygital retailing, where seamless customer experiences are prioritized across all touchpoints (Piotrowicz and Cuthbertson, 2014).

In this highly competitive landscape, factors influencing operational efficiency, such as cost control variables, are inherently critical. However, the importance of structural strategies, particularly partnerships between modern retailers and small-scale farmers, has gained prominence. Collaborating with farmers allows retailers to cater to the market's needs as concerns about health, food security, and social and environmental issues arise (Slamet et al., 2020). The pandemic exposed vulnerabilities in global supply chains, allowing retailers to rethink their sourcing and partnership models.

The efficiency of online food retail is influenced by both internal and macroenvironmental factors, with varying levels of adoption across countries. For example, in European nations such as Norway, Sweden, and Finland, there has been significant growth in online food retail, driven by high levels of internet penetration and robust e-commerce infrastructure (World Bank, 2024; Portulans Institute, 2024). These factors are worth noting in response to online retail efficiency. Given the

limited empirical evidence on efficiency benchmarks for both digital and phygital retail models, this study endeavors to identify both internal and external factors for retailers to maintain competitiveness in an increasingly dynamic market.

OBJECTIVE

This study aims to assess the efficiency of digital and phygital food retailers globally. It focuses on evaluating and comparing the efficiency of the two retail models and identifying the financial, structural, and macroenvironmental factors that influence their efficiency.

METHODOLOGY

This study utilized secondary data from S&P Capital IQ, reflecting current and real-world financial data from both public and privately held companies (Beauchamp et al., 2019). The data were screened to include global online food retailers. From an initial list of 1,712 companies, 59 were selected for further analysis based on the availability of financial data from 2019 to 2023 and their consistent focus on online food retail. These were categorized into digital (n=17) and phygital (n=42), the latter combining online and physical stores.

Data Envelopment Analysis (DEA) was conducted to evaluate the efficiency and performance of decision-making units (DMUs) across multiple inputs and outputs using the CCR model by Charnes et al. (1978), the BCC model by Banker et al. (1984), and the scale efficiency (SE) model. Following this, Tobit regression was performed to identify the factors influencing efficiency in online food retailing.

RESULTS AND DISCUSSION

Variable Selection for DEA

The selection of input and output variables for efficiency estimation must be aligned with the research context and operational characteristics of the decision-making units (DMUs). Following prior research on food retailing across both traditional and digital channels, as summarized in Table 1, this study employs four input variables: number of employees, assets, liabilities, and operating expenses. Revenue was used as the sole output variable.

Table 1 Previous evidence on the efficiency estimation in related domains

Author(s)	Research domain	DMUs	Input variables	Output variables
Sellers-Rubio and Mas-Ruiz (2006)	Supermarket chains	100	(1) Employees (2) No. of outlets (3) Capital (equity, debt)	(1) Revenue (2) Net income
Gupta and Mittal (2010)	Food and grocery retail outlets	43	(1) Total area of the store (2) Total no. of SKUs (3) No. of POS machine (4) Labor cost (5) Employees (6) Working hours	(1) Sales (2) Customer conversion ratio
Wang et al. (2020)	E-commerce	10	(1) Assets (2) Liabilities (3) Equity	(1) Revenue (2) Net income
Zheng and Khan (2021)	E-commerce	65	(1) Total assets (2) Total operating cost (3) Employees	(1) Revenue (2) Net income

Source: Author's compilation

Descriptive Statistics

Table 2 reveals significant differences between phygital and digital food companies. Phygital retailers have significantly higher labor forces and variability in assets, liabilities, and operating expenses. Similarly, it reported higher average revenue than digital companies, reflecting their larger scale and operational scope.

Table 2 Descriptive statistics of the variables (2019-2023)

Variables	Phygital (n=42)				Digital (n=17)			
	Min	Max	Mean	SD	Min	Max	Mean	SD
Employees	26	385,250	77,987	98,721	24	18,834	3,232	5,602
Assets	290.74	84,987.86	13,691.94	19,983.97	0.53	5,114.60	617.04	1,230.96
Liabilities	124.04	62,413.78	9,909.20	14,840.01	0.21	3,046.52	370.96	737.08
Operating cost	854.74	86,424.66	16,830.04	21,774.39	0.73	3,506.50	788.12	1,105.12
Revenue	1,082.56	90,334.46	19,172.65	24,864.79	0.82	3,159.84	687.52	1,011.76

Note: Units are expressed in USD million except for number of employees in absolute value

Estimation of Efficiency

The DEA was performed to assess efficiency and performance across multiple inputs and outputs of the decision-making units (DMUs). There are two (2) common approaches to modeling efficiency: CCR and BCC. The BCC model assumes variable returns to scale, given by Eq. 1.

$$\max z_0 = \theta + s_r^+ + \varepsilon \sum_{i=1}^m s_i^- \quad (1)$$

where

$$\sum_{j=1}^n x_{ij} \lambda_j + s_i^- = x_{r0}$$

$$\sum_{j=1}^n y_{rj} \lambda_j - s_r^+ = \theta y_{i0}$$

$$\sum_{j=1}^n \lambda_j = 1$$

Here, θ represents the efficiency score of the analyzed unit. A DMU is deemed efficient if $\theta = 1$ and all slack variables are equal to zero.

Given that the data were collected at the onset and during the pandemic, food retailers likely experienced both expanding and downsizing their operations to adapt to market demands—such as over 70,000 store closures from 2019 to 2023 and the notable growth of online retailing (Centre for Retail Research, 2024). Consequently, this study adopts scale efficiency (SE) as the most appropriate model to account for these operational changes (Dellnitz et al., 2018).

SE estimated by removing the convexity constraint $\sum_{j=1}^n \lambda_j = 1$, resulting in the CCR model (Charnes et al., 1978). As CCR efficiency scores are always less than or equal to BCC scores, SE is defined by Eq. 2.

$$SE_i = \frac{\theta_{CCR}^*}{\theta_{BCC}^*} \quad (2)$$

If $SE_i = 1$, the analyzed DMU operates at scale efficiency. Conversely, if $SE_i < 1$, it indicates the presence of scale inefficiencies.

Tables 3 and 4 present the efficiency results for the top digital and phygital food retailers from 2019 to 2023, with the digital retailers having an average SE of 0.8767 and the phygital retailers slightly lower at 0.8696. Both groups operate close to the optimal scale, but digital retailers show a slightly better ability to optimize their scale of operations. These findings support previous research suggesting that pure-play digital businesses achieve higher efficiency because of lower operational costs (Li and Chen, 2010).

Table 3 Results of the top 5 most efficient digital food retailers (2019-2023)

Retail name	Headquarter	Year	CCR	BCC	SE
ACL	United Kingdom	2000	1.0000	1.0000	1.0000
ORD	Japan	1997	0.7175	0.7177	0.9997
OCD	United Kingdom	2000	0.3662	0.3665	0.9992
EBH	China	2005	0.4540	0.4547	0.9985
ODA	Norway	2013	0.4563	0.4572	0.9980
Mean (n=17)			0.5482	0.6253	0.8767

Phyigital retailers show a greater number of players operating at scale efficiency, whereas only one digital retailer achieves full scale efficiency. This suggests that phyigital retailers have more flexibility in optimizing their scale despite the disruption caused by the pandemic.

Table 4 Results of the most efficient phyigital food retailers (2019-2023)

Retail name	Headquarter	Year	CCR	BCC	SE
CSA	France	1959	1.0000	1.0000	1.0000
ASL	India	2000	1.0000	1.0000	1.0000
KMO	Finland	2004	1.0000	1.0000	1.0000
LCO	Mexico	1930	0.7092	0.7092	1.0000
VSM	United States	1937	0.6876	0.6876	1.0000
SPI	China	2001	0.6349	0.6349	1.0000
CBC	Brazil	1954	0.5574	0.5574	1.0000
Mean (n=42)			0.6510	0.7486	0.8696

Evaluation of the Variables Influencing Efficiency

The analysis then employs a Tobit regression model to identify factors influencing efficiency in online food retail, using financial indicators such as fixed assets and selling, general, and administrative (SG&A) costs; structural factors including years in business, number of stores, and explicit farm partnerships; and macroenvironmental indicators like the Network Readiness Index, which assesses digital technology capabilities across 133 economies (Portulans Institute, 2024), and the internet penetration rate, reflecting household telecommunication access (World Bank, 2024). The network readiness index evaluates a country's digital readiness across four pillars: technology, focusing on infrastructure and access; people, measuring information technology skills and usage; governance, assessing policies and digital trust; and impact, analyzing social, economic, and environmental outcomes. The Tobit model, in which the efficiency scores from DEA are used as the dependent variable, is described by Eq. 3.

$$Eff_{it} = C + \alpha_1 FA_{it} + \alpha_2 SGA_{it} + \alpha_3 YR_{it} + \alpha_4 STR_{it} + \alpha_4 FP_{it} + \alpha_5 NRI_{it} + \alpha_5 IP_{it} + \varepsilon_{it} \quad (3)$$

Where C represents the constant term, while $\alpha_1, \dots, \alpha_5$ are the regression coefficients for each variable. ε_{it} is the error term, where I denote the company number ($i = 1, \dots, 59$), and t for the time period from 2019 to 2023). Furthermore, multicollinearity among the variables was assessed using the Variance Inflation Factor (VIF), with all values remaining below 3.0, well within the suggested threshold of 5.0 (Hair et al., 2019). This confirms the absence of multicollinearity in this study.

The results presented in Table 5 highlight the multifaceted nature of efficiency determinants for retailers, with both financial and structural variables playing a significant role. The positive impact of fixed assets ($\beta = 0.00110$) suggests that investments in infrastructure, technology and other tangible resources contribute to improved operational efficiency. Conversely, higher SG&A costs ($\beta = -0.27109$) are associated with reduced efficiency, indicating that excessive overhead expenses and suboptimal resource allocation can hinder performance.

Structural variables such as years in operation ($\beta = 0.00111$), physical stores ($\beta = 0.00001$), and farmer partnerships ($\beta = 0.11855$) positively influenced efficiency, underscoring the importance of

experience and collaborative value chain relationships. Years in operation reflect accumulated knowledge and operational refinement, while physical stores enhance customer reach and provide integrated online-offline experiences, such as home delivery or curbside pick-up strategies during the pandemic that offer unparalleled convenience to consumers (Li and Fisher, 2022). Farmer partnerships emphasize the advantages of stronger supplier relationships, enabling farmers to mitigate market risks and reduce transaction costs (Mangala and Chengappa, 2008). As such, it has helped retailers ensure product quality, reduce wastage, and stabilize value chains (Chengappa et al. 2016). This finding could guide reforms to integrate farmers into the food retail chain and foster a more sustainable and efficient supply system.

Interestingly, internet penetration ($\beta = -0.00484$) has a negative relationship with efficiency, which may be due to higher competition in areas with widespread internet access or inefficiencies in adapting to market demands in these environments. The lack of significance for network readiness suggests that while the technological infrastructure implemented by each country might be crucial, its direct effect on efficiency may be mediated by other inherent factors, such as the managerial capabilities or market strategies of the retailers.

Table 5 Results of Tobit regression (n=59)

Variables	β	Std. Error	z Value	Sig.
Fixed asset	0.00110	0.00051	2.15605	*
Selling, general, and administrative cost	-0.27109	0.12845	-2.11058	*
Years in operation	0.00111	0.00046	2.44264	*
Stores (Phygital = 1; digital = 0)	0.00001	0.00000	2.17312	*
Farmer partnership (with = 1; without = 0)	0.11855	0.03966	2.98930	**
Network readiness index	0.00451	0.00343	1.31426	
Internet penetration	-0.00484	0.00225	-2.15038	*
Constant	0.68957	0.16388	4.20765	***

Note: Significant levels are shown as follows: * $p < .05$, ** $p < .01$, *** $p < .001$; Log likelihood = 36.444; Wald statistic = 57.814; $R^2 = 0.495$

CONCLUSION

Digital retail models have proven to be marginally more efficient than their phygital counterparts, particularly in light of significant scaling activities from 2019 to 2023. During this period, digital retailers benefitted from streamlined operations, reduced overhead costs, and enhanced supply chain efficiencies, all of which were more readily achieved in a fully digital environment. Key contributors to this efficiency include lower administrative and operational expenses, the absence of costs associated with physical store maintenance, and agility afforded by technology-driven processes.

Simultaneously, structural and relational factors, such as years in operation and partnerships with farmers, play a crucial role in boosting efficiency across both digital and phygital models. These factors highlight the importance of experience and strong supplier relationships in creating more efficient retail systems. Therefore, phygital retailers do not lag far behind digital retailers' efficiency due to their business tenure and scale of operations through their expansive physical networks.

Developing competitive strategies for highly penetrated markets, such as personalization, exclusive offerings, and active customer engagement, may effectively mitigate inefficiencies caused by market saturation and intense competition. Despite the network readiness of a nation in terms of its overall digital infrastructure, it did not contribute to online food retail efficiency.

Further studies comparing retailers by geographic scope could also offer a more granular understanding to identify localized strategies for improvement and analyze efficiency trends over time as digital and phygital retailers continue to scale and adapt to market dynamics, particularly in post-pandemic settings.

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Transforming Septic Tank Sludge into Agricultural Resources: A Pathway for Sustainable Development and Rural-Urban Synergy

RONNIE H. ENCARNACION*

School of Urban and Regional Planning, University of the Philippines

Email: rhencarnacion@up.edu.ph

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Abstract Urbanization, coupled with inadequate sewage infrastructure, results in the accumulation of septic tank sludge, which poses significant environmental and public health risks. This study explored the potential of transforming dewatered septage into a valuable agricultural resource through composting, aligning with the goals of sustainable development and rural-urban synergy. This study investigated the composting of dewatered septage mixed with bulking agents (rice straw, sawdust, and wood chips), focusing on key environmental management aspects such as pathogen reduction, nutrient cycling, and heavy metal stability. Pathogen reduction was significant, with *E. coli* levels in rice straw and sawdust compost falling below the EPA Class A standard of 1,000 MPN/g, whereas wood chips met Class B standards with levels below 2,000,000 MPN/g. The composts contained no viable helminths, ensuring their safety for agricultural use. Nutrient analysis revealed suitable levels of nitrogen (2.20% in rice straw, 1.08% in sawdust, and 2.22% in wood chips), phosphorus (1.98% in rice straw, 0.70% in sawdust, and 1.97% in wood chips), and potassium (0.77% in rice straw, 0.04% in sawdust, and 0.14% in wood chips), which support soil fertility and land conservation efforts. This study provides a sustainable, circular approach to septage management, highlighting its potential to enhance soil quality, reduce environmental pollution, and promote climate resilience. This composting method offers an innovative pathway for transforming urban waste into agricultural resources, fostering rural-urban synergy, and supporting sustainable development. Future studies should optimize composting conditions and explore the long-term benefits of composting for agricultural productivity and environmental health.

Keywords septage composting, sustainable agriculture, waste repurposing, climate resilience in waste management, co-composting

INTRODUCTION

The lack of, or improper disposal of, septic tank sludge, commonly known as septage, remains a critical environmental and public health issue in the Philippines. Numerous private desludging operators dispose of sludge in street drains, esteros, canals, or open vacant land without treatment (Baltazar et al., 2021). Studies have shown that 64% of households in rural areas (USAID, 2023) and 67.1% in urban areas (Statista Research Department, 2022) depend on septic systems for wastewater treatment. In many developing and underdeveloped countries, septage management has historically been overlooked, with untreated sludge often disposed of in vacant lots, water bodies, and poorly managed landfills (Kiely, 1996). This institutional neglect, especially in urbanizing low-income contexts, reflects the historical underdevelopment of fecal sludge treatment infrastructure and regulatory frameworks (Strande et al., 2014). These practices contribute to groundwater contamination, the proliferation of pathogens, and greenhouse gas emissions, exacerbating environmental degradation and posing serious public health risks (Haug, 1993).

Addressing these challenges is vital to achieving Sustainable Development Goal (SDG) 6 on *Clean Water and Sanitation*, which emphasizes access to sustainable sanitation and wastewater management (UN, 2023). Sustainable solutions are urgently needed to mitigate the environmental

and health impacts of septage mismanagement while fostering community awareness and participation in improved sanitation practices.

Although composting is widely recognized as a sustainable method for managing biodegradable organic waste, its application to septage has not been extensively explored. The existing literature has predominantly focused on thermal, chemical, and anaerobic treatment methods, which, while effective at pathogen reduction, are often cost-prohibitive and inaccessible for rural communities (Girovich, 1996). Recent studies have demonstrated the potential of co-composting, or the process of combining septage with carbon-rich bulking agents such as rice straw, sawdust, or woodchips, to address these limitations (Haug, 1993; Obeng and Wright, 1987). Research has shown that co-composting septage with carbon-rich bulking agents, such as rice straw, can improve compost quality and enhance economic returns (Din et al., 2017). This approach aligns with SDG 12 on *Responsible Consumption and Production* by converting waste into valuable resources for agriculture and supporting circular economy principles. However, several knowledge gaps remain.

1. *Optimization of Composting Parameters.* The influence of mixing ratios and bulking-agent type on co-composting performance (sanitization, nutrient conservation, and end-product quality) has been empirically demonstrated in faecal-sludge systems, underscoring the need for systematic optimization (Cofie et al., 2009).
2. *Pathogen Reduction Efficacy.* While previous research has highlighted the role of thermophilic composting in pathogen reduction, few studies have provided empirical data on the effectiveness of co-composting septage with specific carbon-rich bulking agents in achieving the United States Environmental Protection Agency (EPA) Class A standards for the use or disposal of sewage sludge, as outlined in the 40 CFR Part 503 rule (EPA, 1993).
3. *Practical Feasibility in Rural Settings.* There has been limited exploration of the safety and hygienic quality of septage co-composting products for agricultural use in resource-constrained rural areas (Mara, 2003).

Addressing these gaps is crucial for advancing sustainable waste management practices that align with global efforts toward circular economies. The transformation of septage into pathogen-free, nutrient-rich compost offers dual benefits in terms of reducing environmental pollution and enhancing soil health, particularly in rural agricultural systems. Moreover, integrating urban-generated waste with rural agricultural needs fosters rural-urban synergy, promoting sustainable development (Pausta et al., 2023).

This study addresses these research gaps by investigating the co-composting of dewatered septage with locally available bulking agents. By evaluating pathogen reduction, compost maturity, and nutrient enhancement, this study aims to provide valuable insights into the feasibility of septage co-composting as a low-cost, community-centered solution for sustainable waste management and agricultural productivity.

OBJECTIVE

The primary objective of this study was to determine the feasibility of co-composting dewatered septage with bulking agents to produce pathogen-free, agriculturally beneficial compost. The specific objectives are as follows:

- (i) To characterize dewatered septage in terms of physio-chemical and microbial parameters.
- (ii) To determine the optimal volumetric mixing ratios of septage and bulking agents for pathogen reduction, compost stability, and maturity and
- (iii) To evaluate the final compost product against sanitation standards set by the United States

EPA, Department of Environment and Natural Resources (DENR), and Fertilizer and Pesticides Bureau (FPB) in the Philippines.

METHODOLOGY

Feedstock Preparation and Characterization

Septage collection: Septage were sourced from 28 household septic tank at various locations within Quezon City, Metro Manila, Philippines and was pre-processed by a mechanical decanter mounted on the collection truck. A total of three (3) cubic meter of dewatered septage was collected and homogenized using a mechanical mixer to create a composite feedstock as a preparation for the composting.

Bulking agent preparation: Three bulking agents, specifically rice straw, sawdust, and woodchips, were selected based on their availability, biodegradability, and cost-effectiveness. These materials were reduced in size manually to improve porosity, surface area, and microbial accessibility, with woodchips reduced to approximately 1-3 inches and rice straw to 3-4 inches. The bulking agents were then homogenized using the coning and quartering method to ensure uniformity in the compost feedstock mixture.

Mixing proportions: The feedstock was mixed at different volumetric ratios (1:1, 1:2, and 1:3 of septage to each bulking agent). Each ratio aimed to optimize moisture content, temperature control, and microbial activity during the composting process. A one (1) cubic meter by one (1) cubic meter wooden box was used to uniformly achieve the desired mixing ratio.

Compost windrow pile construction: Thirteen windrow piles were prepared, including 12 experimental piles with varying septage-to-bulking-agent ratios (1:1, 1:2, and 1:3) and one control pile with only septage. The windrow method was used, with each feedstock mixture arranged into long, narrow trapezoidal cross-sections to ensure proper aeration, temperature control, and ease of manual turning of the compost. Plastic straw sheets were used to cover the windrows to protect them against rainfall and retain heat from microbial activity. Water collection canals were installed around the perimeter of each pile to direct leachate away from the environment and prevent environmental contamination.

Composting Process Maintenance

Turning and aeration: Manual turning of the windrow piles using a shovel was carried out weekly to ensure proper aeration and prevent anaerobic conditions. This process facilitated the transfer of oxygen throughout the compost pile, thereby promoting microbial activity and optimizing the composting process.

Temperature and moisture control: Temperature was monitored daily using thermocouples inserted at multiple points in each pile to ensure compliance with the recommended conditions for pathogen reduction, as outlined by the EPA guidelines. Moisture content was measured every three days to track the composting process. Moisture levels were adjusted as necessary by spraying water or allowing passive drying.

Monitoring and Analysis of Composting Parameters

Environmental parameters: To align with EPA (1993) composting standards, the frequency of monitoring and analysis of other key composting parameters throughout the composting process was as follows: every three (3) day for pH, total solids (TS), total volatile solids (TVS), moisture content (MC), and total organic carbon (TOC); and for total nitrogen (TN), the analysis was carried out on the initial mixture and final compost product. These parameters were measured using standardized laboratory methods (gravimetric, potentiometric, and colorimetric analyses).

Microbial Analysis: Representative samples were submitted to accredited laboratories for pathogen testing. Microbial load was assessed at the beginning and end of the composting process using indicators such as fecal coliforms (*E. coli*), total coliforms, and pathogenic microorganisms including *Salmonella* and helminth eggs. These analyses were conducted in accordance with the U.S. EPA (1993) Class A standards for the use or disposal of sewage sludge.

Duration of Composting: The composting process was monitored over a period of three (3) months. The end of active decomposition was determined using environmental indicators, including temperature, pH, and reductions in volatile solids. The compost was considered mature once the window pile temperature stabilized within $\pm 2^{\circ}\text{C}$ of ambient levels and the pH approached neutral (~ 7.0). This behavior is consistent with typical composting profiles, where temperatures decline from thermophilic ($> 45^{\circ}\text{C}$) into the mesophilic zone and ultimately approximate surrounding air temperature during curing and stabilization phases (ASABE, 2005; Utah State University Extension, 2009)

Compost Quality and Nutrient Analysis

Manual sieve analysis: The final compost product was harvested and screened using an 8 mm pore-size wire mesh to separate larger particles of bulking agents from the finer, mature compost. This process ensured uniformity in the compost product, making it suitable for its intended applications.

Nutrient analysis: The final compost product was analyzed for nutrient content, focusing on nitrogen (N), phosphorus (P), and potassium (K) concentrations to determine its suitability for agricultural use. The samples were sent to the Bureau of Soils and Water Management for Nutrient analysis.

Pathogen analysis: The presence of pathogens, such as *Salmonella*, helminth eggs, and fecal coliform, was assessed in the final compost product, benchmarked against the United States EPA 503 regulations for pathogen reduction (1993). These analyses are critical for ensuring the safety of compost for land application, as defined by the EPA, to include agricultural, silvicultural, and land reclamation uses.

Stability and maturity testing: The stability of the compost was evaluated based on parameters such as TS, TVS, and starch content, which reflect the extent of decomposition. The starch content method was chosen because of its reliability in assessing compost maturity and its applicability to the studied feedstock.

Physical and semi-qualitative analyses: Physical properties such as texture, color, and particle size were also assessed visually, alongside semi-qualitative tests like odor evaluation and gas production during compost storage in sealed plastic bags. These tests provided additional insights into compost maturity and microbial activities.

RESULTS AND DISCUSSION

Compost Feedstock Characteristics

The composite dewatered septage exhibited a high moisture content of 72.18% (Table 1), indicating a pasty texture that necessitated the addition of bulking agents to improve porosity and moisture regulation. Comparable studies have documented how bulking agents such as dry leaves effectively reduced moisture from $\sim 89\%$ to 57% and enhanced physical stability during composting (Jain et al., 2019); other work with dewatered sludge found that coffee-ground, corncob, and wheat husk additions significantly improved water removal during biodegradation (Hu et al., 2023).

The total volatile solids (TVS) content of 14.51% is relatively low compared to typical fresh domestic septage, suggesting that the sludge has undergone significant anaerobic decomposition within septic tanks prior to dewatering. The U.S. EPA (1995) and Ahmed et al. (2019) further noted that volatile solids content is widely recognized as an indirect measure of organic matter and biodegradability, and its values tend to closely track total solids (TS) in stabilized sludge, consistent with the 27.82% TS measured in this study.

The measured pH of 7.9 is slightly alkaline and well within the EPA Part 503 acceptable range of 6.0-12.0, which is favorable for beneficial reuse processes, including land application, while also suppressing certain pathogenic microorganisms (EPA, 1994). However, the fecal coliform count of 1.8×10^4 MPN/g exceeds the Class A pathogen limit (1.0×10^3 MPN/g) and falls within Class B specifications, indicating that additional pathogen reduction steps, such as thermophilic composting, are necessary prior to unrestricted land application (EPA, 1994).

Table 1 Characteristics of composite dewatered septage

Parameter	Value	EPA part 503 specifications (dry basis)
Moisture content (%)	72.18	30 – 60
Total solids (%)	27.82	12 (Class B)
Total volatile solids (%)	14.51	–
pH	7.9	6.0 – 12.0
Fecal coliform (MPN/g)	1.8×10^4	1.0×10^3 (Class A)

Table 2 shows that compost piles formulated from the composite dewatered septage, both unamended (control) and amended with carbon-rich bulking agents, started with initial moisture contents exceeding the optimal range for aerobic composting (50-60%), reaching as high as 72.1%. This excessive moisture can limit aeration, induce anaerobic zones, and reduce microbial activity, thereby prolonging the composting process (Kim et al., 2016; APHA, 2016).

Table 2 Initial characteristics of compost piles (dewatered septage plus bulking agents)

Septage and bulking agent mixtures		Initial operating parameter (dry basis)					
		%TOC	%TN	C/N	%TVS	%MC	Fecal coliform (<i>E. coli</i>) CFU/g
Rice straw						Bulk density (wet basis) kg/m ³	
	1:1	51.37	1.55	33.23	53	69.0	1.40×10^4
	1:2	59.61	1.54	38.74	50	68.9	1.15×10^4
	1:2R	66.45	1.72	38.74	56	72.1	1.15×10^4
Sawdust	1:3	67.29	1.55	43.50	50	69.1	9.72×10^3
	1:1	65.66	1.15	57.33	50	65.4	9.13×10^3
	1:1R	63.29	1.10	57.33	54	64.1	9.13×10^3
	1:2	80.16	0.96	83.86	61	64.0	6.12×10^3
Wood chips	1:3	87.43	0.82	107.10	71	62.2	4.60×10^3
	1:1	53.14	1.07	49.56	59	63.3	9.11×10^3
	1:1R	51.59	1.04	49.46	64	62.2	9.11×10^3
	1:2	72.26	1.04	69.67	82	67.2	6.09×10^3
Control plot (pure septage)	1:3	69.07	0.79	87.81	61	61.5	4.58×10^3
		46.25	6.22	7.43	52	72.1	1.80×10^4

The calculation of C/N ratio was based on the initial C and N content of septage and bulking agent respectively. The 'R' denotes replicate windrow pile of a feedstock mixing ratio. The term 'dry basis' refers to the measured characteristics such as total organic carbon (TOC), total nitrogen (TN), carbon to nitrogen ratio (C/N), total volatile solids (TVS), moisture content (MC), bulk density, and fecal coliforms with the moisture content excluded (APHA, 2017; ASTM, 2020).

Carbon-to-nitrogen (C/N) ratios in sawdust and woodchips mixtures exhibit high values, generally exceeding the ideal range of 25:1–35:1 for composting (Haug, 1993; Wiater, 2020), reaching up to 107.1 due to the high carbon and low nitrogen content of lignocellulosic materials. In contrast, pure septage had a low C/N ratio of 7.43, with high nitrogen (6.22%) and limited carbon content, reflecting prior anaerobic decomposition in septic tanks.

The generally recommended initial C/N ratio for initiating aerobic composting is between 15:1 and 30:1 (Haug, 1993). A stable and mature compost is typically achieved when the C/N ratio drops to ≤ 20 , assuming the initial ratio was within 25-30:1 (Hirai et al., 1983). Maintaining a balanced C/N ratio is critical because excessive carbon can slow microbial activity, whereas excessive nitrogen can lead to ammonia volatilization and odor problems (Haug, 1993). Over time, carbon-rich materials decompose under low-oxygen (anaerobic) conditions, leaving behind a more stable sludge that is high in nitrogen but low in easily degradable carbon (Tchobanoglous et al., 1993). Studies on composting have also indicated that C/N ratios decrease progressively during the composting process due to organic carbon loss and relative nitrogen enrichment, and that this decline can serve as a reliable indicator of maturity (Hirai et al., 1983; Manga et al., 2022). Despite exceeding conventional

C/N thresholds, recent studies suggest that effective composting is still achievable with C/N ratios above 60:1, although the composting rate is slow and the time period is long (Oshins, 2022).

Initial fecal coliform (*E. coli*) concentrations in all mixtures exceeded the EPA Class A biosolids standard of <1,000 CFU/g TS, with the control plot registering the highest at 1.80×10^4 CFU/g, followed by the bulking mixtures, which ranged from 1.40×10^4 to 4.58×10^3 CFU/g (EPA, 1993; Boczek, L. 2019). These values confirm the need for sustained thermophilic composting to meet sanitation standards. Collectively, these initial operating values demonstrate the physicochemical suitability of bulking agents for co-composting, while emphasizing the need for moisture management and C/N ratios to support microbial degradation and pathogen reduction.

Pathogen Reduction Efficiency

Table 3 revealed significant pathogen reduction in composted septage mixed with various carbon-rich bulking agents, despite compost pile temperatures not reaching the thermophilic threshold of 55°C recommended by the EPA (1993) for Class A biosolid treatment. The maximum recorded temperatures ranged between 33 and 42°C across all compost treatments, with the highest observed in the sawdust mixtures. While these temperatures are considered suboptimal for rapid microbial inactivation, the extended composting duration (≥ 90 days), consistent aeration through manual turning, and favorable pH conditions (approaching neutral) may have collectively contributed to pathogen decline, consistent with the multi-factor inactivation pathways noted in previous studies (Haug, 1993; Sidhu and Toze, 2009).

Table 3 Pathogen reduction in the 1:2 septage and bulking agents' mixture (dry weight)

Parameters	Rice straw	Sawdust	Wood chips	Standards (1993)	
				EPA Class A	EPA Class B
Initial value, <i>E. coli</i> (g MS)	1.15×10^4	6.12×10^3	6.09×10^3	< 1000	< 2,000,000
Final value, <i>E. coli</i> (g MS)	503	307	2,012		
<i>Salmonella</i> (per 10 g MS)	< 1	< 1	< 1	< 3 MPN/4 g	< 1,000 MPN/4 g
Total helminths (per 10 g MS)	972	280	87	< 1 viable/4 g	< 1,000 viable/4 g
<i>Ascaris</i> (per 10 g MS)	420	20	53	< 1 viable/4 g	< 1,000 viable/4 g
<i>Trichuris</i> (per 10 g MS)	552	260	34	< 1 viable/4 g	< 1,000 viable/4 g
Viable helminths (per 10 g MS)	0	0	0	< 1 viable/4 g	< 1,000 viable/4 g

Several studies have reported similar outcomes, where pathogen removal was achieved even in the absence of prolonged thermophilic conditions. For instance, Mengistu et al. (2018) observed a general reduction in helminth eggs during the latter stages of the composting process, with more than 75 percent of the total reduction recorded after the 60th day. Likewise, Harroff et al. (2019) noted that relatively low temperatures can considerably impact *Ascaris* viability and suggested that mesophilic temperatures can be used in waste treatment processes to inactivate pathogens. Moreover, Manga et al. (2023) investigated the effect of turning frequency on the survival of fecal indicator pathogens (*E. coli*, *Enterococcus* spp., *Salmonella* spp. and helminth eggs) during fecal sludge co-composting with sawdust. Their findings indicate that, even under relatively low composting temperatures (maximum average temperatures of compost piles or treatments were 54°C, 52.8°C and 52.1°C), increased turning frequency can substantially improve pathogen inactivation. This insight is particularly relevant for rural contexts where the availability of suitable organic solid waste for co-composting with fecal sludge to achieve sustained thermophilic conditions may be limited.

The complete absence of viable helminths in the final compost products suggests that factors beyond temperature were effective in pathogen inactivation in the present study. Khadra et al. (2019) investigated helminth eggs (HE) removal and inactivation efficiency by co-composting. The viability of ascaris eggs was examined using a light microscope and the percentage of the embryonated eggs was determined. No viable eggs were observed in the final compost sample.

Agronomic Benefits and Heavy Metal Safety

The final compost product (Table 4) demonstrated acceptable agronomic and environmental properties. Nutrient analysis of the 1:2 feedstock mixtures revealed sufficient nitrogen (N), phosphorus (P), and potassium (K) levels, suitable for use as a soil conditioner, in accordance with international and Philippine standards (EPA, 1993; Caneda et al., 2013). The metal concentrations were below the regulatory thresholds, minimizing environmental risks. The compost also showed satisfactory stability and maturity, as evidenced by the absence of starch, lack of offensive odors in water-soaked samples, and no bulging in the packed bags, meeting the quality parameters of the Philippines National Standards 40 (2013) for Organic Fertilizer (Caneda et al., 2013).

Table 4 NPK and heavy metals content of 1:2 septage to bulking agent compost

Compost feedstock and standards	Parameters (dry basis)						
	Nutrients			Metals (mg/kg)			
	%N	%P ₂ O ₅	%K ₂ O	Zinc (Zn)	Copper (Cu)	Manganese (Mn)	Iron (Fe)
Rice straw	2.20	1.98	0.77	2,462	271	788	19,443
Sawdust	1.08	0.70	0.04	1,497	1475	392	13,679
Wood chips	2.22	1.97	0.14	2,302	265	507	22,550
Typical values for compost or soil conditioner (PNS 40)	2.5 - < 5%	2.5 - < 5%	2.5 - < 5	5	300	N.L.	N.L.
Typical values for use or land application (EPA rule 503)	N.S.	N.S.	N.S.	2,800	1,500	N.S.	N.S.

U.S. EPA 40 CFR Part 503, Standards for the use and disposal of sewage sludge (1993 and 1994);

N.S. – Not Specified; PNS – Philippine national standards 40:2013 for organic fertilizer.

CONCLUSION

This study demonstrated both the feasibility and effectiveness of co-composting dewatered septage with carbon-rich bulking agents, namely rice straw, sawdust, and wood chips, as a sustainable strategy for managing urban organic waste and supporting rural agricultural systems. The feasibility of the process was supported by preprocessing the initial physicochemical parameters, allowing for stable compost pile construction and aeration. Effectiveness was evaluated based on two key outcomes. First, the composting process achieved significant pathogen reduction, as evidenced by the marked decline in fecal *Escherichia coli* concentrations, meeting the United States Environmental Protection Agency (EPA) 503 Class A criteria, confirming its suitability for land application in agricultural contexts. Second, the final compost products satisfied the Philippine National Standards (PNS) 40:2013 specifications for organic fertilizers, featuring favorable agronomic properties in terms of nitrogen (N), phosphorus (P), and potassium (K), along with low concentrations of heavy metals, supporting their suitability as organic soil amendments. These findings affirm the potential of septage co-composting to contribute to sustainable waste valorization, pathogen-safe compost production, and soil fertility enhancement in rural areas of developing countries. However, for widespread adoption and integration into municipal or city level waste management systems, economic and logistical feasibility must also be considered. Critical implementation challenges include the transport costs of septage and bulking agents, land availability for composting facilities, capital investment for operational equipment, and financial incentives for local governments or private actors. Although not empirically assessed in this study, these variables are fundamental to the long-term viability of septage co-composting initiatives. Future research should incorporate cost-benefit analysis, value chain assessment, and financing models to inform policy, guide infrastructure development, and enhance local implementation strategies. The results of this study underscore the potential of septage co-composting with carbon-rich bulking agents as a climate-resilient sanitation

and soil management solution aligned with circular economy principles and the Sustainable Development Goals (SDGs), particularly SDG 6 (clean water and sanitation) and SDG 12 (responsible consumption and production).

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Evaluation of Developed Novel Hybrid Granular Fertilizers for Sustainable Agriculture in Sri Lanka

ARACHCHILLAGE BUDDHIKA PRIYADARSHANI BANDARA

Graduate School of Agro-Environmental Science, Tokyo University of Agriculture, Tokyo, Japan

MACHITO MIHARA*

Faculty of Regional Environment Science, Tokyo University of Agriculture, Tokyo, Japan

Email: m-mihara@nodai.ac.jp

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Abstract This study developed and evaluated novel hybrid granular fertilizers by blending urea with locally available organic materials using molasses as a binder. Six treatments (T1-T6) were prepared with varying ingredient ratios and granulated using a small concrete mixer. Granule uniformity and size distribution (2.01-4.75 mm and 4.76-8.00 mm) were determined by hand sieving, indicating their suitability for bulk production and industrial application. Water stability was assessed using an aggregate analyzer for over two hours. Nutrient dissolution experiments were conducted to measure the initial release of nitrate and potassium. The results showed low uniformity indices, indicating consistent granule size and production scalability. Molasses alone did not dictate granule formation; a balanced mix of organic materials was essential for this process. Molasses enhanced water stability, but compost (T4) was the most effective for granule stability, outperforming chicken manure. Compost is recommended as a core organic component for stable slow-release granules. One-way ANOVA confirmed a highly significant treatment effect on nutrient release ($P < 0.001$). T5 and T6 were optimal for crops requiring rapid early season nutrition (leafy vegetables), whereas T4 was suitable for perennials or leaching-prone soils. Biochar-rich T1 and T2 treatments are recommended for soils requiring long-term nutrient cycling. Further optimization is required to tailor the formulations to specific agronomic requirements. These findings contribute to the development of slow-release hybrid fertilizers, thereby supporting sustainable agriculture in Sri Lanka.

Keywords hybrid fertilizer, nutrient loss, water resistance, Sri Lanka

INTRODUCTION

Sri Lanka's commercial agriculture has long relied on chemical fertilizers to achieve high crop yields, primarily because of their high nutrient content, rapid nutrient release, and ease of application. However, a substantial proportion of these nutrients is lost through leaching, runoff, and volatilization, resulting in economic inefficiency and environmental pollution. These losses contribute to water contamination, soil degradation, and adverse effects on human health (United Nations, 2022). The incorporation of organic matter into agricultural systems has been shown to enhance soil quality and fertility by increasing soil organic carbon, improving nutrient retention, and enhancing soil structure (Kim and Mihara, 2022).

Despite these benefits, the overreliance on chemical fertilizers in Sri Lanka has led to a significant decline in soil organic matter, further diminishing the soil structure and nutrient retention capacity. The National Agriculture Policy (2021) explicitly promotes the integration of organic components into farming systems as a balanced approach to ensure sustainable agricultural production. Despite these government efforts, the adoption of organic fertilizers by farmers remains low in China. A field survey conducted by the authors in 2023 in the Anuradhapura District revealed that only a minority of paddy farmers incorporate organic matter into their soils, with most citing slow nutrient release and the large quantities required as major barriers to its adoption. Consequently,

most farmers continue to rely on chemical fertilizers for immediate and manageable nutrient supply, underscoring the urgent need for practical, cost-effective solutions that bridge the gap between conventional and organic farming approaches. There is growing interest in hybrid fertilizers that combine the rapid nutrient release of chemical fertilizers with the soil health benefits of organic amendments, such as compost. High production costs and technological complexity in the production methods of commercially formulated organic-chemical blended fertilizers have limited their adoption in Sri Lanka.

Therefore, this study aimed to develop a simple and low-cost production technique for hybrid fertilizers using locally available organic materials and urea, with molasses as a binding agent. The results are expected to provide valuable insights into improving hybrid fertilizer production and adoption in Sri Lanka and other developing countries facing similar agricultural challenges.

OBJECTIVES

The objectives of this research were:

- to formulate hybrid granular fertilizers from locally available organic materials and urea
- to evaluate the stability of these fertilizers under field-like conditions and
- to assess the nutrient release of the developed hybrid fertilizers

METHODOLOGY

Materials Selection for Making Hybrid Granular Fertilizers

The selection of materials for hybrid granular fertilizers was based on a critical literature review, nutrient content analysis, and practical considerations related to Sri Lankan agriculture. Leafy compost, cow manure, and chicken manure were chosen as organic fertilizers due to their balanced nutrient composition and organic matter content. Biochar has been used for its ability to improve soil physicochemical properties (Herath et al., 2013). Molasses served as a binder to aggregate the ingredients. Urea was included as a readily available source of nitrogen to complement the slow release of nutrients from organic sources.

All materials utilized in this study were procured locally within Japan from certified agricultural supply firms, but closely resembled those commonly available in Sri Lanka, ensuring the relevance of the results for Sri Lankan conditions. The chemical composition of the ingredients is presented in Table 1.

Table 1 Chemical properties of the ingredients

Component	Total nitrogen (mg/kg)	Total phosphorus (mg/kg)	Total potassium (mg/kg)
Urea	460,000	-	-
Leafy compost	10,000	3,000	10,000
Cow dung	10,000	5,000	10,000
Chicken manure	30,000	30,000	20,000
Rice husk biochar	3,000	1,000	15,000
Molasses	1,200	200	40,000

Preparation of Hybrid Granular Fertilizers

Urea and organic materials (except molasses) were ground to less than 1 mm in size. Six treatments (T1-T6) were developed (Table 2), based on oven-dry mass basis ratios (dried at 105 °C for 24 hours). According to the ratios, the ingredients were mixed in a small-scale concrete mixer operated at a rotation speed of 16 rpm and a 30-degree inclination angle. These parameters were determined based on preliminary optimization trials to promote a gentle mixing.

Distilled water was evenly sprayed during mixing to promote wet granulation. Granules were collected and air-dried for 2 to 4 days at a controlled temperature of 24°C and used for subsequent experiments. A schematic of the granulation process is shown in Fig. 1.

Table 2 Mixing ratios of ingredients (%)

Treatment	Urea	Compost	Cow manure	Chicken manure	Rice husk biochar	Molasses
T1	10	50	10	10	16	4
T2	10	48	10	10	16	6
T3	15	51	10	10	10	4
T4	15	61	10	-	10	4
T5	10	51	25	10	-	4
T6	10	49	25	10	-	6

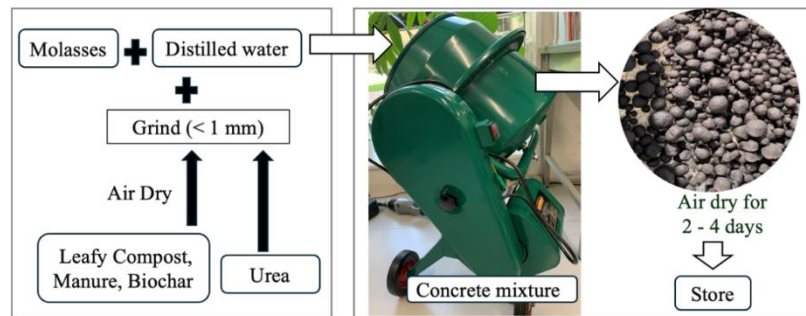


Fig. 1 Schematic diagram of the granulation process

Determination of Granule Uniformity

Following granulation, the uniformity of the granules for each treatment was determined by hand sieve analysis using standard laboratory sieves. Sieves with aperture sizes of <0.5 mm, 0.51-2 mm, 2.01-4.75 mm, 4.76-8 mm, and >8 mm were arranged in descending order. The samples were placed on the top sieve and gently shaken by hand for 15 min to ensure proper particle separation. The mass retained on each sieve was recorded, and the particle sizes at which 10% (D_{10}) and 95% (D_{95}) of the sample (by mass) passed through the sieves were determined by interpolation. The uniformity index (UI) was calculated for each treatment using Eq. (1) (Ohio State University Extension 2025; Ivell and Nguyen 2014). Assessing the uniformity of the bulk sample ensured that the fertilizer was spread evenly, minimizing product loss.

$$UI = (D_{95}/D_{10}) * 100 \quad (1)$$

Where, D_{95} size of sieve opening that retains 95% of the sample, and D_{10} size of sieve opening that retains 10% of the sample

Determination of granule size distribution

The granule size distribution was determined by sieving the air-dried fertilizer granules into defined size fractions relevant to industry standards: 2.01-4.75 mm, 4.76-8.00 mm, and >8.00 mm (Fig. 2).

Granules within the 2.01-4.75 mm range are most suitable and commonly used for field applications because of their optimal handling and spreading characteristics (Kasmadi et al., 2019). Granules sized 4.76-8.00 mm were used to a medium extent, whereas those >8.00 mm were rarely used. This classification ensured that the produced fertilizer granules were aligned with commercial fertilizer quality standards.



Fig. 2 Different granular size ranges

Evaluating Water Stability of Granular Fertilizers

Evaluating the water stability of fertilizer granules is essential for assessing their ability to retain physical integrity under wet conditions and to regulate nutrient release. To analyze the water stability, an aggregate analyzer was used, as shown in Fig. 3. The samples were placed on the top sieve and continuously stirred in water for two hours. After agitation, the material retained on each sieve was collected and oven-dried to determine its quantity.

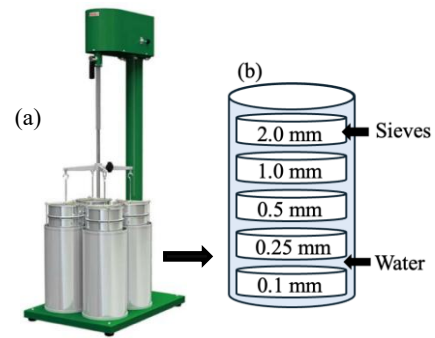


Fig. 3 Aggregate analyzer (a) with sieves (b)

Determination of Initial Nutrient Dissolution

Granules of 2.00–4.75 mm size were analyzed for initial nutrient release analysis. Triplicate samples of each granule were mixed with distilled water at a 1:10 solid-to-liquid ratio in 50 mL centrifuge tubes (Violamo centrifuge tube, Sigma-Aldrich, USA). The samples were then shaken using a reciprocating shaker at 150 rpm for 30 min at 24°C to ensure uniform nutrient extraction. Subsequently, the suspensions were filtered and analyzed for nitrate (NO_3^-) and potassium (K^+). This method provided an assessment of nutrient release under controlled conditions, mimicking the initial field interactions between fertilizer and soil moisture. This procedure was chosen for its practicality and alignment with the commonly used practices in nutrient release studies.

RESULTS AND DISCUSSION

Granule Uniformity

The calculated UI values for treatments T1, T2, and T3 were 24, while the remaining had a value of 25, exhibiting uniformity index values well below 40. The industry standard considers UI values within 40–60 to indicate a uniform particle size; values below 40 are not explicitly defined in the reference (Ohio State University Extension, 2025). However, the observed lower UI values suggest that the developed granular fertilizers possess even more uniform particle sizes and distributions. Therefore, all treatments ensured that the bulk production would spread evenly and minimized product loss.

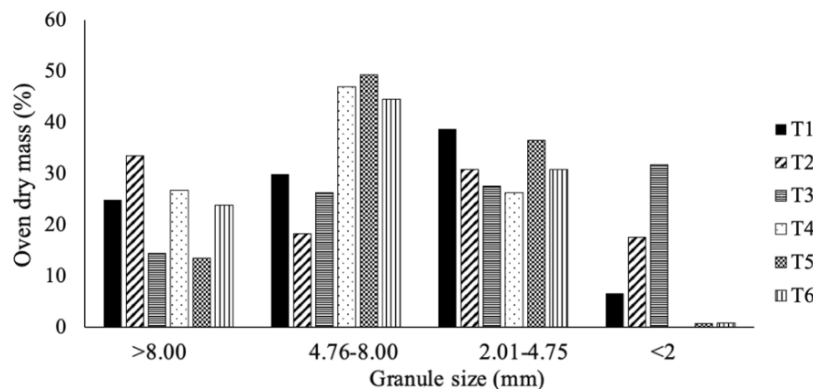


Fig. 4 Granular size distribution of developed fertilizers

Granule Size Distribution

Figure 4 shows that the granule size distribution varied among the treatments. Increasing the molasses content from 4% to 6% did not consistently improve the granule size distribution,

suggesting that molasses alone is not the sole factor affecting granule formation. Instead, a balanced combination of organic materials is important for optimal granule size and reducing fines. Notably, T4, T5, and T6 produced minimal fines (<2 mm), likely due to differences in their compost, cow dung, and manure contents. For example, T4 contained high compost and no chicken manure, T5 contained higher cow dung and no biochar, and T6 contained higher cow dung and molasses. In industrial production, excessive fines and oversized particles are undesirable and can lead to wastage. Therefore, further formulation and optimization are recommended to achieve the most uniform granule size distribution possible.

Water Stability of Granular Hybrid Fertilizers

The results in Table 3 show that molasses increased granule stability (T2>T1, T6>T5). However, T4, with higher compost and no chicken manure, was the most stable of all, surpassing even those with higher molasses. This demonstrated that the absence of chicken manure and high compost content were the primary factor for T4's water stability, as the fibrous nature of chicken manure could reduce granule stability. This suggested that compost was an effective organic fertilizer for strong, water-stable granules, while chicken manure was less effective for binding.

Table 3 Mass percentage left on the sieve after 2 hours of shaking

Sieve (mm)	Mass percentage left on the sieve after shaking for 2 hours					
	T1	T2	T3	T4	T5	T6
2.0 mm	93.19	96.47	95.80	99.35	94.83	97.91
1.0 mm	5.77	2.47	1.81	0.29	2.12	0.78
0.5 mm	0.52	0.49	1.08	0.10	1.65	0.62
0.1 mm	0.53	0.57	1.30	0.26	1.40	0.70

Nutrient Dissolution

Figure 5 shows the initial nutrient release from the developed fertilizers. One-way ANOVA revealed that the release of NO_3^- and K^+ from hybrid fertilizer granules (2.01-4.75 mm) varied significantly across treatments. Treatments T5 and T6, which contained higher amounts of cow manure, exhibited the highest nitrate and potassium release, while T4, with no chicken manure, showed the lowest nutrient release. These results suggest that cow manure, as a readily mineralizable organic nitrogen source, and molasses, as a microbial energy substrate, synergistically promote rapid nutrient release. In contrast, compost's stabilized organic matter content contributes to its slow-release characteristics. Biochar-rich treatments demonstrated moderate nutrient release, likely due to the porous structure and nutrient retention capacity of biochar.

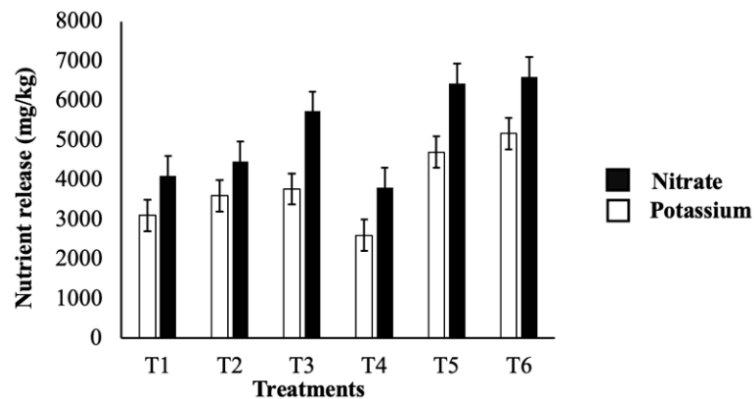


Fig. 5 Nutrient release from developed fertilizers

As a recommendation, T5 and T6 are particularly suitable for crops requiring rapid early-season nutrition, such as leafy vegetables. Treatment T4, with its slow-release properties, is ideal for

perennial crops or soils prone to nutrient leaching, where sustained nutrient availability proves critical. Biochar-rich treatments (T1 and T2) are recommended for degraded soils requiring improved water retention and long-term nutrient cycling.

CONCLUSION

The hybrid granular fertilizers developed in this study, using locally available organic materials and urea with molasses as a binder, demonstrated improved nutrient release and stability compared to urea alone. The granules exhibited uniformity, ensuring better handling, especially for smallholders. Slow-release properties minimize nutrient leaching and runoff, enhancing nutrient use efficiency and water stability. This study focused on short-term nutrient release in laboratory conditions. The nutrient release dynamics observed in this study may differ under field conditions because of factors such as soil microbial activity, weather, and plant uptake. Further field trials are required to validate these findings in real agricultural scenarios. Studies linking nutrient release kinetics to plant growth and soil microbial diversity would further strengthen the practical relevance of these results.

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Data-Driven Techniques for Identification of Factors Affecting Hydroponic Tomato: A Case Study in Hino City, Tokyo, Japan

HETTIGE SAMITHA LAKSHAN GUNASEKARA*

*Graduate School of International Food and Agricultural Studies,
Tokyo University of Agriculture, Tokyo, Japan
Email: 13823001@nodai.ac.jp*

RAMADHONA SAVILLE

Tokyo University of Agriculture, Tokyo, Japan

NINA N. SHIMOBUCHI

Tokyo University of Agriculture, Tokyo, Japan

KATSUMORI HATANAKA

Tokyo University of Agriculture, Tokyo, Japan

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Abstract Hydroponic greenhouses are a potential solution to the increasing demand for food and nutrition for the global human population. However, agriculture is influenced by complex relationships between multiple variables, particularly in regard to controlled environments, making it challenging for farmers to identify essential factors to create and manage optimal conditions for higher crop yields. Data-driven decision-making is an appealing solution for overcoming this challenge. The objective of this study was to use data science methods to identify the essential factors affecting a hydroponic tomato farm in Hino City, Tokyo, Japan. Specifically, this study identified the essential microclimatic and hydroponic factors that affect tomato yield. Further, this study compared the application of linear multiple regression and random forest regression models to identify the essential factors impacting the tomato harvest. Data sensors were installed in the greenhouse to obtain microclimatic and hydroponic data. Farm records, plant growth records, and tomato harvest data from three crop cycles (November 2021 to July 2024) were also collected. The moving average method was applied to smooth the data during preprocessing. The random forest regression model outperformed the linear regression model with a higher R^2 value of 0.9, whereas the linear model had a lower R^2 value of 0.31. Both models identified electrical conductivity supply, temperature, and the amount of water per plant as significant factors affecting tomato yield. Electrical conductivity showed a negative correlation, whereas temperature and the amount of water per plant showed a positive correlation, highlighting the importance of maintaining optimal levels for higher yields. This study provides practical insights into the essential yield-influencing factors and supports the implementation of customized management practices through data-driven decision-making, empowering smallholder hydroponic farmers to increase productivity.

Keywords linear multiple regression, machine learning, random forest regression, smart agriculture, yield optimization

INTRODUCTION

Agriculture continues to be the foundation of global food and nutritional security with more than 608 million family farms contributing significantly worldwide. Smallholder farmers account for 70–80 percent of global farmland and produce approximately 80 percent of the world's food by

value (FAO, 2021). In Japan, eighty percent of tomatoes are produced in smallholder greenhouses (MAFF 2022). Despite their pivotal role, smallholder farmers in Japan face multiple challenges, including unpredictable environmental conditions, resource limitations, labor shortages, and an aging farm worker population. These issues are particularly relevant in Japan, where smallholder farmers play a vital role in the agricultural sector. Therefore, the Japanese government has recognized the importance of supporting the agricultural sector by promoting smart agriculture (MAFF, 2024). Through subsidies and financial incentives, the government encourages farmers to adopt advanced technologies such as precision farming, data-driven decision-making, and automated systems (MAFF, 2023). These measures aim to mitigate labor shortages, enhance resource efficiency, and ensure the sustainability of smallholder farming operations. By integrating smart technologies, smallholder farmers can overcome traditional barriers and contribute to food security and economic sustainability in Japan. A promising approach for addressing these challenges is the adoption of smart hydroponic greenhouses. Smart hydroponic farming integrates hydroponic production techniques with sophisticated technologies such as Internet of Things (IoT) sensors, automated fertilizer delivery systems, and climate management to boost productivity and resource efficiency in a controlled setting (MAFF, 2024; Shareef et al., 2024). These systems offer a controlled environment for crop production in which nutrients are delivered through irrigation without soil, resulting in higher yields, better quality, and reduced resource use. This method is especially advantageous for smallholder farmers because it optimizes space, minimizes water consumption, and reduces dependency on traditional farming practices. However, managing hydroponic systems introduces complexities, requiring farmers to navigate the complex relationships between factors, such as temperature, humidity, CO₂ levels, solar radiation, and nutrient concentrations (Shareef et al., 2024). Even slight imbalances can significantly affect crop yields, underscoring the need for decision support tools.

Data-driven agriculture, a core component of smart agriculture, leverages technological advancements, IoT sensors, and data analytics to provide insights into farm management (Saiz-Rubio and Rovira-Más, 2020). In this type of agriculture, decisions are made by analyzing historical and real-time data by using data-driven techniques to help farmers identify critical variables, optimize growing conditions, and enhance productivity. Data science offers powerful yield prediction and optimization methodologies, ranging from traditional statistical models to advanced machine learning algorithms. The statistical method of linear multiple regression is effective in identifying linear relationships between variables (Breiman, 2001). However, this method has limitations in capturing complex nonlinear interactions. Machine learning regression methods can capture complex nonlinear interactions and have higher prediction power. Most machine learning algorithms focus solely on predictions. However, they cannot reveal how each variable impacts the predictive outcome or its importance (Carvalho et al., 2019). Random forest regression is a machine learning regression analysis method capable of yield prediction (Jeong et al., 2016). It also calculates feature or variable importance, providing insights into the contribution of each variable to the predicted outcome. This dual capability makes random forest regression particularly valuable in regard to understanding agricultural phenomena. Despite the potential of these data-driven techniques, their adoption in agriculture is limited to larger scale farms because smallholder farmers often face challenges such as a lack of awareness, technical expertise, and resources, leaving them unable to fully benefit from these advancements (Adereti et al., 2023). Therefore, addressing these barriers is crucial for democratizing access to smart-farming technologies and ensuring that smallholder hydroponic farmers can leverage data-driven methods to improve productivity and sustainability.

OBJECTIVE

The objective of this study was to identify the essential environmental and hydroponic variables that influence tomato production using data science methods for smallholder hydroponic farmers. Specifically, this study focused on identifying the microclimatic and hydroponic variables that significantly influence the tomato yield and analyzed the effectiveness of data-driven methods by

comparing the predictive power of linear multiple regression and random forest regression for the yield of hydroponic tomatoes.

METHODOLOGY

Study Design and Location

This study was conducted in a smallholder smart hydroponic greenhouse (“N Farm”) in Hino City, Tokyo, Japan (Fig 1). While the N Farm greenhouse cultivates multiple tomato varieties, this study focused solely on the Momotaro tomato variety (660 plants grown inside a 237 m² area), as complete datasets (microclimatic, hydroponic, and farm management data) were available for this tomato variety. The research design involved collecting, preprocessing, and analyzing data from three consecutive crop cycles to identify key variables influencing tomato yield.

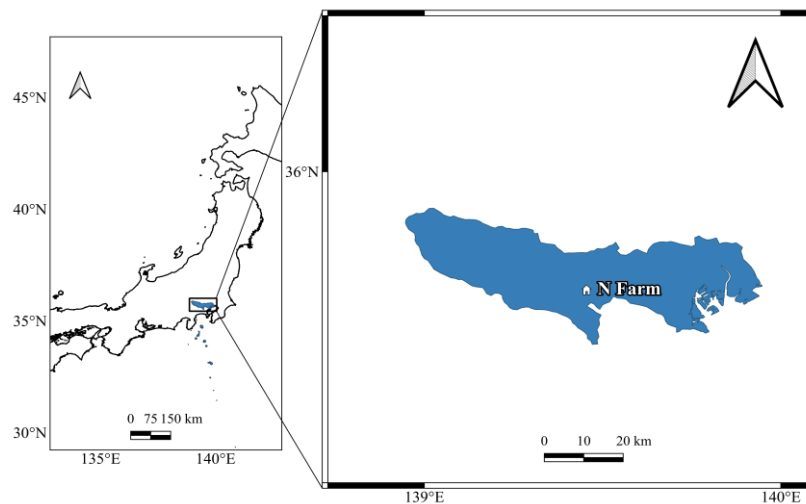


Fig. 1 The study location, Hino City, Tokyo Japan

Data Collection

Data was collected over three crop cycles from November 2021 to July 2024. The 1st cropping period was 2021-11-29 to 2022-06-27, the 2nd cropping period was 2022-10-30 to 2023-05-13, and the 3rd cropping period was 2023-10-16 to 2024-06-17. The study utilized a combination of microclimatic data (temperature [°C], CO₂ levels [parts per million - ppm], humidity [%], and cumulative sum of solar radiation [MJ/m²]), hydroponic data (water supply per plant [ml], electrical conductivity (EC) [mS/cm] and pH value of the nutrition supply) (Fig 2), yield data (daily tomato harvest [kg]) and plant growth records (number of cultivating days, number of internodes) from the farm records (Fig 3) were used in this study.

Data Preprocessing

Handling missing data: Missing hydroponic data points were addressed using the forward-filling method, in which previous data values were replaced with missing values. This method ensures continuity without artificial fluctuations that can skew the analysis.

Moving average (MA): The MA technique was applied to reduce fluctuations and capture underlying trends. The window period was determined based on the average internode growth period of tomato cultivations.

Variance inflation factor value (VIF): A VIF analysis was conducted to detect multicollinearity among the independent variables in the regression models, as high multicollinearity can distort the

interpretation of the regression coefficients (Craney and Surles, 2002). The variables identified as having high multicollinearity (>10) were reviewed and adjusted to improve the performance and reliability of the regression models.

Data scaling: The dataset included variables with different units and scales. Before the analysis, the data were standardized using the Z-score method to ensure consistency and comparability, with a mean of zero and a standard deviation (SD) of one (D'Agostino et al., 2017). The standardized data were analyzed using linear multiple regression and random forest regression.



Fig. 2 Hydroponic data record by farmer



Fig. 3 Farmer demonstrates how plant growth data record

Data Analysis

Results from regression analysis: Two predictive models, linear multiple regression and random forest regression, were developed to analyze the relationships between the collected variables and tomato yield. Data aggregated from all three crop cycles were applied to these two models to explore the relationship between the independent variables, including environmental and hydroponic factors, and the dependent variable, the 11-day moving average (MA11) Momotaro tomato harvest.

Linear multiple regression: The linear multiple regression method was employed to explore the linear relationships between variables (Grégoire, 2014). The model estimates the impact of each independent variable on the tomato yield, providing coefficients that quantify their contribution to the predicted outcome.

Random forest regression: Random forest regression is an ensemble machine-learning algorithm that builds multiple decision trees and aggregates their predictions to deliver a more accurate and robust output for regression tasks (Breiman, 2001). By averaging the predictions from all individual decision trees, this method enhances overall accuracy and performance. This algorithm introduces randomness into the subset of features at each node for splitting, which reduces overfitting, enhances generalization, and effectively captures nonlinear relationships and complex interactions between variables, making it particularly useful for datasets with diverse features. Additionally, it provides insights into feature importance, helping identify the most influential factors in predicting the target variable (Gregorutti et al., 2017). This versatility, combined with its robustness to minimize noise and outliers, makes random forest regression a powerful tool for modeling in fields such as agriculture, where environmental and operational variables exhibit complex interdependence. The random forest regression model was trained on 70% of the dataset and tested on the remaining 30% of the data using a hyperparameter optimization grid search cross-validation to optimize the random forest regression model (Probst et al., 2019). For the random forest regression model, feature importance analysis was conducted to calculate the feature importance values and identify the most influential variables affecting tomato yield. After identifying the essential features, the Pearson correlation method was used to determine the effect of each variable on the 11-day Momotaro tomato harvest period.

Model Evaluation: The performance of the linear multiple regression and random forest regression models was evaluated using R^2 score, mean absolute error (MAE), and root mean squared error (RMSE) (Emmert-Streib and Dehmer, 2019). The R^2 score indicates the proportion of variance in the tomato yield that the model can explain, with higher values indicating better model performance. MAE measures the average magnitude of the prediction errors, indicating that the predictions are close to the actual values. The RMSE emphasizes the more significant errors by squaring them, indicating model accuracy with a bias toward more significant deviations.

RESULTS

The results provide insights into the key microclimatic hydroponic factors influencing tomato yield in the study's smallholder smart hydroponic greenhouse. Table 1 provides the descriptive results for all data variables used in this study for the three cropping periods as well as over the 1st to 3rd cropping periods. A higher average daily tomato harvest (15.4 ± 10.01 kg) was observed in the 1st cropping period, which declined gradually to 10.34 ± 6.34 kg by the 3rd cropping period.

Table 1 Descriptive statistics results for microclimatic and hydroponic data variables

	1 st cropping period		2 nd cropping period		3 rd cropping period		1 st to 3 rd cropping period	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Harvest Data								
Daily Momotaro tomato harvest	15.44	10.01	11.50	8.04	10.34	6.34	12.96	8.52
Hydroponic Data								
Daily EC Supply	1.74	0.31	1.90	0.22	2.45	0.84	1.95	0.65
Daily pH Supply	6.64	0.40	6.33	0.41	5.77	0.77	6.41	2.25
Daily Total Water Per Plant	248.92	74.29	211.05	21.16	239.56	44.68	212.47	75.25
Microclimatic Data								
Daily Mean Temperature	18.25	3.37	17.35	1.61	19.33	4.00	19.05	3.71
Daily Humidity	85.68	8.67	87.70	6.60	81.61	10.65	83.60	9.45
Daily Mean CO ₂	505.02	61.77	516.90	66.47	466.38	38.13	485.55	57.85
Daily Cumulative Sum of Solar Radiation	625.33	220.60	603.31	222.88	624.88	229.77	641.18	238.42
Growth Data								
Number of Cultivating Days	210	-	195	-	245	-	216.67	-
Number of Internodes	21	-	17	-	24	-	20.67	-

Also, when considering the hydroponic variables, EC increased from 1.74 ± 0.31 mS/cm in the 1st cropping period to 2.45 ± 0.84 mS/cm in the 3rd cropping period, suggesting that the farmer increased fertilization. The pH value measured each day in the hydroponic solution gradually decreased from 6.64 ± 0.40 in the 1st cropping period to 5.77 ± 0.77 in the 3rd cropping period. In addition, the water supply per plant had a higher value of 248.9 ± 74.29 ml in the 1st cropping period, which decreased to 211.05 ± 21.16 in the 2nd cropping period, but increased to 239.56 ± 44.68 ml in the 3rd cropping period. When considering the microclimatic variables, temperatures ranged from 17.35 ± 3.37 °C to 19.33 ± 4 °C, averaging 19.05 ± 3.71 °C over the entire period. The mean daily humidity was highest at $87.7 \pm 6.6\%$ in the 2nd cropping period and dropped to $81.61 \pm 10.65\%$ during 3rd cropping period. The mean daily CO₂ levels recorded the highest value of 516.9 ± 66.47 ppm in the 2nd cropping period but decreased to 466.38 ± 38.13 ppm in the 3rd cropping period. The cumulative sum of solar radiation was similar for the 1st cropping period (625.33 ± 220.60 MJ/m²) and the 3rd cropping period (624.88 ± 229.77 MJ/m²) but decreased to 603.31 ± 222.88 MJ/m² in the 2nd cropping period. The average number of cultivation days for three crop cycles was 26.67 days. In the three crop cycles, the tomato plants had an average of 20.67 internodes, which was rounded to 21. Therefore, the average internode growth period was 10.34 days, which was rounded to 11 days. Figure 4 illustrates the daily Momotaro tomato harvest and the 11-day moving average (MA11) trend for the 3rd cropping period. The 3rd cropping period has

been selected for visualization purposes because it represents the most recent and complete dataset, allowing a clear illustration.

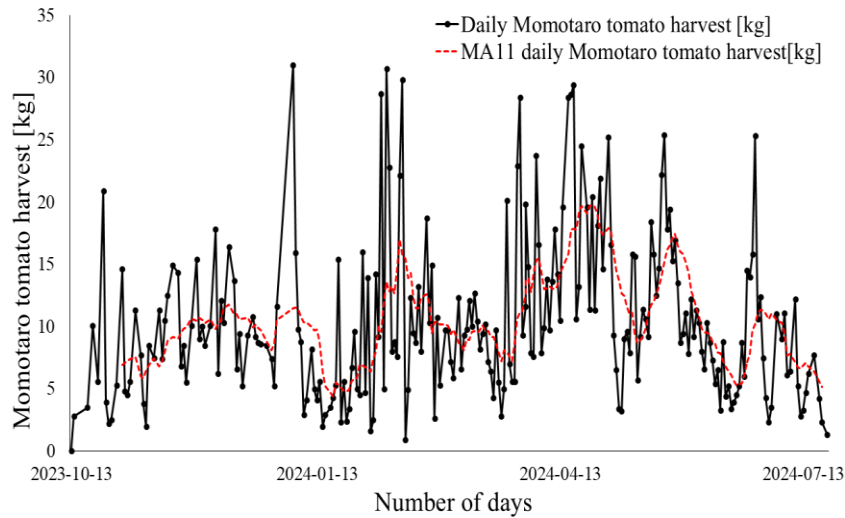


Fig. 4 Daily and MA11 days of Momotaro tomato harvest trend for 3rd cropping period

Regression Analysis Results

After preprocessing the dataset using the MA method, the dataset was analyzed using the VIF method to identify intercorrelated variables. The MA11 daily humidity had a high VIF value (>10). After removing the MA11 daily humidity variable, the remaining variables (which had VIF values below five) were standardized and used for the regression analyses.

Linear Multiple Regression

First, a linear regression model was developed to analyze the effects of microclimatic and hydroponic variables on tomato yield. The coefficient estimates and their significance levels are summarized in Table 2. The results showed that the model explained approximately 31% of the variability in the dependent variable, with an R^2 value of 0.31. Additionally, the low MAE of 0.67 and RMSE value of 0.81 highlight the predictive accuracy of the linear multiple regression model. The positively significant variables included the MA11 daily mean temperature, MA11 daily mean CO_2 , and MA11 daily cumulative sum of solar radiation. Notably, it was seen that the MA11 daily EC supply was the only significant negative variable.

Table 2 Results from linear multiple regression analysis

Variables	Estimate	Std. Error	t value	Pr ($> t $)
(Intercept)	0.00	0.03	0.00	1.00
MA11 Daily EC Supply	-0.37	0.04	-9.07	$< 2e-16$
MA11 Daily pH Supply	0.02	0.05	0.32	0.75
MA11 Daily Total Water Per Plant	0.06	0.03	1.87	0.06
MA11 Daily Mean Temperature	0.25	0.04	5.72	0.00
MA11 Daily Mean CO_2	0.09	0.04	2.41	0.02
MA11 Daily Cumulative Sum of Solar Radiation	0.34	0.04	8.14	0.00

Random Forest Regression

Second, a random forest regression model was developed to analyze the impact of microclimatic and hydroponic variables on tomato yield. The hyperparameter optimization grid search cross-validation including 100 trees (“n_estimators”) with a maximum depth of 20, minimizing the split size of (“min_samples_split”) and square root feature selection (“max_features”), which improved

the random forest regression model prediction performance offering its reliability for yield forecasting. The random forest regression model achieved an R^2 score of 0.9 on the test dataset, which explained 90% of the variability in the tomato harvest. Furthermore, the low MAE (2.63) and RMSE (1.63) values demonstrate higher prediction accuracies. As shown in Table 3, the random forest feature importance scores are reported alongside the correlation coefficients between variables and yield. The feature importance scores revealed that the most influential variables were the MA11 daily mean temperature value, MA11 daily EC supply, and MA11 daily total water per plant, which explained more than 63% of the variance affecting the MA11 daily Momotaro tomato harvest. Following the MA11 pH supply, the MA11 daily means CO_2 and MA11 daily cumulative sum of solar radiation were moderately important, meaning that they had a lower but still meaningful contribution to the model, with individual importance scores ranging between 0.11 and 0.15. The MA11 cumulative sum of solar radiation showed the lowest feature importance score of 0.11, and it exhibited the highest positive correlation (0.42) with the MA11 daily Momotaro tomato harvest. These results highlighted the essential environmental and hydroponic variables for hydroponic greenhouse productivity. After calculating the random forest regression, Pearson's correlation was used to examine the relationships between variables. The MA11 daily EC supply was negatively correlated with the MA11 daily Momotaro tomato harvest. In contrast, MA11 daily mean temperature and MA11 daily total water per plant were positively correlated with MA11 daily Momotaro tomato harvest.

Table 3 Feature importance and correlation analysis from random forest regression

Variables	Feature Importance	Correlation
MA11 Daily Mean Temperature	0.22	0.26
MA11 Daily EC Supply	0.21	-0.28
MA11 Daily Total Water Per Plant	0.18	0.13
MA11 Daily pH Supply	0.15	0.04
MA11 Daily Mean CO_2	0.13	-0.10
MA11 Daily Cumulative Sum of Solar Radiation	0.11	0.42

DISCUSSION

The MA method with an 11-day window was used to smooth the dataset, with the window size determined based on the average internode growth period. An internode refers to the segment of a plant stem between two nodes, where branches and leaves develop during flower growth (Korol, 2022). In tomato plants, internodes are key indicators of growth and directly correlate with stages such as flowering and fruiting, which are critical for managing nutrient and water supply. Aligning the smoothing window with the internode growth period revealed biologically relevant patterns in the data. Subsequently, the prepared data were analyzed using the linear multiple regression and random forest regression methods.

When considering the linear multiple regression and random forest regression results, random forest regression had a higher model performance (R^2 score), explaining 90% of the phenomenon. In contrast, the linear multiple regression had a value of only 0.31, which explained 31% of the variance. This indicates that the random forest regression can better identify the nonlinear relationship than linear multiple regression methods. When considering the linear multiple regression and random forest regression, it was identified that MA11 days of tomato harvest, microclimatic variables of MA11 daily mean temperature, hydroponic variables of MA11 daily EC supply, and MA11 daily total water per plant are important by significant value in linear multiple regression and importance value in random forest regression. The MA11 daily mean temperature and MA11 daily total water per plant were positively correlated with the MA11 daily Momotaro tomato harvest. These findings are consistent with previous studies. Ullah et al. (2021) reported that reduced water supply under deficit irrigation conditions negatively impacts tomato yield in soilless systems, which supports this study's identification of water per plant as a significant

positive factor. John and Stephen (2024) and Van Ploeg and Heuvelink (2005) explained in their studies that suboptimal temperatures limit photosynthesis and fruit development, aligning with our findings that increased temperatures improve yield performance. The negative relationship between EC and tomato yield is also supported by Solis-Toapanta et al. (2020), who found that excessive EC concentrations delay ripening and increase susceptibility to blossom-end rot. This suggests that overfertilization may be occurring in the greenhouse, resulting in diminished productivity. Lee et al. (2017) further observed that nutrient uptake efficiency declines under high EC conditions, reinforcing the importance of maintaining a balanced nutrient supply. The MA11 daily cumulative sum of solar radiation showed the lowest feature of importance in the random forest model. However, it had the highest positive correlation with the MA11 daily Momotaro tomato harvest and was highly significant in the linear regression model. This suggests that solar radiation plays a biologically important, yet partly indirect, role in tomato yield, likely through its influence on photosynthesis, fruit development, and the regulation of tomato growth (Teixeira, 2020). In contrast, variables such as MA11 days mean temperature, MA11 daily total water per plant, and MA11 daily EC supply were consistently identified as primary drivers of yield by both models. The comparatively negative lower feature importance for solar radiation may result from shared variance with other variables, which often dominates in model splits in tree-based algorithms (Gregorutti et al., 2017). Nevertheless, the strong correlation and statistical significance of solar radiation explain that it should not be overlooked in greenhouse management. Therefore, model-derived feature importance should always be interpreted in conjunction with statistical evidence, biological mechanisms, and expert agronomic knowledge to avoid dismissing variables that contribute meaningfully to crop productivity.

While these findings support prior research, this study also extends the literature in several keyways. First, it is one of the few to apply both linear regression and random forest regression to small-scale hydroponic greenhouse data, enabling comparative analysis of model performance and variable importance. Second, the use of an internode-aligned moving average window provides a novel approach that links physiological plant growth stages to data preprocessing, thereby enhancing the biological relevance of the analysis. Lastly, the study focuses specifically on smallholder hydroponic production in Japan, a context often overlooked in existing data-driven agriculture studies, such as Jeong et al. (2016), which primarily address larger scale farm systems.

According to the descriptive results, the hydroponic greenhouse had an average temperature of 19.05 ± 3.71 °C while the optimal temperature range for tomatoes is approximately 25 °C to 30 °C (John and Stephen, 2024). Increasing the temperature is important for increasing tomato yield productivity, because suboptimal temperatures can decrease the rate of photosynthesis, slow plant metabolic processes, and negatively impact fruit development and ripening. Therefore, the farmer needs to take the necessary actions to increase their temperature levels. In addition, Ullah et al. (2021) mentioned in their study how a water deficit can result in a reduced tomato harvest. Consistent with this finding, our results suggest that ensuring an adequate water supply is essential for maximizing productivity. The MA11 days of EC negatively affected the MA11 days of the tomato harvest. Therefore, it can be expected that the farmer has been overfertilizing and that higher EC values would reduce crop productivity. Therefore, based on the findings, consistent temperature controls must provide favorable conditions for photosynthesis, nutrient uptake, and overall plant health. As for the hydroponic variance variables, providing balanced nutrient management to mitigate the potential stress caused by over-fertilization and maintaining precise water management is essential to avoid over-irrigation, which can adversely affect the yield. Although the MA11 daily cumulative sum of solar radiation exhibited lower feature importance in the random forest model, it showed the highest positive correlation with tomato yield and was statistically significant in the linear multiple regression analysis. This indicates that solar radiation plays a meaningful, though partially indirect, role in yield performance. Therefore, the farmer should not overlook monitoring solar radiation levels and implement strategies to enhance light exposure, such as using reflective surfaces or installing supplementary lighting during periods of low radiation, which can contribute to improved crop yield.

CONCLUSION

This study aimed to identify the key microclimatic and hydroponic factors influencing tomato yield in a hydroponic greenhouse system and evaluate the predictive performance of data-driven models. Using environmental and hydroponic data from three crop cycles (2021-2024) at N Farm in Hino City, Tokyo, this study identified that MA11 daily mean temperature, MA11 daily EC supply, and MA11 daily total water per plant are the most important factors for the MA11 Momotaro tomato yield by using linear multiple regression and random forest regression models. Temperature and water supply showed positive correlations with yield. On the other hand, EC showed a negative effect, indicating yield penalties of over-fertilization. Although the MA11 daily cumulative sum of solar radiation received only lower feature importance in the random forest model, it had the highest positive correlation. Also, it was highly significant in the linear multiple regression, suggesting that it is likely due to overlapping effects with other variables. Despite this, solar radiation remains important and should be managed in a greenhouse alongside other factors. Random forest regression captured these complex nonlinear relations more effectively ($R^2 = 0.90$) than the linear multiple regression model ($R^2 = 0.31$). In addition to these results, this study offers several significant contributions. First, it integrates environmental and hydroponic data with a biologically informed 11-day moving average aligned with the tomato internode growth period, enhancing the physiological relevance of the analysis. Second, this study compared statistical regression with machine learning in a hydroponic setting, demonstrating that machine learning models can deliver both high accuracy and the importance of interpretable variables at this scale. Third, concentrating on an operational Japanese hydroponic greenhouse fills a practical gap in the literature, as data-driven techniques are feasible and valuable for smallholder farmers. These findings and methods create a replicable, data-driven framework that delivers practical guidance for temperature control, nutrient balance, and irrigation scheduling. Therefore, this study implements customized management practices through data-driven decision-making, empowering smallholder hydroponic farmers to increase productivity.

The limitations of this study include identifying only the essential variables and their effects on tomato yields using historical data. Therefore, future studies should focus on identifying the optimal conditions for each identified variable, the applicability of real-time data integration, and broader applications across diverse smallholder hydroponic farming systems to enhance the impact of data-driven agriculture.

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Local Eco-Entrepreneurship in Coffee Farming Communities of Sultan Kudarat, Philippines

LIGAYA R. LEAL*

University of the Philippines Mindanao, Davao City, Philippines
Email: lrleal@up.edu.ph

MARILOU O. MONTIFLOR

University of the Philippines Mindanao, Davao City, Philippines

ROXANNE T. AGUINALDO

University of the Philippines Mindanao, Davao City, Philippines

THADDEUS R. ACUÑA

University of the Philippines Mindanao, Davao City, Philippines

DAVE LAURENCE Q. DELA CRUZ

UP Strategic Research and Management Foundation, Inc., Davao City, Philippines

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Abstract Eco-entrepreneurship refers to social enterprises formed to address local and global problems such as poverty and climate change. This study examines two developing coffee enterprises based in the municipalities of Kalamansig and Lebak in the province of Sultan Kudarat and employs focus group discussions and SWOT analysis to understand the strategies adopted by coffee farmer associations. A survey was conducted to assess the participants' readiness to engage in community-based entrepreneurial activities. The two producer associations represent less than 5% of the total coffee growers in their Barangays. These farmer associations were formed to access assistance from the government and other donors. Additionally, they aim to consolidate their production to meet the volume and quality specifications of major buyers in the future. Moreover, the members expressed interest in establishing a trading store to consolidate coffee beans from both members and nonmembers. However, they currently lack working capital, as the association is expected to pay cash upon delivery of Green Coffee Beans (GCB). Association members also face several ecological and erratic climatic conditions, such as heavy rains and landslides, which continually affect coffee production. These challenges present significant obstacles to their operations; however, the spirit of cooperation among members signals growth and progress. One of the community activities that the association members participated in was tree planting in forested areas to reduce landslide incidence. Despite entrepreneurial and environmental uncertainties, the association has been exploring consolidated trading by engaging with a cooperative for a possible market arrangement. The association plans to unite and enhance each member's competencies and inspire other farmers to join by implementing meaningful capacity building and entrepreneurial activities. Moreover, the association has joined a network of coffee farmers to collectively address the environmental and economic challenges they face.

Keywords eco-entrepreneurship, poverty, climate change, coffee farming

INTRODUCTION

Ecological or eco-entrepreneurship, which shares similar meanings with environmental, green, or sustainable entrepreneurship, is a relatively emerging subfield of entrepreneurship research (Gast et al., 2017). Eco-entrepreneurship refers to the inclusion of ecological considerations in livelihood

decision-making processes and the application of strategies to address current environmental challenges. This type of entrepreneurship is driven by key actors committed to preserving cultural, ecological, and environmental sustainability while simultaneously identifying pragmatic approaches to generate economic benefits.

Farming communities and their families face the daily challenge of survival, particularly in terms of securing food as a basic necessity. Sultan Kudarat is one of the top coffee-producing provinces in the Philippines. Recent typhoons have caused severe damage to rural farming communities, destroying infrastructure such as roads and bridges, causing the displacement of families, and disrupting their livelihoods. Smallholder communities face a recurring dilemma: how to recover after each typhoon hits. When their crops are destroyed by floodwaters, families regroup to replant their crops and hope to recover their losses. They remain eager and hopeful to receive available support from the government, such as the provision of seedlings, fertilizers, and technical assistance.

Eco-entrepreneurship initiatives have emerged to address local communities' concerns: starting a sustainable livelihood while protecting the environment. These communities engage in the sale of their agricultural produce to reduce wealth inequality.

This study focuses on two smallholder producer associations and how they demonstrate the characteristics of eco-entrepreneurs. Both associations began their entrepreneurial journeys recently during the post-pandemic period. While some members have been engaged in coffee farming for decades, they have only recently initiated a collective effort to market their produce.

OBJECTIVES

This study uses two case studies of entrepreneurial initiatives in coffee-growing communities to address local poverty and climate action issues. It also presents the results of an assessment of the personal entrepreneurial competencies of the officers from the two organizations.

METHODOLOGY

Primary data were collected using various research tools. First, an organizational assessment method was adopted from the Organizational Capacity Assessment (OCA) Tool. The OCA Tool served as the primary reference in developing the guide questions for the Focus Group Discussions (FGD). A series of FGD were conducted with the two producer associations in December 2023. A total of 32 participants, including both officers and members, attended. The participants were divided into three FGD groups: officers, board of directors/working committees, and members. The FGD outputs were further processed using the Strengths, Weaknesses, Opportunities, and Threats (SWOT) Analysis. Additionally, key informant interviews were conducted in March 2024.

Another tool used in this research was a self-assessment survey on personal entrepreneurial competencies (PEC). The text of this survey was translated into the local dialect, and enumerators were hired to interview 28 officers from the two associations. PEC is a framework originally developed by McClelland (1987) to assess 10 entrepreneurial characteristics.

RESULTS AND DISCUSSION

The FGD results were compiled using a thematic analytical framework. The six thematic areas are: (1) governance and leadership, (2) operations and management, (3) human resource development, (4) financial management, (5) business service delivery, and (6) external relations.

Case Study 1: Coffee Farmers Association of Hinalaan (COFAH)

COFAH was registered with the Department of Labor and Employment on February 28, 2023. It currently has 39 members. The main motivation for joining the association is to access government

support services and training, sell to Nestlé, and receive assistance from various stakeholders. Both officers and members express a collective goal for each member to succeed in coffee production. In the short term, the officers aim to establish a physical store for the association; however, a lack of financing hinders this goal. The association capitalizes on its internal network, particularly the influence of two members who are elected as village officials.

Table 1 Thematic analysis of FGD results

Thematic areas	Producer's group 1: COFAH	Producer's group 2: NCGA
Governance and leadership	To strengthen the organization, set up a store for their coffee trading; consultative leadership.	Coffee farming to reduce poverty incidence; Train members in coffee production, increasing their volume of production.
Operations and management	To engage in consolidation and trading of coffee, completing the registration process of the organization.	To engage in consolidation and partner with Bacbacan Cooperative
Human resource development	To undergo training provided by Nestle (or an international agribusiness company); train on how to manage an association	To undergo leadership trainings and team-building, farm management, and soil analysis
Financial management	To maintain a logbook of transactions; prepare an annual budget; and collect contributions of members for working capital	To keep records and report the transactions during the general assembly
Business service delivery	To buy GCBs from both members and non-members; consolidated trading	To sell in bulk quantities to both members and non-members
External relations	Limited connections so far; need to link to partners who can assist the organization.	Need information on what organizations to tap for various services.

Note: Six themes and concerns were compiled from the FGD of the two producer associations.

COFAH is currently involved in the buying, consolidation, and trading of green coffee beans (GCBs). On average, members own relatively large coffee farms, ranging from 2.5 to 7 ha. Each member contributes a certain volume of coffee to fulfill supply commitments to Nestlé, although some members also independently sell to other traders as well.

Case Study 2: Nulling Coffee Growers Association (NCGA)

The NCGA was registered as an association with the Department of Labor and Employment on May 31, 2021. Currently, it has 143 registered members in the group.

The FGD results indicate that all respondents' primary motivation for establishing the association was to gain access to government support services, such as seedlings and fertilizers, which are channeled through registered associations rather than to individual farmers. The officers acknowledged that several members are inactive and do not attend meetings because of their busy schedules related to coffee production and marketing. Since its inception in 2021, the respondents stated that the association had not engaged in any clearly defined business activities. The NCGA is actively seeking assistance from external stakeholders for the acquisition of materials and machinery. Currently, members rely on traders, independent lenders within the community, microfinance institutions, and cooperative banks to access financial services.

Both associations face the challenge of declining membership engagement. Complaints center around a lack of transparency in financial records and the failure of officers to implement clearly defined programs. These issues are particularly evident in the NCGA, which has been slow to transition into consolidated trading among its members. These concerns must be addressed promptly to prevent a decline in activity and possible dormancy of these producer associations.

Personal Entrepreneurial Competencies

This study used the Personal Entrepreneurial Competency (PEC) framework to determine the characteristics of community-based entrepreneurs. McClelland (1987) defined personal entrepreneurial competency as an underlying characteristic of a person that results in effective and superior performance in a business venture. There is a strong link between PECs and entrepreneurial motivation because individuals with strong PECs are more likely to demonstrate a higher level of willingness to start and manage a new business venture. Table 2 presents the ranking of PEC characteristics among the officers of the NCGA and COFAH. Most respondents identified two dominant characteristics; these multiple answers were tallied in the “number of respondents” column. Among NCGA officers, the most cited entrepreneurial trait was information seeking. Officers from this producer organization value the acquisition of new knowledge and technologies related to coffee production, marketing, and the management of their association. They continue to generate resources, such as the forthcoming coffee dehuller from the local government. This shows that, as entrepreneurs, they recognize that continuous participation in training programs and seminars is essential for enhancing their skills and capacities. Through this project, the NCGA established a plant nursery in the village center. Machinery acquisition, training, and nurseries are good value-adding strategies aimed at improving operations (Esnard et al., 2024).

The PEC results for COFAH showed a more balanced distribution across various traits. However, the key entrepreneurial trait among COFAH officers was goal setting, which denotes the importance of identifying clear objectives and purposes for collective action, as follows: One of COFAH’s primary goals is to establish a trading store that would function as a one-stop hub where traders can enter contracts and coordinate the transport of consolidated GCBs to processing units. During the off-harvest season, COFAH officers also plan to diversify into rice trading, which would be accessible to both members and non-members. COFAH also benefited from the extension services of the project with the construction of five units of elevated, all-weather dryers. These infrastructures will be useful in their post-harvest activities to achieve the goal of producing quality coffee beans.

Table 2 Entrepreneurial characteristics of officers of NCGA and COFAH

Rank	NCGA's characteristics	Number of respondents	%	COFAH's Characteristics	Number of respondents	%
1	Information-seeking	11	78.57	Goal setting	5	35.71
2	Self-confidence	3	21.43	Information-seeking	4	28.57
3	Commitment to the work contract	2	14.29	Commitment to the work contract	3	21.43
4	Systematic planning/controlling	2	14.29	Systematic planning/controlling	2	14.29
5	Persistence	1	7.14	Persistence	1	7.14
6	Demand for quality	1	7.14	Demand for quality	1	7.14
7	Goal setting	1	7.14	Self-confidence	1	7.14

Note: NCGA officers identified information-seeking as their top entrepreneurial characteristic.

COFAH officers generally possess goal-setting abilities.

The NCGA PEC scores by gender are shown in Figure 1. Consistent with the findings in Table 2, both males and females exhibited a strong inclination toward information seeking. In addition, male officers demonstrated higher levels of self-confidence, whereas female officers showed stronger competencies in systematic planning and control, higher demand for quality, and a slight advantage in opportunity-seeking.

Figure 2 shows COFAH’s PEC scores disaggregated by gender. Both gender groups displayed goal-setting skills, although male officers tended to exhibit this trait more frequently. In contrast, female officers showed higher scores in self-confidence, persistence, and opportunity-seeking. Male officers exhibited information-seeking behavior, systematic planning, and self-confidence. The correction factor was used to determine whether a person tried to present a very favorable image of himself or herself.

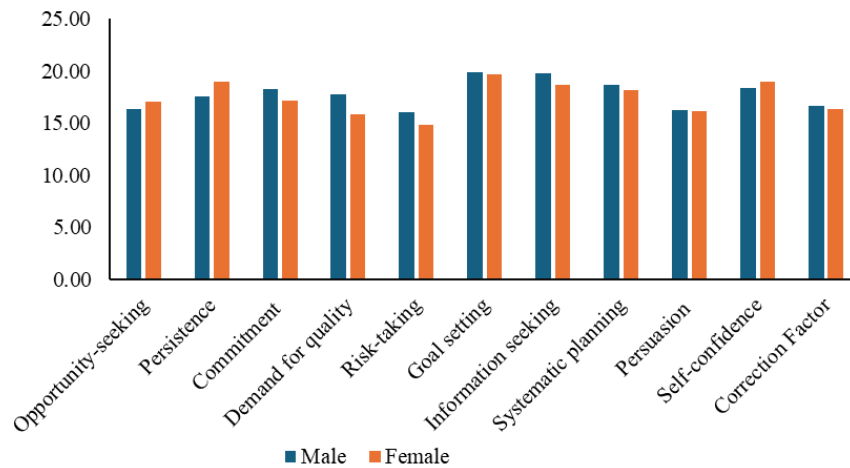


Fig. 1 Personal entrepreneurial competency by gender of NCGA

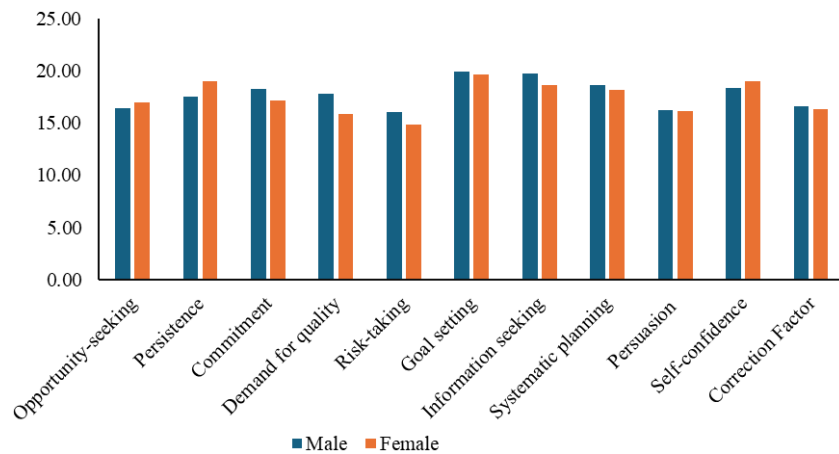


Fig. 2 Personal entrepreneurial competency by gender of COFAH

Environmental Challenges and Opportunities

The Philippines lies within the tropical biome and faces the highest disaster risk levels in the world. It is located in the “cyclone belt” and is one of the most cyclone-prone countries worldwide. Despite these challenges, the Philippines is endowed with favorable climatic conditions and a suitable environment, which are important prerequisites for producing high-quality coffee. The province of Sultan Kudarat has fertile soil and a cool climate that is highly favorable for coffee farming. However, the onset of heavy rain poses a significant threat to farming communities. Intense rainfall disrupts the formation and growth of coffee flowers, whereas flooding increases the risk of landslides that damage farms, erode coffee trees, and destroy critical infrastructure such as bridges, houses, and roads. These environmental threats make farmers feel less motivated to continue with coffee farming. In response to these challenges, members of the coffee associations encourage one another and frequently seek assistance from the Municipal Agriculturist’s Office (MAO), which provides new planting materials to replace damaged coffee trees.

To reduce damage from flooding and landslides, both groups of eco-entrepreneurs adopted the bayanihan method—a traditional Filipino practice of collective community effort. One of these activities is revegetation using native plants with deep roots, as their root systems help stabilize soil strength. They also involve all members in planting coffee and native trees along the slopes to act as natural barriers to reduce the incidence of landslides. During calamities, members help each other repair damaged infrastructure.

Both the NCGA and COFAH have adopted sustainable development practices that align with the preservation of ecological systems and resources. Their environmental efforts reflect a long-term commitment to safeguarding present and future generations. Other studies have documented how entrepreneurs contribute to community development and environmental protection while achieving profitability by utilizing available natural resources. Santiago (2013) highlights the importance of integrating sustainability into business strategies and suggests expanding educational and policy support to foster sustainable entrepreneurship. Social entrepreneurs can drive sustainable development in developing countries by balancing poverty reduction, profitability and environmental sustainability (Aquino et al., 2021; Azmat, 2013; Thiel, 2011). Supporting such entrepreneurs is crucial for fostering innovative approaches to face various challenges, which could generate benefits for people, profits, and the planet.

CONCLUSION

Coffee farming in Sultan Kudarat provides a vital source of livelihood for local communities. The increasing demand for coffee, both locally and in the international market, assures producers that it is a highly valued commodity. Their green coffee beans represent a potential pathway to lift their families out of poverty. Many farmers own relatively large planting areas that they can manage as enterprises, and the yield and quality of their coffee production largely determine their household income.

However, natural calamities continue to disrupt farming activities. The increasing frequency and intensity of typhoons visiting Central Mindanao, coupled with severe rainfall patterns, have destroyed coffee trees, caused landslides on farms, and damaged bridges and public roads. In the aftermath of such events, both farmers and non-farmers adopt the traditional bayanihan system to help rebuild and replant the affected farms.

Eco-entrepreneurs take the lead in addressing these pressing environmental problems. They are committed to preserving the community's ecological systems and resources. They acknowledge that these resources are essential for sustaining life in future generations. Coffee-based eco-entrepreneurship offers a case study of how smallholder farmers can adopt locally driven initiatives to combat poverty, mitigate climate risks, and protect their livelihoods and the environment.

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Development of Erosion Risk Zones in the Skopje Region, Republic of North Macedonia

IVAN MINCHEV*

*Hans Em, Faculty of Forest Sciences, Landscape Architecture and Environmental Engineering,
Ss. Cyril and Methodius University in Skopje, Republic of North Macedonia
Email: i_mincev@sf.ukim.edu.mk*

IVAN BLINKOV

*Hans Em, Faculty of Forest Sciences, Landscape Architecture and Environmental Engineering,
Ss. Cyril and Methodius University in Skopje, Republic of North Macedonia*

BOZHIN TREDAFILOV

*Hans Em, Faculty of Forest Sciences, Landscape Architecture and Environmental Engineering,
Ss. Cyril and Methodius University in Skopje, Republic of North Macedonia*

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(*Corresponding Author)

Abstract The project “Erosion Study and Action Plan for the City of Skopje” was initiated by the administration of the City of Skopje, as well as the expert community, after a catastrophic flood event occurred in August 2016 in the Skopje region, resulting in the loss of 22 lives and causing immense damage and losses. According to Article 135 of the Law on Water: “On the basis of technical documentation, the state administrative body competent for environment, the council of the municipalities of the City of Skopje and the water management enterprises for their respective areas, shall determine the boundaries of both the erosive area and the area endangered from erosion, and specify the measures and the activities pertaining to the protection of land from erosion and regulation of torrents.” Based on this legal framework, a methodology was developed to define the actual and potential erosive areas. The starting point was the creation of an erosion map using the Erosion Potential Method, in which all identified erosive areas were considered and analyzed. To define the erosion risk, the erosion map was overlaid with critical infrastructure, inhabited areas, and main transport infrastructure. In the Skopje region, 5,874 ha of actual erosion risk areas and 36,332 ha of potential erosion risk areas were delineated as part of the Action Plan. The Action Plan proposed administrative measures and technical work, including prohibited and obligatory activities specific to actual and potential erosive areas.

Keywords soil erosion, erosion risk, erosive area, areas affected by erosion

INTRODUCTION

Soil erosion has occurred throughout geological time. However, inappropriate human activities can significantly accelerate these processes. Soil erosion by water is a widespread problem throughout Europe, with the southern and southeastern regions being particularly prone to water erosion. In some areas, erosion has reached an irreversible stage, whereas in others, it has practically ceased owing to the complete loss of soil. Almost 7.7% of the total annual soil losses in Europe originate from the Western Balkan countries (Albania, North Macedonia, Serbia, Montenegro, Bosnia and Herzegovina, and Kosovo), and the average erosion intensity in the region is 2.42 times higher than the European average. Soil erosion is widespread across the Balkan Peninsula and represents one of the most significant environmental challenges (Blinkov et al., 2022).

The project “Erosion Study and Action Plan for the City of Skopje” was initiated by the administration of the City of Skopje and the expert community after a catastrophic disaster occurred in August 2016 in the Skopje region, resulting in the loss of 22 lives and causing immense damage to the city. According to Article 135 of the Law on Water, “On the basis of technical documentation,

the state administrative body competent for environment, the council of the municipalities, of the City of Skopje and the water management enterprises for their respective areas, shall determine the boundaries of both the erosive area and the area endangered from erosion, and specify the measures and the activities pertaining to the protection of land from erosion and regulation of torrent.”. Based on this legal provision, a methodology was developed to define the actual and potential erosive areas.

In this context, Actual erosion risk area (Erosive area) refers to land already affected by active erosion processes, where the surface soil layer is degraded and may lead to significant social, economic, environmental, and other impacts. Potential erosion risk area (Area endangered by erosion) is land where visible signs of erosion are not yet present, but which is susceptible to erosion due to improper land use, agricultural practices, or forestry activities. In such areas, intense erosion processes can be initiated, leading to serious social, economic, environmental, and other consequences.

OBJECTIVE

Since the Law on Water, under the section “Harmful Effects of Water,” prescribes, in general terms, the delineation of actual and potential erosion risk areas, the specific procedure and methodology for developing these zones was not defined. Therefore, this study describes the steps taken to develop erosion risk zones. The main objective of this study was to develop a methodology for erosion risk zoning in the Skopje region.

METHODOLOGY

The study area is situated in the Skopje region, Republic of North Macedonia. Skopje is the capital of the country, and a significant portion of the national economy is concentrated there. Almost half of the population is present in the city on either a permanent or impermanent basis. According to the latest census in 2021, Skopje has a population of 526,505 permanent residents. Most of the country’s critical infrastructure is located in the capital.



Source of map of Europe: <https://www.worldatlas.com/geography/how-many-countries-are-in-europe.html>

Fig. 1 Location of the Skopje region within the Republic of North Macedonia and in the broader context of Europe

The Skopje region is characterized by a diverse and complex relief, primarily forming a large basin shape with a high peripheral zone and a low central area. The high peripheral parts of the valley are formed by the surrounding mountains: Skopska Crna Gora (north), Zeden mountain (west), Vodno mountain (central part 1,066m above sea level - a.s.l.), and the Jakupica mountain massif to the south (2,540 m.a.s.l.). The Skopje Valley lies at an average altitude of 220-340 meters a.s.l., oriented in a northwest-southeast direction, and covers a surface area of 361 km².

The Skopje valley is a very dry area, receiving an average annual rainfall of around 500 mm, with a highly uneven distribution. Recent climatic changes have led to several extreme rainfall events

during the spring-summer period, increasing the risk and vulnerability to rain-related natural hazards. Most of the lower-altitude areas exhibit semi-arid characteristics, while in the higher southern altitudes, annual rainfall exceeds 1000mm. The annual temperatures range from 1°C to 14°C (Aksoy et. al., 2020).

The soil properties of the study area are diverse. The valley is dominated by fluvisols (12% of the total area). Other soil types present in the hilly and mountainous areas include rendzic leptosols (14.5%), complex of cambisol, humic eutric, and umbric regosol (16.5%), complex of vertisol, chromic luvisol on saprolite, regosol (7%), and cambisol (7%) (Filipovski, 2017).

The geological structure is also diverse and includes marl clay, sand and gravel (13%), alluvium (12.8%), marble, muscovite double mica gneiss (10.4%), muscovite gneiss (9.6%), quartz-sericite and biotite schists (8.2%), conglomerate, sand, marl, and claystone (8.1%), conglomerate, sand, claystone and massive limestone (7.7%) and marble (7.3%) (Dumurdzanov et al., 2004; Stafilov et al. 2019). Regarding land cover, nearly half of the study area is covered with forest and forest land (49.3%), 33% is arable land, 6% grasslands, and 6% is artificial land (EEA, Corine land cover 2018). The methodology for the development of erosion risk zones in the Skopje region consisted of several steps.

Development of Soil Erosion Map

There are many methodologies used for soil erosion estimation. Blinkov and Kostadinov (2010) provide a review of the applicability of various models for different usage scenarios, including EUROSEM, USLE, PESERA, KINEROS, WEP, WEPP and EPM.

The Erosion Potential Method (EPM) was developed in the Balkan region, south Serbia, which has climatic conditions very similar to those in North Macedonia. Therefore, the model was well-adapted to the study area. Moreover, the EPM can predict sediment transport and deposition because it was calibrated using measurements of deposited sediments in existing reservoirs.

$$Z = \gamma \cdot Xa \cdot (\varphi + \sqrt{I_{sr}}) \quad (1)$$

Where Z is the coefficient of erosion by Gavrilovic (dimensionless), γ the reciprocal value of soils/rocks resistance on erosion processes, Xa the protection of the basin under natural conditions and after erosion control, φ the coefficient of visible processes of erosion and I_{sr} the mean slope of the basin.

The EPM (developed by Gavrilovic) was originally designed to be used with hardcopy maps, and the mapping process itself was carried out on a basin level. With the advent of GIS tools and the availability of a wide range of geographic data (Corine LC/LU, soil maps, geology maps, elevation data-DEM, etc.), the mapping process has evolved and can now be conducted on much smaller mapping units.

Although these datasets are often of good quality, the production scale should be carefully considered, and the data may need to be reclassified according to the classes defined in the methodology section. The use of a global dataset is recommended due to their transferability and the comparability of the results across regions (Minchev, 2015).

The input parameters used for the EPM were as follows: national soil map (scale 1:50,000); land cover: Corine LC/LU 2018 (developed by the European Environmental Agency, scale 1:100,000), later improved using visual photo-interpretation of aerial imagery with a spatial resolution of 0.3 m (2009) and Google Earth imagery; and DEM spatial resolution of 5 m.

After preparing the input parameters in the office, the study team conducted several field visits to assess the visible erosive processes (φ). Field observations were used to refine the existing data, after which the final erosion map was produced.

The methodology has been validated several times in many research publications, where sediment transport was validated with water reservoir sedimentation (Minchev, 2015; Minchev et al., 2023).

Defining Erosion Hot Spots

General erosion hotspots were defined using the erosion map. Only locations with the most severe erosion processes, the II and III erosion categories, were considered. These erosion hotspots express the on-site effects of erosion. However, to account for the off-site effects of erosion, the identified hotspots overlapped with the river network and land cover data, including critical infrastructure. The sediment produced from these hotspots, through the stream network, is transported downstream and can reach the main riverbed and impact settlements, road and railway networks, agricultural land, or reservoirs. Depending on the type of land cover impacted, the risk was classified into risk severity categories. The highest risk is assigned to critical infrastructure (hospitals, government institutions, schools, and embassies). Next in line were the inhabited areas, which were classified according to the number of inhabitants impacted. The third severity risk is the transport infrastructure, which was classified depending on the road category (highway highest – local road lowest). The lowest risk ranking was assigned to agricultural land.

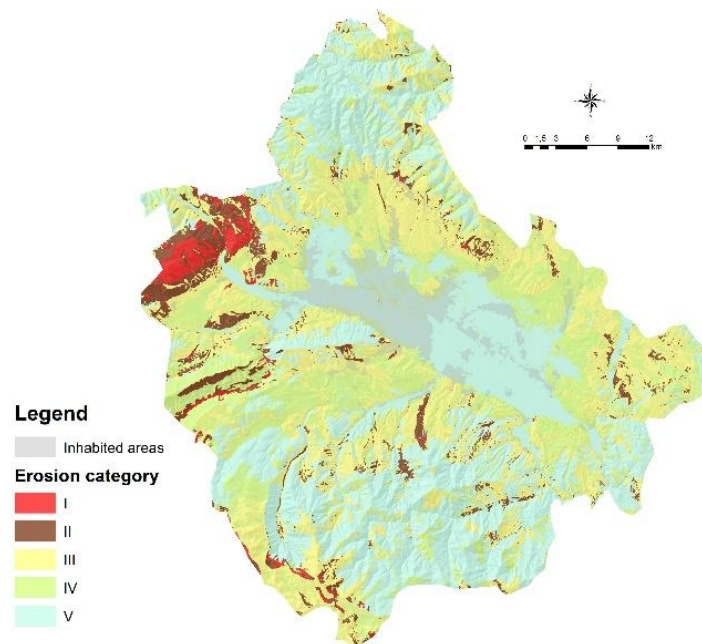


Fig. 2 Erosion map of the Skopje region

Development of actual and erosion risk areas: In order to define the actual erosion risk areas, the classified land cover risk areas overlapped with the highest erosion categories. Finally the resulting polygons were simplified into meaningful erosion risk areas, discarding the remnant polygons which were under the area threshold.

Defining erosion hot spots: General erosion hotspots were identified from the erosion map. Only locations with the most severe erosion processes (categories I, II, and III) were considered. These erosion hotspots represent the on-site effects of erosion.

To consider the off-site effects of erosion, the identified hotspots were overlaid with the river network and land cover data, including critical infrastructure. Sediment produced in these hotspots is transported downstream via the stream network, potentially reaching the main riverbed and impacting settlements, road and railway networks, agricultural land, and reservoirs.

Depending on the type of land cover impacted, the erosion risk was classified into risk-severity categories. The highest risk was assigned to critical infrastructure (e.g., hospitals, government institutions, schools, and embassies). The next level of risk included inhabited areas, which were further classified based on the number of inhabitants impacted.

The third risk level was assigned to transport infrastructure and classified according to the road category (with highways representing the highest risk and local roads the lowest). The lowest risk rank was assigned to agricultural land.

Development of actual and erosion risk areas: To define the actual erosion risk areas, the classified land cover risk areas were overlaid with the highest erosion risk categories. Finally, the resulting polygons were simplified into meaningful erosion risk areas by discarding remnant polygons that fell below the area threshold.

Development of potential erosion risk areas: Potential erosion risk areas were delineated using what-if scenarios. These areas are defined as future risk zones in the event of significant disturbances or where erosion-related disasters have been recorded in the past. One example is Vodno Mountain, located to the south of the most densely populated part of Skopje. Prior to the 1950s, Vodno Mountain was completely barren and lacked tree cover. After every rainfall, the base of the mountain is regularly flooded by torrential streams. In 1951, a fatality was recorded due to such an event. In the early 1950s, large-scale afforestation efforts were undertaken. Currently, the inhabited areas at the foot of the mountain are of high economic value, and the slopes of Vodno Mountain are under intense urbanization pressure. For this reason, Vodno Mountain was designated as a potential erosion risk area to safeguard the existing “protective forest.”

RESULTS AND DISCUSSION

The figure below shows the delineated actual and potential erosion risk areas in the Skopje region, North Macedonia. It can be observed that most of these risky areas are located in close proximity to inhabited areas.

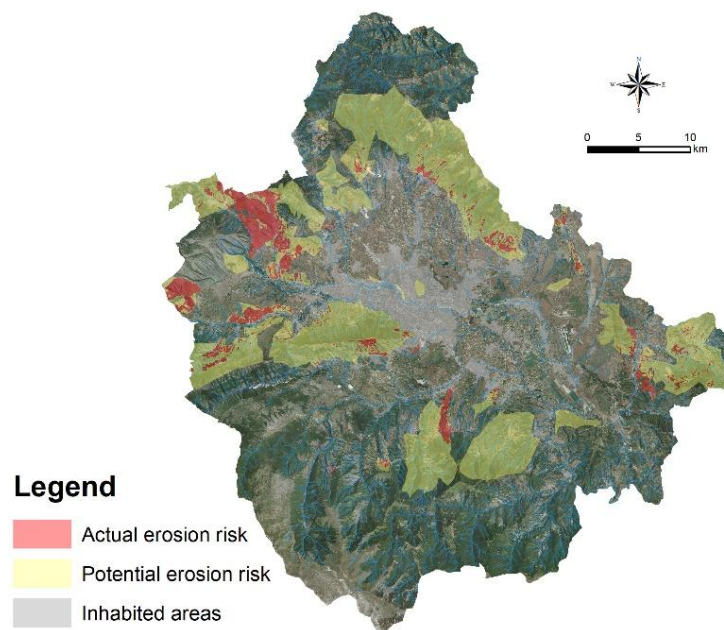


Fig. 1 Actual and potential erosion risk area in the Skopje region

The final step was to prescribe activities that would not exacerbate erosive processes in the identified erosion risk areas. These activities were categorized by the main land-use sectors that influence erosion processes.

The first priority is to implement measures that address the enabling environment, including institutional roles and management instruments, which will form the foundation for and serve as preparatory steps toward more technical measures. In parallel, as the legal and regulatory framework is established and organizational structures and institutional capacities are developed, technical measures will be implemented in a structured “learning-by-doing” approach.

Technical measures for erosion and torrent control were organized into the following areas: Protection from erosion on agricultural land; Protection from erosion in forest and semi-natural areas; Protection from erosion in small streams; Protection from erosion on artificial land; Reduction of

hazard severity; Increase of torrent bed conveyance capacity; Reduction of sediment transport, and Reduction of exposure to risk. Depending on the erosion risk level and expected type of erosion, a set of administrative measures was proposed to mitigate erosion. Experience shows that the best results are achieved through the following sector-specific administrative measures.

Agriculture: Prohibition of plowing on steep terrain (in accordance with the Law on Agricultural land); Prohibition on plowing perpendicular to the slope; Prohibition of grazing on degraded pastures; Obligation to practice contour plowing; Obligation to convert degraded arable land into meadows or forests; Obligation to rehabilitate degraded pastures; Obligation to convert perennials into vineyards or orchards.

Forestry: Prohibition of clear-cutting; Prohibition of grazing in forest; Ban on collecting foliage for fodder; Obligation to afforest barren lands; Obligation to designate protective forests and implement appropriate silvicultural measures; Obligation to practice sustainable forest management, with erosion controls as guiding principle.

Urbanism, construction, mining: Prohibition of urbanization in erosion-prone areas; Obligation to implement urban green infrastructure; Obligation to develop urban green areas in accordance with erosion control principles; Obligation to conduct sustainable planning and responsible execution of mining and metallurgical activities, with mandatory preparation and adherence to the "Plan for protection from erosion and sediment deposition on mining and metallurgical surfaces".

In the Skopje region, 5,874 ha of actual erosion risk areas and 36,332 ha of potential erosion risk areas were delineated. Within the Action Plan, both administrative measures and technical interventions—including prohibited and obligatory activities—were proposed separately for the actual and potential erosion areas.

CONCLUSION

The main motive for preparing this paper was to develop a methodology for erosion risk zoning. The resulting map of actual and potential erosion risks provides an outline of the erosion-prone areas. If municipalities want to implement these zones for operational purposes, they should be further defined at the cadastral level and officially proclaimed through a municipal rulebook.

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Impact of Transplanting Date Shifts on Rice Production in Rain-fed Northeast Thailand

HIROKI ODA*

Graduate School of Frontier Science, The University of Tokyo, Chiba, Japan
Email: 2215920513@edu.k.u-tokyo.ac.jp

MALLIKA SRISUTHAM

Khon Kaen University, Khon Kaen, Thailand

SUPRANEE SRITUMBOON

Land Development Department Regional Office 5 Khon Kaen, Khon Kaen, Thailand

KOSHI YOSHIDA

Graduate School of Frontier Science, The University of Tokyo, Chiba, Japan

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Abstract Northeast Thailand, home to 60% of the nation's rice paddies, is a crucial rice-producing area. Over 90% of its fields are rain-fed, making them highly vulnerable to climate variability. Therefore, studying the impact of climate change on rice cultivation and proposing adaptation strategies is essential. One such strategy is shifting the transplanting date (TPD), which can help avoid extreme summer temperatures and increase water availability. Many studies have shown that shifting the TPD can improve rice yields, but in rain-fed systems, the harvest area is equally vital because of water limitations. Thus, this study examined the differences in the effects of TPD adjustments when evaluated using unit yield versus total rice production. A model was developed to estimate both crop growth and harvest area, with TPD determined by the condition that free water levels remained above a threshold for three consecutive weeks. The threshold was set at 12.9 mm based on a previous study. The model was calibrated using data from 2007 to 2016 and validated using data from 1997 to 2006. The model accuracy during both periods, evaluated using RMSE, demonstrated good agreement with the observed data for all provinces except Loei. To identify the optimal TPD for maximizing unit yield and total production, the threshold was adjusted in 5 mm increments, ranging from 12.8mm to 32.8mm. In 1991, the results showed that 10 out of 16 provinces had different optimal TPDs depending on whether the objective was to maximize unit yield or total production. Specifically, in seven provinces, the optimal TPD for total production occurred later than that for unit yield, likely due to heterogeneous rainfall patterns. These findings suggest that climate change adaptation strategies should prioritize total rice production over unit yield when assessing their impacts.

Keywords climate change adaptation, rain-fed rice cultivation, production model

INTRODUCTION

The global hunger assessment for 2023, measured by the prevalence of undernourishment (PoU), indicates a lack of progress toward achieving Zero Hunger. Hunger rates surged from 2019 to 2021 and have since stagnated, with a global PoU of 9.1% in 2023 (FAO et al., 2024). Rice, which contributes 23% of cereal-derived calories in Low-Income Food-Deficit Countries (FAO, 2022), plays an important role in global food security.

Within Thailand, where rice cultivation is widespread, Northeast Thailand stands out as it is home to 60% of the nation's paddies. However, over 90% of these fields are rain-fed, making them highly vulnerable to climatic variability. Limited water availability causes significant fluctuations in transplanting dates and planted areas. Sawano et al. (2008) reported over a month's variation in

transplanting dates and substantial area reductions in drought years (e.g., a 20% reduction of planted area in 2005 compared to 2004). Given that precipitation patterns are expected to become more extreme due to climate change, studying its impacts on rice cultivation and proposing adaptation strategies is essential.

Optimizing transplanting dates (TPD) offers a cost-effective adaptation strategy by avoiding high temperatures and enhancing water availability. Abbadi et al. (2015) found that increased precipitation in May shifted the optimal TPD from June to May. Sujariya et al. (2020) identified late May to early June as ideal for maximizing yields. Using CERES-Rice, Babel et al. (2011) projected a 10% yield increase by shifting TPD 30 days earlier, and 34% or 23% increases by delaying it 20 days under future scenarios. Boonwichai et al. (2019) suggested that advancing TPD by a week under RCP4.5 was effective, and the study implied that differences in findings arise from model assumptions and climate scenarios.

While these studies have proposed an optimal TPD, two factors must be refined for effective TPD optimization. First, rice in Northeast Thailand is photoperiod-sensitive, with heading triggered as the day length shortens. Late-season TPDs conflict with this trait, limiting their feasibility despite increased late-season water. Studies proposing delayed TPD often overlook these factors. Second, few studies have considered fluctuations in planted areas. Prior research focused on yield per unit area (ton/ha), but addressing hunger requires maximizing total production (tons), a product of yield and planted area. Optimal TPD must prioritize total production to enhance food security.

OBJECTIVE

The objective of this study was to develop a production estimation model for rain-fed rice that accounts for fluctuations in the planted area and to verify whether the optimal TPD based on yield differs from that based on total production.

METHODOLOGY

As of 2024, the study area in northeastern Thailand consisted of 20 provinces. However, the provinces of Nong Bua Lamphu, Bung Kan, and Amnat Charoen were excluded from the analysis during the calculation period (1997-2016), due to changes in their administrative status, which could affect data consistency and availability.

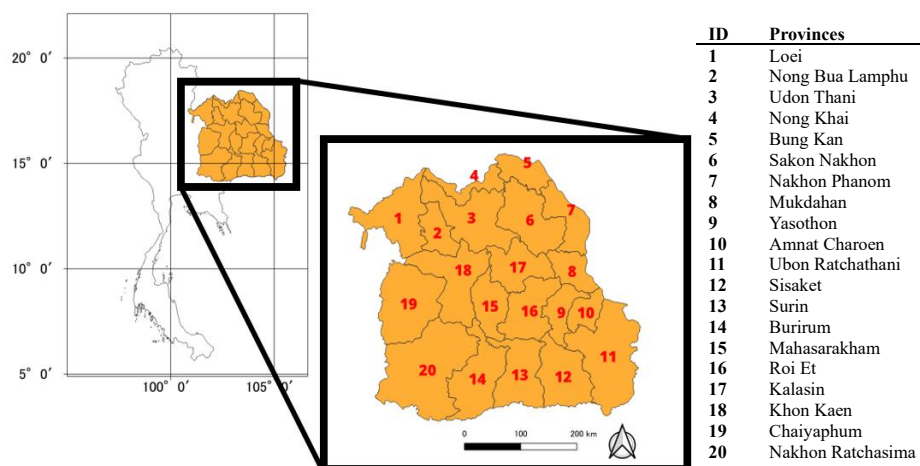


Fig. 1 Study area and provincial boundaries

This study developed a production estimation model for rain-fed rice, consisting of three sub-models: 1) planted area, 2) harvest rate, and 3) yield.

The planted area sub-model estimates the areas where rice is planted using a one-dimensional water-balance model. Each 1 km² paddy pixel retrieved from the 2015 land use map of the Land Development Department Thailand was treated as a single bucket, with changes in the free water level calculated as follows:

$$H_i = H_{i-1} + R_i - (ET_i + P_i) \quad (1)$$

Where, H is free water level in a paddy pixel [mm], R is precipitation, retrieved from Thai Meteorological Department [mm], ET is evapotranspiration [mm], P is percolation [mm] and i is the time step [day].

The transplanting date (TPD) was defined according to Inthavong et al. (2011), when H in equation (1) exceeded 12.8 mm for three consecutive weeks. The planted area was determined as the number of planted pixels within the planting season (1st July–31st August, Sawano et al., 2008).

The harvest rate sub-model estimates the ratio of the harvested area to the planted area. The harvest rate was calculated using the equation from FAO (1979).

$$Hr_i = \frac{\sum ETa_i + a}{\sum ETp_i + a} \quad (2)$$

Where, Hr is harvest rate [-], ETa is actual evapotranspiration [mm], ETp is potential evapotranspiration [mm], a is initial water depth [mm], and i is the time step [day].

The yield sub-model estimates rice yield using the approach of Monteith (1977), taking into account photoperiod sensitivity (Hasegawa et al., 2008). Crop phenology was modeled using the Heat Unit Index (HUI):

$$HUI_i = \frac{\sum (T_i - T_b) * PE_i}{PHU} \quad (3)$$

$$PE_i = 1 - \exp(\min(DL_i - DL_c), 0) \quad (4)$$

Where, HUI is a Heat Unit Index [-], T is daily mean temperature, retrieved from National Oceanic and Atmospheric Administration [°C], T_b is the crop-specific base temperature, below which no growth occurs [°C], PHU is the Potential Heat Units required for crop maturity [°C], PE is the photoperiod effect, ranging from 0 to 1 [-], DL is the day length [hour], and DL_c is the critical day length above which no growth occurs [hour]. In this study, the calculation of the HUI began when a pixel was planted, and the pixel was considered harvested when the HUI exceeded 1. From the TPD to harvest date, yield is calculated using the following equations.

$$Yield = HI * Bm \quad (5)$$

$$Bm = \sum \Delta B_i \quad (6)$$

$$\Delta B_i = BE * PAR_i * \min(TS_i, WS_i) \quad (7)$$

Where Yield [g m⁻²] is the economic yield, HI is the harvest index [-], Bm is the total biomass [g m⁻²], ΔB is the biomass increment [g m⁻²], BE is the radiation-to-biomass conversion coefficient [g MJ⁻¹], PAR is the intercepted solar radiation [MJ m⁻²], TS is the temperature stress [-], and WS is the water stress [-].

The model was calibrated using statistical production data from 2007 to 2016 retrieved from the OAE and validated using data from 1997 to 2006.

RESULTS AND DISCUSSION

For model validation, statistical data on provincial wet-season rice production published by the Office of Agricultural Economics, Thailand (OAE) were used to evaluate the accuracy using RMSE. Because a 1 km² pixel is unlikely to be fully covered by paddy fields, the estimated planted area used for production estimation was adjusted using the ratio of the statistical paddy field area in 2015, retrieved from the OAE, to the area derived from the land use map, referred to as the paddy ratio.

Table 1 shows the RMSE of the estimated production and yield in each province during the validation period. The units are ton and ton ha⁻¹ for production and yield, respectively, and the

numbers in parentheses indicate values expressed as percentages. Figure 3 shows the changes in production and yield in Loei, which had a maximum RMSE of more than 30% for both production and yield. Loei is located in a mountainous area with high forest cover (approximately 57%) and fragmented paddy fields, which pose challenges for accurate land classification at a 1 km resolution. In such regions, contiguous paddy areas are often underrepresented on land use maps, resulting in an underestimation of the actual paddy field extent per pixel. Consequently, Loei was the only province where the paddy ratio exceeded one. This likely led to an overestimation of the planted area, which in turn caused an overestimation of the production. Additionally, Loei has a high forest cover of 57%, and because the model does not account for the fertility of soil and groundwater supply provided by forests, it is believed that this resulted in an underestimation of yield. Therefore, the analysis was conducted without Loei. To improve the model accuracy for that area, considering groundwater movement and soil fertility maps would be beneficial.

Table 1 RMSE of estimated production and yield in each province during validation period

Province	RMSE of production (%)	RMSE of yield (%)
Nong Khai	40358 (13.7)	0.20 (10.5)
Loei	57931 (35.8)	0.79 (31.1)
Sakon Nakhon	151268 (31.2)	0.20 (10.6)
Udon Thani	176588 (22.2)	0.17 (9.1)
Nakhon Phanom	44320 (16.9)	0.17 (9.1)
Kalasin	66340 (17.1)	0.36 (16.9)
Khon Kaen	144751 (23.1)	0.37 (19.1)
Mukdahan	15815 (14.6)	0.26 (13.8)
Chaiyaphum	102532 (30.7)	0.25 (12.9)
Maha Sarakham	116042 (22.2)	0.42 (20.5)
Roi Et	109276 (14.0)	0.36 (18.1)
Yasothon	71734 (24.5)	0.19 (10.2)
Ubon Ratchathani	99171 (8.7)	0.16 (9.2)
Nakhon Ratchasima	251218 (28.6)	0.28 (15.3)
Buri Ram	99122 (11.8)	0.29 (14.8)
Si Sa Ket	150082 (21.0)	0.32 (15.5)
Surin	137792 (15.9)	0.38 (18.8)
Average	525550 (20.2)	0.29 (14.6)

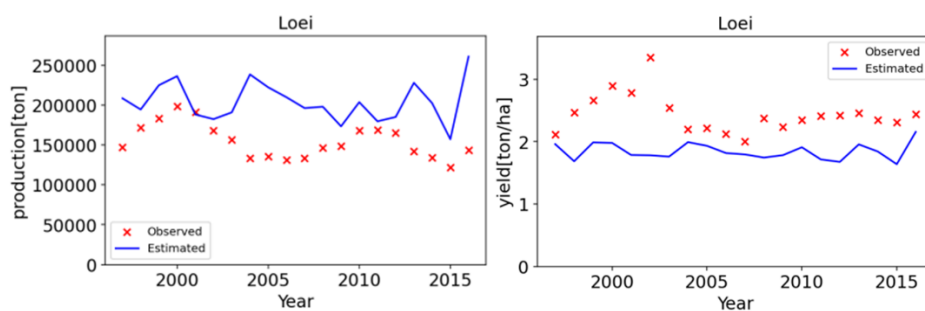


Fig. 3 Changes in production and yield in Loei (left: production, right: yield)

Figure 4 compares provincial production and yield under various planting thresholds in 1991. In this study, the planting threshold is defined as the free water level [mm] that H in equation (1) must exceed for consecutive 3 weeks. This threshold was incrementally increased by 5 mm up to 32.8 mm from a baseline of 12.8. In 1991, most provinces exhibited different optimal transplanting dates (TPD) when assessed based on yield versus production during the calculation period. Three provinces were excluded because they were not established by 1991. Among the 16 remaining provinces, 10 Bung Kan, Udon Thani, Chaiyaphum, Roi Et, Yasothon, Amnat Charoen, Ubon Ratchathani, Nakhon Ratchasima, Buri Ram, and Si Sa Ket showed different optimal TPDs for yield

and production. These findings highlight that the optimal TPD for yield does not necessarily maximize production. Furthermore, Udon Thani, Roi Et, Yasothon, Ubon Ratchathani, Nakhon Ratchasima, Buri Ram, and Si Sa Ket (Group A) indicated later TPD for maximizing production compared to yield. These results suggest that transplanting date recommendations based solely on yield optimization, as proposed in previous studies by Abbadi et al. (2015) and Sujariya et al. (2020), may not be suitable when the goal is to maximize total production. Since production depends not only on yield but also on planted area, models that incorporate planting area estimation such as the one used in this study are essential for identifying transplanting date that better reflect the actual conditions and decision-making processes faced by farmers.

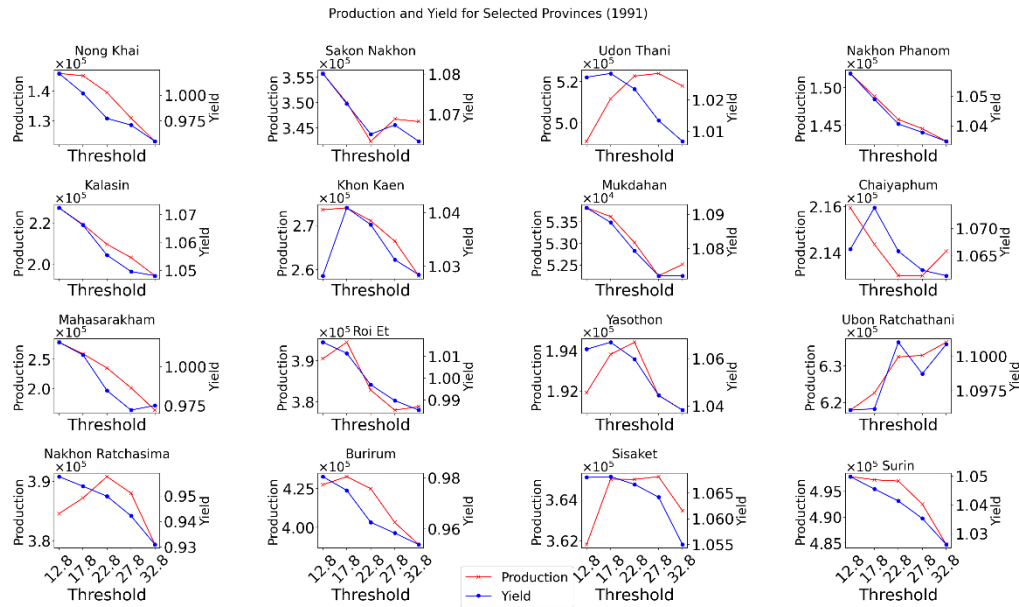


Fig. 4 Provincial yield and production for each planting threshold in 1991

Figure 5 shows the daily average rainfall of Group A and other provinces during the simulation period, from 1st May to 31st October 1991. The arrows in the figure indicate the cumulative rainfall from May 1 to July 31 (first half of the simulation period) and from August 1 to October 31 (second half of the simulation period). In 1991, provinces in Group A experienced 36 mm less rainfall in the first half of the rainy season and 95 mm more rainfall in the second half compared to other provinces. Typically, a higher yield leads to higher production; therefore, the optimal transplanting date (TPD) for yield was obtained in a previous study. However, in rainfall patterns like that observed for Group A in 1991, accepting a shorter growing period and reduced yield to avoid a decrease in the harvest area ratio caused by water deficits could lead to higher total production. In the future, research aimed at optimizing farmers' crop calendars will be needed through analyses that quantitatively demonstrate rainfall patterns in which the production-based optimal TPD is later than the yield-based optimal TPD for such reasons.

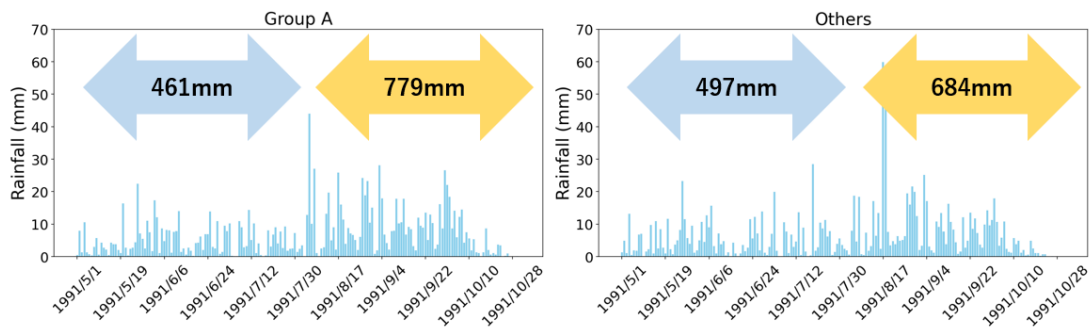


Fig. 5 Daily average rainfall of Group A and other provinces in 1991

CONCLUSION

This study developed a production estimation model for rain-fed rice, accounting for fluctuations in the planted area and yield. These findings highlight that the optimal TPD for maximizing production often differs from that for maximizing yield, emphasizing the importance of prioritizing total production over unit yield in climate change adaptation strategies. The model integrates rainfall patterns, water availability, and planting area dynamics, offering a framework to understand their impact on rice production and optimize crop calendars to mitigate water deficits sustainably.

Model validation using statistical data confirmed its ability to estimate production and yield in northeastern Thailand. However, the accuracy was lower in Loei, with the highest RMSE for both metrics. This is likely due to Loei's mountainous terrain, fragmented paddy fields, and high forest cover (57%), which the model did not account for, leading to an overestimation of the planted area and production and an underestimation of the yield. Loei was excluded from the analyses to ensure consistency. In addition, recent climate variability, including the increased frequency of floods and droughts, may influence model accuracy. While drought-related damage can be represented in the model through decreases in the water stress index (WSi) and harvest rate (Hri), the impact of flooding is not incorporated. Therefore, if flood events have become more frequent since 2016, the model's accuracy may have declined in more recent years. Moreover, the model defined paddy fields based on the 2015 land use map. Although significant changes in the paddy area could reduce estimation accuracy, statistical data from the Office of Agricultural Economics indicate that the planted area in Northeast Thailand has fluctuated within $\pm 5\%$ between 2015 and 2024. This suggests that the impact of land-use change on model performance remains limited.

In 1991, the largest number of provinces exhibited differences between the optimal TPDs based on production and those based on the unit yield. This discrepancy was mainly due to the different rainfall patterns. Provinces with lower rainfall during May–July and higher rainfall during August–October tended to adopt TPDs later. Although delaying TPD shortens the growing period due to photoperiod sensitivity, leading to reduced unit yields, it mitigates water deficits, prevents reductions in harvest area, and maximizes total production. These findings indicate that the optimal TPD based on production often differs from that based on the yield. This implies that the optimal transplanting date proposed by previous studies based on yield may differ from that based on production. Furthermore, if future advancements allow for approximate predictions of rainfall patterns within the growing period, it may become possible to propose TPDs that depend on regional rainfall patterns, thereby maximizing the production.

ACKNOWLEDGEMENTS

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Water Quality Characteristics of the S River – Effect of Livestock Grazing, Hokkaido, Japan

YURI YAMAZAKI*

Faculty of Agriculture, Tottori University, Japan

Email: y.yamazaki@tottori-u.ac.jp

TOSHIMI MUNEOKA

Obihiro University of Agriculture and Veterinary Medicine, Hokkaido, Japan

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Abstract Forest grazing, which uses grassland and woodlands for livestock grazing, is generally considered an environmentally friendly method of livestock management. However, its implementation is rare, and the full extent of its environmental impact is poorly defined. Here, we examined the effect of forest grazing on the current state of river water quality. The study site was the S River, which flows through K Farm, located in eastern Hokkaido, Japan. The K Farm offers forest grazing for its beef cattle. River water was collected at nine points on the main S river and at five tributaries that join the main river near the pastureland and upstream of the dam. The mean ion concentration of river water was 8.1–16.4 mg/L for cations and 6.5–11.5 mg/L for anions. The concentrations were relatively low at all the sampling points. The average total nitrogen (T-N) concentration ranged from 0.18 to 0.75 mg/L, which is below the environmental standard of 1.0 mg/L. In the tributaries, the nitrate nitrogen (NO₃-N) ratio was approximately 45%, which was greater than the main river value of 30%. Regarding the relationship between the first and second principal components of the PCA results, the plot trends differed between the main river upstream and downstream and between the tributaries. The overall ion concentration in the main river upstream was low. In contrast, the five tributaries showed a different trend from the main river; in particular, the overall water quality concentration of tributary T2 was high, and K⁺, PO₄²⁻, and T-N were high. It is necessary to conduct long-term observations of seasonal and temporal fluctuations in the tributaries flowing through grazing areas to investigate the effects of grazing.

Keywords forest grazing, livestock management, T-N concentration, PCA

INTRODUCTION

Grazing livestock farming is attracting international attention as an environmentally friendly method of food production that may help solve future food problems associated with population growth and climate change. However, several studies have reported the recognition of the evolving emphasis on improving management methods that have less adverse impact on the environment (Agouridis et al., 2005; Hubbard et al., 2004). For example, Chaubey et al. (2010) used a water quality assessment model to simulate the effects of different grazing management methods on water quality in the United States. They showed that nitrogen and phosphorus runoff increased with grazing density. They also showed that nitrogen and phosphorus runoff varies with changes in weather conditions.

In Japan, there are few examples of grazing livestock farming. The environmental impact of livestock grazing has not been thoroughly investigated. Our study, which analyzed the quality of river water at K Farm, aims to shed light on the impact of beef cattle grazing livestock farming on river water quality. This study reports on the few water quality survey results available for grazing lands, which is an issue that has been highlighted internationally. (Agouridis et al., 2005). This study provides important basic information for considering grazing management methods for water quality conservation in Japan.

METHODOLOGY

Study Sites

The research site was the S River, which flows through K Farm in eastern Hokkaido. K Farm is a 100-hectare (ha) ranch where beef cattle are grazed year-round in the pastures and forests. The farm raises Aberdeen Angus cattle, and as of 2019, it had a stock of approximately 80 head. The pasture is open from April to November, and grass harvested from the K Farm's meadows is fed from December to March, as snow cover prevents grass from being foraged on the pasture. During the survey period of this study (May to October 2019), the precipitation and average temperature at the weather station closest to the grazing area were 851 mm and 11.6 to 20.2°C, respectively.

The S River, a class B river in Japan, has a channel length of 19.0 km and a catchment area of 2,029 km². We surveyed nine sites from the upper to lower reaches of the S River and five tributaries that flow into the S River. A flood control dam is located in the downstream area of the pasture, and the S River flows through the pasture and into the flood control dam before continuing downstream to the residential area and emptying into the Pacific Ocean. Fig.1 shows the locations of the sampling points. M1, the point on the main river, is located upstream of the pasture. M2 and M3 were sampling points within the pasture, and M4 was located downstream of the pasture. Five water sampling points (M5–M9) were established on the main river downstream of the dam. Of the five tributaries, T1 to T4 are tributaries that flow through the pastureland and into the main river. T1 flows through the uppermost part of the pastureland, and T2 flows through the pastureland on the north side, where beef cattle are grazed in winter. T3 and T4 flow through pastureland used for grazing cattle from May to November, excluding the snow season. T5 flows downstream from the lower reaches of K Farm and was determined to be unaffected by K Farm.

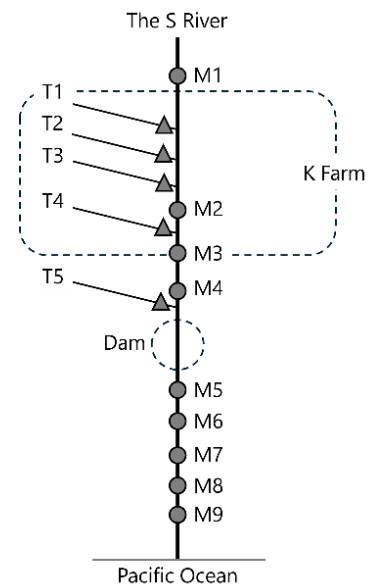


Fig. 1 Sampling points

Water Quality Investigation

River water was sampled at nine sites on the main S river and five sites on its tributaries during periods of low water flow when the water was not affected by flow fluctuations due to the rainfall. The river water was directly collected into clean, dry plastic bottles, stored in a cool, dark container, and immediately transported to the laboratory for analysis. Water was sampled once a month from May to October 2019, for a total of six samples. Using liquid chromatography and well-established protocols, we analyzed the following ion components in each sample: F⁻, Cl⁻, Br⁻, NO₃⁻, NO₂⁻, PO₄²⁻, SO₄²⁻, Na⁺, K⁺, NH₄⁺, Ca²⁺, and Mg²⁺. Total nitrogen (T-N) was mineralized using the alkaline potassium peroxydisulfate decomposition method and measured using a UV-visible spectrophotometer. Organic nitrogen (Org.-N) was calculated by subtracting ammonia (NH₄-N), nitrite (NO₂-N), and nitrate nitrogen (NO₃-N) from T-N.

Principal Component Analysis

We used the scikit-learn package in Python (Python3) to perform principal component analysis (PCA) of the water quality. The PCA was performed using two data types: 1. the average ion and T-N concentrations and 2. ion and T-N concentrations for all sampling dates. However, NH₄-N and NO₂-N were excluded from the PCA because they were below the detection limit of liquid chromatography (NH₄-N < 0.05 mg/L, NO₂-N < 0.02 mg/L) on most of the sampling dates.

RESULTS AND DISCUSSION

Average Ion Concentration and Ion Composition Ratio at Each Sampling Point

Figure 2 (a) and (b) show the average cation and anion concentrations, and Figure 2 (c) and (d) show the ion composition ratios. The average ion concentration was 8.1–16.4 mg/L for cations and 6.5–11.5 mg/L for anions. Cation concentrations tended to increase from upstream to downstream in the main river. In the tributaries, concentrations were similar to those in the downstream section of the main river, with the highest concentration recorded at T2 in the tributary. There were no significant differences in the anions in the main river, but as with cations, T2 in the tributary had the highest concentration. Regarding the ion composition ratio, Na^+ and Ca^{2+} were the primary ions, accounting for approximately 30% and 50% of the cations, respectively, while Cl^- and SO_4^{2-} were the primary anions, accounting for approximately 45% of each. Although there were differences in the ion concentrations at each sampling point, the ion composition ratios showed a similar trend.

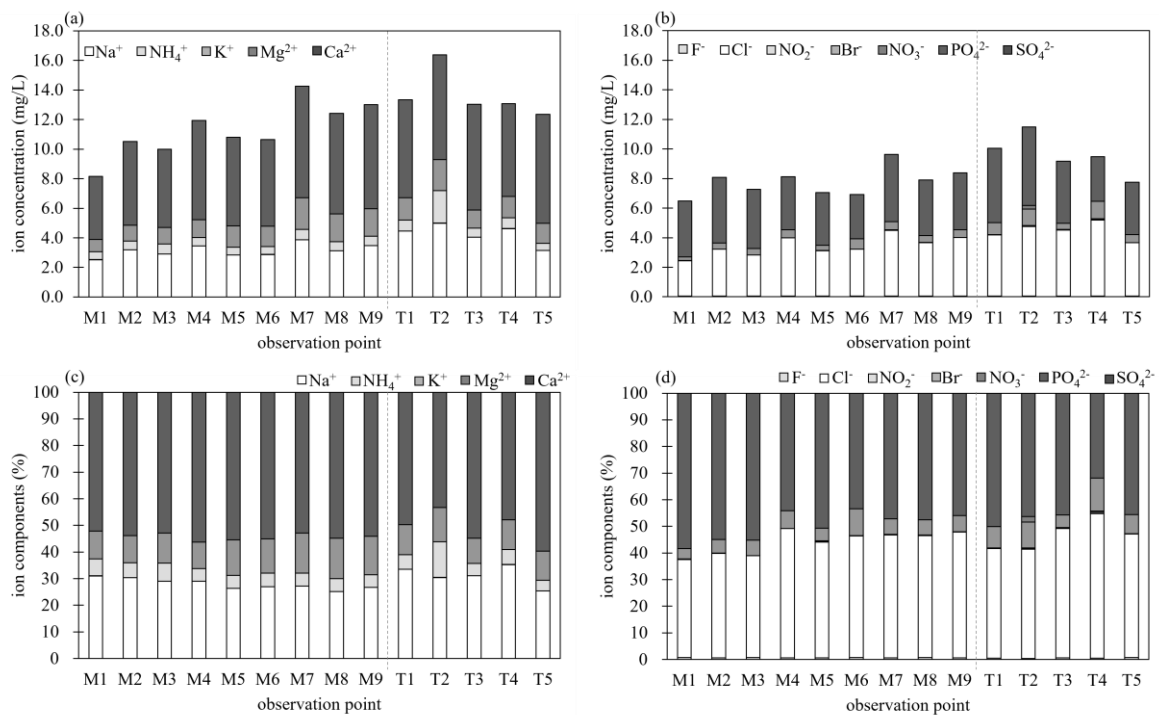


Fig. 2 Average ion concentration and ion composition ratio (a) to (d)

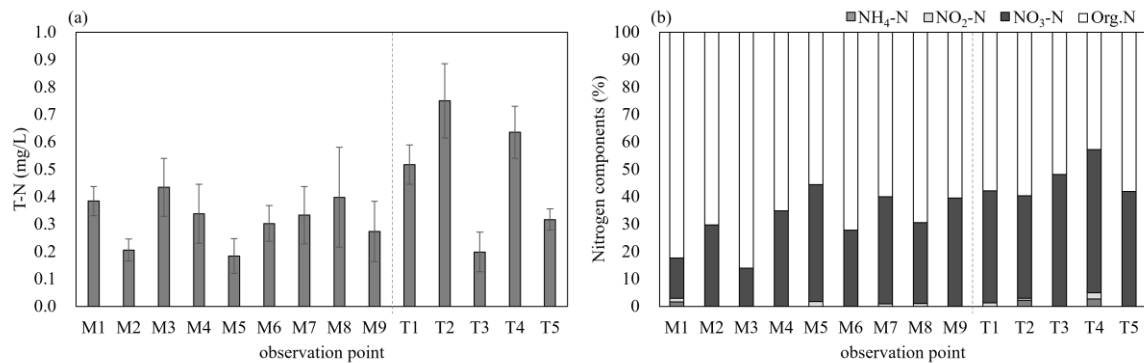


Fig. 3 T-N concentration and nitrogen composition ratio (a) and (b)

T-N Concentration and Nitrogen Composition Ratio at Each Sampling Point

Figure 3 (a) and (b) show the average T-N concentration and nitrogen component ($\text{NH}_4\text{-N}$, $\text{NO}_2\text{-N}$, $\text{NO}_3\text{-N}$, and Org.-N) composition ratios. The average T-N concentration ranged from 0.18 to 0.75 mg/L, which was below the environmental standard of 1.0 mg/L. There were no significant differences in the T-N concentrations in the main river. The T-N concentrations of tributaries T1, T2, and T3 tended to be greater than those of the main river. Regarding the composition ratio of nitrogen components, organic nitrogen accounted for approximately 70% and $\text{NO}_3\text{-N}$ for approximately 30% in the main river. In the tributaries, the ratio of $\text{NO}_3\text{-N}$ was approximately 45%, which was greater than that of the main river.

Correlation Matrix of Nitrogen Components

Figure 4 (a) shows the correlation matrix of the average concentrations of each nitrogen component ($\text{NH}_4\text{-N}$, $\text{NO}_2\text{-N}$, $\text{NO}_3\text{-N}$, and Org.-N) between the sampling points. The correlation coefficients between the concentrations of each nitrogen component were very high, indicating that the nitrogen composition ratios at all sampling points were similar. However, the correlation coefficients of T3 and T4 in the tributaries were lower than those at the other sampling points.

Figure 4 (b) shows the correlation matrix for the T-N concentration between the sites on each sampling day. The correlation coefficients between the four sites in the upper reaches of the main river (M1 to M4) were high, ranging from 0.82 to 0.99. The correlation coefficients between the four sites in the upper reaches of the main river and the five sites in the lower reaches of the main river (M5–M9) tended to be low. Conversely, the correlation coefficients between the upstream sites of the main river and the tributaries were high. In contrast, the correlation coefficients between the downstream sites and the five sites on the tributaries were low. In other words, the seasonal variation in T-N concentration showed a similar trend at the upstream sites of the main river and tributaries.

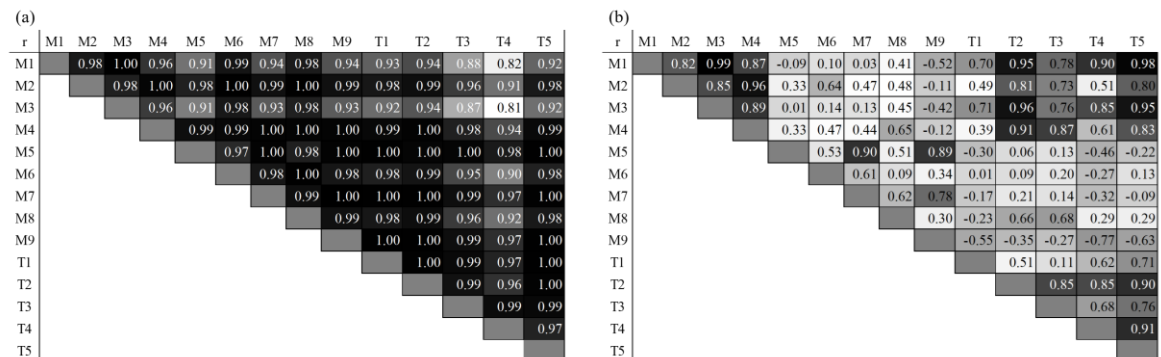


Fig. 4 Correlation matrix of nitrogen components (a) and (b)

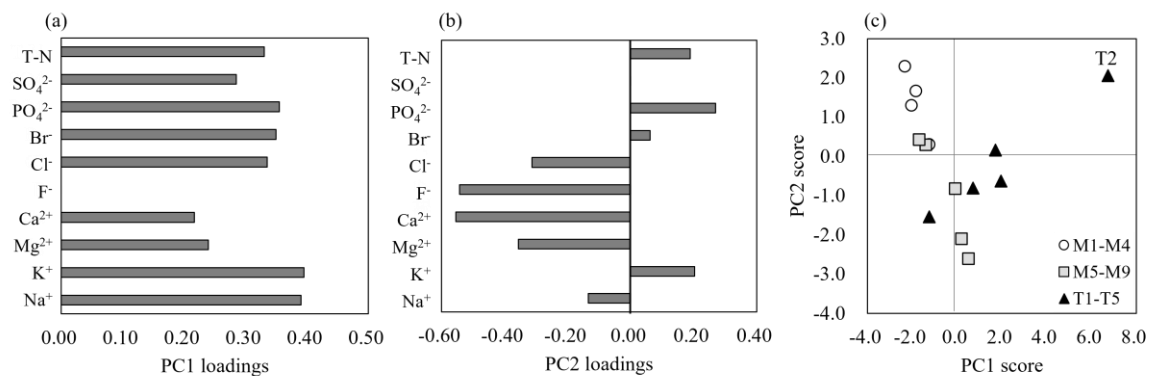


Fig. 5 PCA loadings and relationship between PC1 and PC2 of the average ion and T-N concentration (a) to (c)

PCA of Average Ion and T-N Concentrations

Figure 5 (a) and (b) show the PCA loadings for the average ion and T-N concentration values. The contribution ratio of PCA using the average values was 53% for the first principal component, PC1, and 21% for the second principal component, PC2; therefore, it was judged that two principal components, PC1 and PC2, could explain the 10 water quality items. The loadings of PC1 were positive for all water quality parameters; therefore, the higher the value of PC1, the higher the overall water quality concentration. On the other hand, K^+ , Br^- , PO_4^{2-} and T-N showed positive values for the PC2. K^+ , PO_4^{2-} , and T-N were considered potential indicators of livestock manure inputs.

Figure 5(c) shows a scatter diagram with PC1 on the x-axis and PC2 on the y-axis. Related to the relationship between the first and second principal components, the plot trends differ for the main river upstream, downstream, and the tributary. The plot of the main river showed a linear transition from the second quadrant to the fourth quadrant. The nine points on the main river had negative values or values close to 0 for PC1, indicating a low overall water quality concentration. In addition, PC1 for the main river increased as it flowed downstream, and the water quality concentration increased slightly downstream. In contrast, PC2 showed positive values at the upper sites of the main river and 0 or negative values at the lower sites of the main river. From this, K^+ , PO_4^{2-} , and T-N tended to be higher at the upper sites of the main river than at the lower sites. The five sites on the tributary river showed a different trend from the main river, with a linear transition from the first to the third quadrant. In particular, T2 was plotted in a position separate from the other four tributary sites, indicating that the overall water quality concentration was high and that K^+ , PO_4^{2-} , and T-N were high.

PCA of Ion and T-N Concentrations for All Sampling Dates

Figure 6 (a) and (b) show the PCA loadings for the ion and T-N concentrations for all sampling dates. The contribution ratios of principal component analysis were 44% for PC1 and 18% for PC2, so PC1 and PC2 could explain the 10 water quality items. The results for the principal component loadings for PC1 and PC2 were similar to those of the PCA using the average values of the ion and T-N concentrations described above.

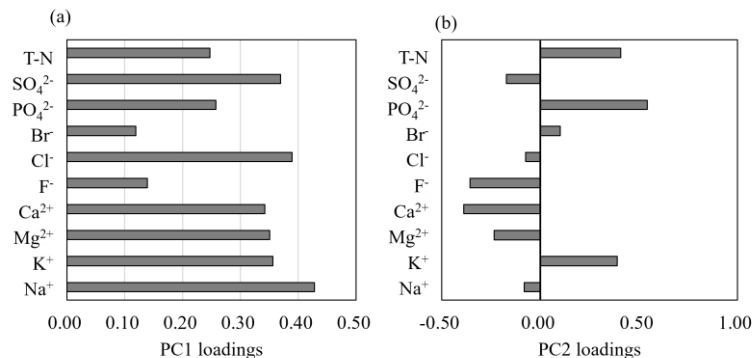


Fig. 6 PCA loadings of the average ion and T-N concentration for all sampling dates (a) to (b)

Figure 7 (a) shows the results for the four sampling points, M1 to M4, in the upper reaches of the main river, Fig.6 (b) for the five sampling points, M5 to M9, in the lower reaches of the main river, and Fig. 6 (c) for the five sampling points, T1 to T5, in the tributary. In terms of the relationship between PC1 and PC2, the main river showed a linear transition from the second to the fourth quadrant. Although there were no significant differences in the principal component scores for any of the sampling points or dates, the PC2 scores were high for M1 and M2 in the upper reaches of the main river only in May. For the tributaries, T1, T3, and T5 showed similar trends, with no significant differences between the sampling points or dates. In contrast, T2 was plotted in a position distant from the other sites, and in particular, as T2 showed positive values for both the first and second principal components in May, it can be seen that the overall water quality concentration was high.

and that the K^+ , PO_4^{2-} , and T-N concentrations were higher than in the other months when the water was sampled.

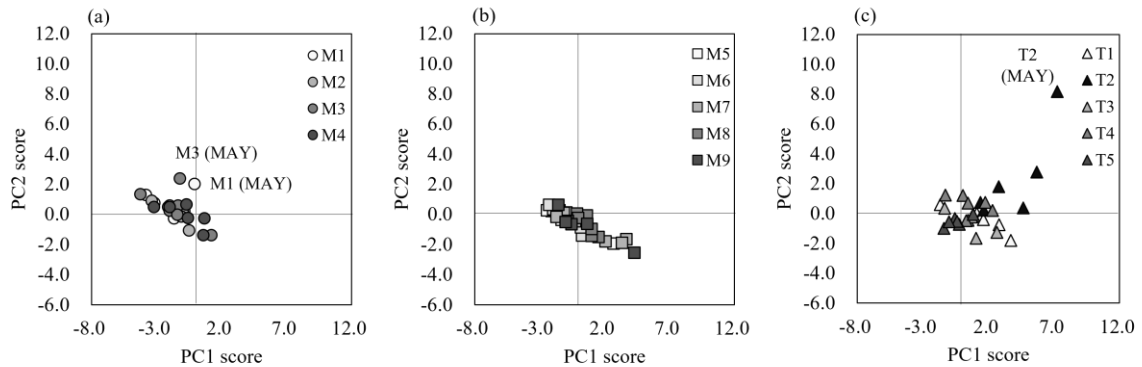


Fig. 7 Relationship between PC1 and PC2 of the ion and T-N concentration on all sampling dates (a) to (c)

CONCLUSION

The ion and T-N concentrations were low at all the sampling points. When comparing the main river and the tributary near the pasture, the tributary tended to have higher water quality. The cation composition ratio was similar at all sites, but the proportion of NO_3-N was high among the nitrogen components in the tributaries. In addition, a strong positive correlation was observed between the upstream section of the main river and the tributary in terms of T-N concentration from May to October. In the PCA of ion and T-N concentrations, the tributary's overall water quality was higher than that of the main river, with particular characteristics in K^+ , PO_4^{2-} , and T-N concentrations. The tributary T2 flowing by the pasture during the snow season showed a distinct water quality trend, with particularly high overall water quality in May, which was also observed at the main river sites M1 and M3. The beef cattle grazing livestock farming does not significantly impact the river water quality; however, water quality fluctuations after snowmelt indicate the need for long-term monitoring of seasonal and temporal variations in tributaries within the grazing area.

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Eutrophication Evaluation and the Estimation of Methane Gas Emissions from Eutrophic Reservoirs

NUTCHANAT CHAMCHOI*

Faculty of Science, Khon Kaen University, Khon Kaen, Thailand

Email: nutcch@kku.ac.th

NATTARIKA KATKAEW

Faculty of Science, Khon Kaen University, Khon Kaen, Thailand

SINLAPHOP PONGDET

Faculty of Science, Khon Kaen University, Khon Kaen, Thailand

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(*Corresponding Author)

Abstract Eutrophic reservoirs play a pivotal role in the carbon cycle by releasing methane (CH₄) from water into the air. However, efforts to estimate these emissions are limited by high analysis costs and inconsistent methodological approaches. Therefore, we surveyed and evaluated the occurrences of violent eutrophication in two reservoirs and estimated CH₄ emissions based on the Intergovernmental Panel on Climate Change guidelines. We studied the physicochemical characteristics of water, nutrient ratio, and trophic state status in two reservoirs, Bueng Si Than and Bueng Kaen Nakhon, in Khon Kaen Province, Thailand. The results demonstrate a violent eutrophication phenomenon at a hypertrophic level. The Total Kjeldahl Nitrogen to Total Phosphorus (TKN:TP) ratio was high at 20.24 in Bueng Si Than, indicating a TP limitation, whereas a low TKN:TP ratio of 4.87 in Bueng Kaen Nakhon indicated that TKN was a limiting nutrient factor for algal blooms. The trophic state index (TSI) (TP) and TSI Chlorophyll *a* (Chl *a*) of greater than 70 confirmed hypertrophic status in both reservoirs. The average scores, ranging from high to low, were: TSI (Chl *a*), TSI (TP), and TSI (SD), with a significant difference ($p < 0.001$) between the two reservoirs. Furthermore, the estimation of CH₄ gas emissions was achieved on the average of 303.41 ± 25.12 and $1,449.23 \pm 186.77$ kgCH₄/day in Bueng Si Than and Bueng Kaen Nakhon, respectively. In addition, the relationship between Secchi depth and Chl *a* with the estimated CH₄ gas emissions was obtained in this study. However, the maximum Secchi depth in the range of 0.38-0.43 m. obtained from the simulation was preliminarily recommended for the estimation of CH₄ gas emissions from eutrophic reservoirs.

Keywords eutrophication, greenhouse gas, chlorophyll *a*, nutrients, eutrophic reservoir

INTRODUCTION

Eutrophication phenomena in reservoirs occur because of the water and environmental characteristics that impact photosynthesis, including sunlight, carbon dioxide (CO₂), and nutrients. Eutrophication leads to the growth of phytoplankton, aquatic plants and macroalgae. The assessment of eutrophication had been achieved using the trophic state index (TSI) (KatKaew and Chamchoi, 2024; Zhang et al., 2023; Mamun and An, 2017). Additionally, changes in eutrophication or trophic state levels can be evaluated through a combination of site surveys and routine monitoring of nutrient levels (Chen et al., 2024). Interestingly, eutrophic reservoirs play an important role in the deterioration of water quality and increasing carbon emissions but are a poorly constrained source of methane (CH₄) to the atmosphere (Deemer and Holgerson, 2021). Likewise, the global warming potential of CH₄ gas emissions has been mentioned, and the emission release was dominated by CH₄ from eutrophic lakes (Sun et al., 2021). A variety of factors affecting CH₄ gas emissions from eutrophic reservoirs to the atmosphere were studied, in particular temperature, productivity of

phytoplankton and algae expressed as chlorophyll *a*, surface area, and water depth. The temperature dependency of CH₄ diffusion and ebullition is strongly modulated by trophic status when total phosphorus is a limiting factor in the system (DelSontro et al., 2016). The high CH₄ gas emissions in summer were due to high CH₄ production in the sediment, which resulted in the high dissolved CH₄ concentration in the surface water, accordingly (Iwata et al., 2020). The study by Sepulveda-Jauregui et al. (2018) indicated that increasing water temperature by 2°C leads to a net increase in CH₄ gas emissions of 101-183% in hypertrophic lakes. High productivity expressed as chlorophyll *a* (Chl *a*) under eutrophication promotes anoxic conditions via associated organic matter respiration, resulting in high CH₄ gas emissions. This is in line with the study by Bartosiewicz et al. (2021), who stated that anoxia associated with algal blooms and heatwaves enhanced CH₄ effluxes by up to 10 times. A study by Xiong et al. (2025) revealed that warming stimulates CH₄ gas emissions in shallow eutrophic lakes. Nevertheless, a study by Li and Xue (2023) pointed out that the higher CH₄ fluxes were mostly found in the littoral zone of large and shallow lakes. This finding may also have occurred in the shallow reservoir because the littoral zone has abundant organic matter available in the sediment from high productivity under eutrophication phenomena.

Previous studies have revealed that the measurement and estimation of CH₄ emissions from eutrophic freshwater sources involves two primary approaches. The first approach focuses on assessing greenhouse gas concentrations within water systems, utilizing sophisticated techniques and technologies such as Gas Chromatography (GC) and Infrared Gas Analyzers to extract, isolate, and precisely measure dissolved gases in water. The second approach evaluates gas flux at the critical air-water interface using three primary techniques: mathematical concentration-based calculations, floating chamber methods, and the eddy covariance technique (Bartosiewicz et al., 2021; Deemer and Holgerson, 2021; Iwata et al., 2020). These methods quantify the complex gas exchange processes between water bodies and the atmosphere. Recently, a methodology based on the Intergovernmental Panel on Climate Change (IPCC) guidelines for estimating CH₄ emissions has provided a variety of average emission rates from reservoirs located in different climate zones (Beaulieu et al., 2020). The appropriate procedures while optimizing costs will pose a challenge and provide benefits for the management of greenhouse gas emissions under eutrophication situations in reservoirs.

According to CH₄ gas emissions from natural surface water sources, particularly small artificial water bodies, including eutrophic reservoirs, have been criticized for missing accounted value from the entire greenhouse gas determination (Grinham et al., 2018). Measuring CH₄ gas samples requires expertise, high analysis costs, and collection techniques that account for the complex gas exchange processes occurring between water bodies and the atmosphere, which pose significant obstacles. Estimating CH₄ emissions using standard water quality monitoring data may help address these issues. Therefore, in this study, we conducted water sampling and analysis and evaluated the trophic state level and violent eutrophication phenomenon in two freshwater reservoirs. The observations were supplemented with an estimation of CH₄ gas emissions based on the IPCC guidelines. The results provide useful information for monitoring and managing the eutrophication status in small-scale reservoirs with related effects of climate change caused by CH₄ emissions. Further studies are required to verify the CH₄ gas emissions from reservoirs, which are targeted for collection as part of Thailand's national greenhouse gas inventory.

OBJECTIVE

The objectives of this study were to evaluate the eutrophic levels and estimate CH₄ gas emissions from two different-sized reservoirs based on the IPCC guidelines.

METHODOLOGY

Study Area

The selected study area was in Khon Kaen Province, Thailand, including two small-scale artificial recreational reservoirs, Bueng Si Than (16°44'37.3"N 102°81'18.0"E) and Bueng Kaen Nakhon (16°24'57.5"N 102°50'18.2"E). Both reservoirs primarily receive rainwater and a portion of the effluent from a nearby domestic wastewater treatment plant. The two reservoirs were selected to compare eutrophic levels and estimate CH₄ gas emissions between a larger and deeper reservoir and a smaller and shallower reservoir. Bueng Kaen Nakhon is larger and deeper than Bueng Si Than, with respective areas of 0.9648 km² and 0.0864 km² (Fig. 1). The water depth in Bueng Kaen Nakhon is approximately 4.0 and Bueng Si Than's depth is approximately 1.6 meters.

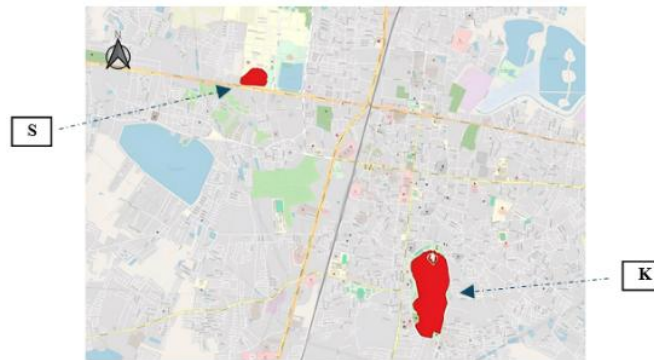


Fig. 1 Study areas: Bueng Si Than (S) and Bueng Kaen Nakhon (K)

Sampling and Measurement of Water Variables

Water sampling was performed during the rainy season (May-October), as defined by the Thai Meteorological Department. Water quality analysis for temperature, pH, dissolved oxygen (DO), electrical conductivity (EC), Secchi depth (SD), biochemical oxygen demand (BOD), total Kjeldahl nitrogen (TKN), and total phosphorus (TP) was conducted following the Standard Methods for the Examination of Water and Wastewater (APHA, 2017). Chl *a* was measured using a UV/VIS spectrophotometer (Hitachi UH-5300).

Evaluation of the Data

Evaluation of the eutrophication phenomenon

The physicochemical properties and nutritional parameters of water: The water's physicochemical properties, Secchi depth (SD), biomass (Chl *a*), and nutritional parameters (TP and TKN) were selected to evaluate the trophic state level and eutrophic phenomenon in the reservoirs (Carlson and Simpson, 1996). The differences in the overall physicochemical properties, biomass, and nutritional parameters between the two reservoirs were interpreted using statistical analysis (t-test).

Relationships between water quality parameters and Chl *a*: The relationship between Chl *a* and nutrients (TKN and TP) in the observed reservoirs was evaluated using Pearson's correlation.

Variations in the TKN:TP, Chl *a*: TKN, and Chl *a*:TP ratios: The differences in the ratios, which indicated the type of nutrient limitation required for algal growth in each reservoir, were compared using a t-test.

Trophic state index: The trophic state index (TSI), such as TSI (TP), TSI (SD), and TSI (Chl *a*), for evaluating eutrophication intensity in the reservoirs was considered in accordance with Mamun and An (2017). The four classifications of trophic states included Oligotrophic (TSI: 30-40), Mesotrophic (TSI: 40-50), Eutrophic (TSI: 50-70), and Hypertrophic (TSI >70). The differences in the TSI scores obtained between the two reservoirs were assessed using ANOVA.

Estimation of CH₄ emissions

The estimation of CH₄ gas emissions from the reservoirs was based on the default emission factors and equations according to IPCC (2019). The principal equation is given by Eq. (1).

$$\text{CH}_4 \text{ gas Emissions} = [(\text{TOW} - \text{S}) * \text{EF} - \text{R}] \quad (1)$$

Where, CH₄ gas Emissions is the CH₄ gas emissions from the reservoirs (kg.CH₄), TOW the total organic matter in the water (kgBOD), S the sludge removal (kgBOD/month [for reservoirs, S = 0]), EF the emission factor (kgCH₄/kgBOD) and R the amount of CH₄ recovered (kgCH₄/kgBOD [for reservoirs, R = 0]).

RESULTS AND DISCUSSION

Evaluation of Eutrophication Phenomenon During the Rainy Season

Overall physicochemical properties and nutritional parameters of water: The overall physicochemical properties and nutritional parameters of water in the two reservoirs during the rainy season are shown in Table 1. The measured physicochemical properties for evaluation of eutrophication occurrence include the average values of Secchi depth (SD), the biomass (expressed as Chlorophyll *a*), the TP, and the TKN demonstrate the violent of the eutrophication phenomenon in Bueng Si Than and Bueng Kaen Nakhon. Based on these variables, the trophic state of the reservoirs was evaluated at the hypertrophic level (Carson and Simpson, 1996). According to the measured SD, reservoirs can be classified as shallow, where no thermal stratification results in a greater seasonal variation in temperature and DO in the hypolimnion compared to deep reservoirs (Zhong et al., 2023). High Chl *a* content was found due to nutrients supplied by high runoff from rain, as postulated by Qi et al. (2024), and increased precipitation accelerated phosphorus (P) leaching to the reservoir. Nevertheless, the results of the t-test indicated a significant difference in the physicochemical properties and nutritional parameters between the two reservoirs ($p < 0.05$). A significant difference in Chl *a* was also observed between the two reservoirs ($p < 0.001$). The larger water capacity and water surface, Bueng Kaen Nakhon, the higher Chl *a* content (994.33 ± 251.09 µg/L) and TKN (6.85 ± 2.83 mg/L). Whereas the average content of TP (145.11 ± 34.96 µg/L) in this reservoir showed a lower amount than that recorded in Bueng Si Than (295.91 ± 130.23 µg/L) (Table 1). A high supply of nutrients and consequently high Chl *a* content would lead to a high probability of CH₄ emissions, as indicated in a previous report by Sun et al. (2021).

Table 1 Classification of the rainy season trophic state level and the physicochemical properties and nutritional parameters in Bueng Si Than and Bueng Kaen Nakhon

Parameters	Bueng Si Than (Mean±SD)	Bueng Kaen Nakhon (Mean±SD)	p-value*	Trophic state**
Temperature (°C)	29.98±0.45	28.48±0.17	< 0.001	-
pH	9.30±0.15	8.71±0.21	< 0.001	-
DO (mg/L)	9.92±0.56	8.55±0.22	< 0.001	-
EC (µs/cm)	389.70±2.66	200.99±2.47	< 0.001	-
BOD (mg/L)	10.49±0.83	15.89±2.51	< 0.001	-
TKN (mg/L)	4.65±1.20	6.85±2.83	0.010	Hypertrophic
TP (µg/L)	295.91±130.23	145.11±34.96	< 0.001	
Secchi Depth (cm)	26.57±2.93	25.81±1.46	< 0.001	
Chlorophyll <i>a</i> (µg/L)	589.68±103.40	994.33±251.09	< 0.001	

*Significant difference at the 0.05 level (2 tailed), **Trophic state evaluation based on Carson & Simpson (1996).

Relationships between water quality parameters and Chlorophyll *a*: Pearson correlation analysis indicated a positive relationship between Chl *a* and TP in Bueng Kaen Nakhon during the rainy season ($r = 0.601$, $p = 0.014$), consistent with previous reports (Kim et al., 2021; Mamun and An, 2017). High DO concentrations and high pH values recorded in this study confirmed the occurrence of eutrophication in the reservoirs, as indicated by the high Chl *a* content. Under eutrophication conditions, photosynthesizing algae cover the surface area and compete for light, resulting in high dissolved oxygen levels during the daytime. Meanwhile, the chemical byproducts of photosynthesis increase the pH of the water. In contrast, in Bueng Si Than, there was no relationship between Chl *a* and TP, which implies that the algal biomass in this reservoir was dominated by the non-nutrient

factor, BOD (Katkaew and Camchoi, 2024; Jargal et al., 2023; Zou et al., 2020). This was confirmed by the significant correlation of $r = 0.395$, $p = 0.041$. However, the measured BOD values higher than the surface water quality standard of Thailand reflected the accumulation of organic matter in the reservoir, which is possibly a source of methane emissions, since it is primarily produced from organics, as mentioned in the IPCC (2019).

Variations in the TKN:TP, Chl *a*: TKN, and Chl *a*:TP ratios: In the current study, the TKN:TP, Chl *a*: TKN, and Chl *a*:TP ratios were used to evaluate the nutrient limitations in the observed reservoirs. The average ratios of TKN:TP, Chl *a*: TKN, and Chl *a*:TP at 20.24, 0.13, and 2.60, respectively, were obtained from Bueng Si Than, respectively. Meanwhile, a higher ratio of Chl *a*: TKN, and Chl *a*:TP at 1.70 and 6.95 was recorded in Bueng Kaen Nakhon. In contrast, a lower TKN:TP ratio of 4.87 was found in this reservoir. Moreover, the results of the statistical analysis (T-test) revealed that there had been a significant difference in the ratios of TKN:TP, Chl *a*: TKN, and Chl *a*:TP between Bueng Si Than and Bueng Kaen Nakhon ($p < 0.001$, $p < 0.001$, $p < 0.001$). In addition, the current results of the TKN:TP ratio indicated that more TP limitation was discovered in Bueng Si Than because the ratio was above 20.0 (Wu et al., 2022), whereas the low value of the TKN:TP ratio of 4.87 indicated that TKN was a limiting nutrient factor for algal bloom in Bueng Kaen Nakhon. Different TKN:TP ratios indicating nutrient limitation have been reported depending on how restrictive the ratio is for each type of water source, which is related to the purpose of water usage and climatic conditions. In the study by Elser et al. (2009), nitrogen: phosphorus (N:P) ratios greater than 16 reflect that the aquatic environment is limited by P, and N:P ratios less than 14 indicate that the limiting factor is N. While the N:P ratio of 2.9 ± 0.5 was suggested that N has been the limiting element (Cardoso-Silva et al., 2018). Meanwhile, the P had been reported that it was a limiting nutrient for the occurrence of eutrophication in the water-supply reservoir (Guo et al., 2018). In addition, Dou et al. (2019) stated that if the light condition is set to a fixed value, the effect of phosphorus on algae growth is greater than that of N.

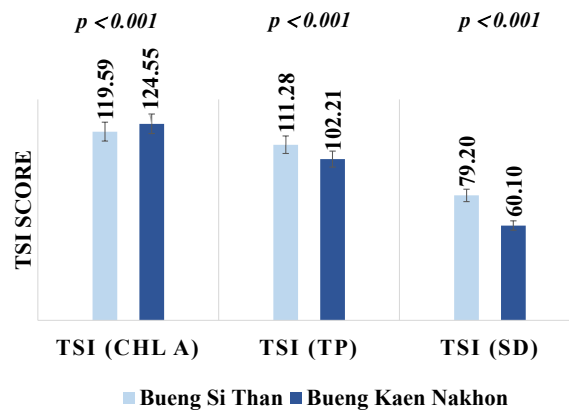


Fig. 2 Comparison of the Rainy Season TSI scores in Bueng Si Than and Bueng Kaen Nakhon

The trophic state index: In our study, the obtained TSI for evaluating eutrophication violence included a TSI (TP) and a TSI (Chl *a*) of higher than 70, indicating that hypertrophic conditions had occurred in Bueng Si Than and Bueng Kaen Nakhon during the rainy season. A slightly lower than 70 scores of TSI (SD), 60.1, were found in Bueng Kaen Nakhon, which also indicated that a eutrophic condition occurred in this reservoir. However, the physical factor, SD, can be an accurate and intuitive observation of the trophic status in the lower-mesotrophic level, while the hypertrophic level is susceptible to being driven by nutrients such as N and P (Du et al., 2019). In addition, the statistical analysis results from ANOVA revealed the significant difference between the TSI (Chl *a*), TSI (TP), and TSI (SD) scores in each reservoir ($p < 0.001$) (Fig. 2). The maximum to minimum scores and average scores ranged in the following order: TSI (Chl *a*), TSI (TP), and TSI (SD), which is consistent with the study by KatKaew and Chamchoi (2024). The study by Zhang et al. (2023)

indicated that the TSI (SD) and the TSI (TP) scores were different from the TSI (Chl *a*) at approximately 10 score deviations. Moreover, the obtained coefficient of range in each index demonstrated that a high coefficient of range of TSI (TP) (13.14% and 4.89%) was observed in Bueng Si Than and Bueng Kaen Nakhon during the rainy season. All obtained TSI scores confirmed the occurrence of hypertrophy in both reservoirs.

Estimation of CH₄ Gas Emissions Using the BOD, Secchi Depth, and Chlorophyll *a*

Eutrophic levels have been reported to be positively correlated with CH₄ emissions (Wang et al., 2022). Under hypertrophic levels existed in the current observed reservoirs, the estimated CH₄ gas emissions of 303.41±25.12 and 1449.23±186.77 kgCH₄/day were obtained in Bueng Si Than (volume of 253,810.5 m³) and Bueng Kaen Nakhon (larger volume of 800,000 m³) based on the default emission factors and equations according to IPCC (2019). Total CH₄ gas emissions of 2,768.61 and 13,224.18 t CO_{2e} per year were obtained accordingly. Moreover, Deemer et al. (2016) indicated that a greater amount of greenhouse gas emissions, the majority of which was CH₄, released from reservoir water surfaces, accounts for 0.8 (0.5-1.2) Pg CO_{2e} per year. In addition to the calculated CH₄ gas emissions based on BOD values, the projected images of the CH₄ gas emissions using SD and Chl *a* in Bueng Si Than are depicted in Fig. 3. The maximum SD of 0.38 m was suggested as a limitation criterion for estimating CH₄ emissions from this reservoir. Concurrent results were obtained for the other reservoir, Bueng Kaen Nakhon, with a limitation criterion of a maximum SD of 0.43 m.

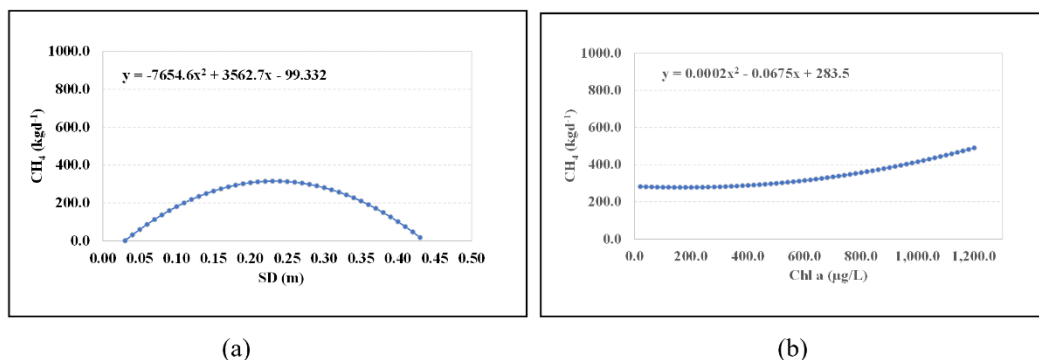


Fig. 3 Estimation of CH₄ gas emissions from Bueng Si Than during the rainy season based on IPCC guideline (2019) (a) SD vs. CH₄ (b) Chl *a* vs. CH₄

The potential error margins in CH₄ gas emission estimation could arise from the fluctuating addition of organics from sewer discharges, which is generally expected to increase CH₄ emissions in the receiving reservoirs (IPCC, 2019). Conducting multiple sampling points in each sampling was essential to obtain representative organic values for the reservoirs. Nevertheless, the CH₄ gas emission estimates in this study would be more intense if they included the proportion of CH₄ emitted from carbon deposited in sediments. Additionally, the error might arise from daily fluctuations in CH₄ gas emission fluxes in the reservoirs, which introduce additional uncertainties when a single-timepoint sampling approach is employed (Zhang et al., 2025). Furthermore, the sensitivity of CH₄ gas emissions to seasonal variations was reported by Iwata et al. (2020); CH₄ gas emissions from the littoral zone of a shallow mid-latitude lake area showed clear seasonal variations, reflecting temperature variations. Higher CH₄ gas emissions were observed in summer due to higher CH₄ production in the sediment, resulting in a higher dissolved CH₄ concentration in the surface water. Although various approaches to estimating CH₄ flux at the critical air-water interface in previous studies provide theoretical reference and data support for CH₄ gas emissions from eutrophic fresh water sources, the complex gas exchange processes occurring between water bodies and the atmosphere may limit accurate quantification. Currently, the procedure estimates CH₄ emissions based on the amount of organic matter generated (BOD) and an emission factor that indicates how much organic matter produces CH₄ (IPCC, 2019). According to the IPCC guidelines, this document

provides emission factor-based guidance for calculations expressed as mass per area, enabling comparisons of CH₄ gas emissions among reservoirs. (Ion and Ene, 2021). Future directions of the quantification and improvements of CH₄ gas emissions allow direct assessment, such as flux measurement techniques incorporating either process-based models (Zhang et al., 2023) and the alignment with methodology-based IPCC guidelines for better representing overall, global, and regional CH₄ gas emissions from eutrophic reservoirs.

CONCLUSION

Attempts to estimate CH₄ gas emissions and evaluate eutrophic occurrences in the reservoirs during the rainy season were accomplished based on IPCC guidelines and trophic state indices. Under the current procedure, the main water characteristics of BOD and the trophic state index of TP, Chl *a*, and SD were utilized. The results of the TSI (TP) and the TSI (Chl *a*) of higher than 70 scores indicated the hypertrophic status in the observed reservoirs. Meanwhile, the TKN:TP ratio was suitable for interpreting nutrient limitations in the reservoirs. Finally, under the worst-case scenario, the estimated CH₄ gas emissions of 303.41±25.12 and 1449.23±186.77 kgCH₄/day were obtained from Bueng Si Than and Bueng Kaen Nakhon. A larger and deeper reservoir (not exceeding 4.0 m depth) with a high supply of nutrients faces high productivity (Chl *a*) and consequently high CH₄ gas emissions. Therefore, the size and depth of artificial reservoirs require careful design considerations to manage eutrophication and methane emissions. The estimation of CH₄ gas emissions in the sediment, combined with the estimated concentration in surface water, is required for future research. Remarkably, the maximum SD in the range of 0.38-0.43 meters was recommended for further assessment of CH₄ gas emissions from eutrophic reservoirs.

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Enhancing Climate Resilience and Coffee Nursery Management in Bukidnon: Empowering Indigenous Coffee Farmers through IoT-Based Technology and Capacity Building

ARIESTELO ASILO

*Varacco, Inc., Batangas, Philippines, FMDS, UP Open University, Laguna, Philippines
Email: ariesteloasilo@gmail.com*

BRYAN BALTAZAR

Varacco, Inc. Department of Science and Technology 3, Pampanga, Philippines

THEODORE DE LEON

Varacco, Inc., Batangas, Philippines

MC LEAN BAYASCA

Varacco, Inc., Batangas, Philippines

JESSA CELINE CARABACA

Varacco, Inc., Batangas, Philippines

Received 29 December 2024 Accepted 6 June 2025 (*Corresponding Author)

Abstract The Philippine coffee industry faces decreasing yields and an increasing reliance on imports. Climate change exacerbates these difficulties, particularly for small-scale coffee farmers who lack the resources and infrastructure to adapt to changing weather, pests and diseases. Internet of Things (IoT) technologies present a promising solution for small-scale coffee farmers as a tool to monitor environmental conditions, manage and improve crop health, and optimize resource use. However, the effective adoption of IoT technology requires targeted capacity building to equip farmers with positive attitudes and essential knowledge and skills. A Pre-Assessment Survey (PAS) was conducted with 40 farmer participants across two coffee farming communities in the province of Bukidnon, Philippines. The PAS evaluated current knowledge, skills, and attitudes in each of the five key components: IoT familiarity, nursery management, plant nutrient management, pest and disease management, and openness to learning new horticultural handling techniques. The results revealed that most farmers were unfamiliar with IoT technologies and had limited or no experience in operating digital tools for agricultural purposes. While some expressed awareness of the potential benefits of technology in farming, this did not translate into actual usage or skills. Nursery management practices are often inconsistent, with many farmers lacking familiarity with proper spacing, shading, and seedling hardening techniques. Similarly, while the importance of plant nutrition has been acknowledged, practical understanding of microbial fertilizers and diagnostic methods, such as soil and leaf testing, remains limited. In terms of pest and disease management, farmers tended to rely on traditional methods, with minimal exposure to or use of technological tools for early detection of pests and diseases. Despite these gaps, farmers demonstrated a strong willingness to learn and were open to adopting new practices aimed at improving seedling quality and productivity. A comprehensive, culturally contextualized training program is recommended to build farmers' capacity, foster technology adoption, and support the transition toward climate-resilient, sustainable coffee production systems.

Keywords coffee production, IoT, PAS, farmer-scientist

INTRODUCTION

The Philippine coffee industry plays a vital role in the country's agricultural economy; however, it is plagued by declining productivity, heightened vulnerability to climate change, and increased dependence on imports (Department of Agriculture, 2017). Small-scale coffee farmers, particularly those from indigenous communities in the province of Bukidnon, Philippines, face unique challenges, including limited access to advanced agricultural technologies, poor infrastructure, and inadequate training on modern practices (Mia and Habaradas, 2021). These factors collectively reduce their resilience to environmental risks and economic pressures, threatening the sustainability of coffee production in this region.

Emerging technologies such as the Internet of Things (IoT) technologies offer a promising solution for addressing these challenges. IoT technologies enable real-time monitoring of environmental conditions, improve decision-making processes, and optimize resource utilization (Sharma and Shivadu, 2024). However, the effective integration of such technologies requires a foundational understanding among farmers, coupled with skill development and behavioral change (Javaid et al., 2022).

This study utilized a comprehensive Pre-Assessment Survey (PAS) to evaluate the existing knowledge, skills, and attitudes (KSA) in utilizing IoT Technologies for coffee nursery management of indigenous small-scale coffee farmers in the province of Bukidnon. By aligning local knowledge with scientific practices, this study addresses a significant gap in the academic discourse on sustainable agricultural development in Indigenous communities in Bukidnon Province.

OBJECTIVE

This study aimed to demonstrate how a Pre-assessment Survey can be used as a tool to design a tailored farmer–scientist training program (FSTP) that can help enhance the climate resilience and productivity of Indigenous coffee farmers in Bukidnon by equipping them with the knowledge, skills, and attitudes necessary to adopt IoT-based technologies and improved nursery management practices through a comprehensive gamified training program.

METHODOLOGY

Study Area and Participants

The study was conducted in two farming communities in Bukidnon Province: the Portulin Talaandig Tribal Association (PTTA) in the municipality of Pangantucan and the Milalittra Farmers Agriculture Cooperative (MILFACO) in the municipality of Talakag. Most of these farmers belong to the Talaandig tribe, one of the seven major tribes in the province of Bukidnon. These communities are characterized by their reliance on traditional farming practices and limited exposure to modern agricultural technology. A total of 40 coffee farmers participated in the study, with 20 farmers from each farming community. The farmers were selected based on their experience in traditional coffee farming, age, and the recommendation of the chieftain of the tribe.

Research Design

This study employed a mixed-methods approach, combining quantitative and qualitative data collection, to assess the baseline knowledge, skills, and attitudes (KSA) of farmers. The pre-assessment survey (PAS) used Bloom's Taxonomy of Educational Objectives to systematically evaluate the cognitive (knowledge), psychomotor (skills), and affective (attitudes) domains (Bloom, 1956). A pre-assessment form containing 30 items (Table 1), divided into five key components — IoT familiarity, nursery management, plant nutrient management, pest and disease management, and horticultural handling— was used to assess and establish baseline measures of knowledge, skills, and attitude (KSA) of the identified 40 indigenous farmers. The survey employed distinct response

formats for each KSA category: knowledge-related questions were answered with either “Familiar” or “Not Familiar,” skills-related questions with “Yes” or “No,” and attitude-related questions with “Agree” or “Disagree.” To facilitate the analysis, the responses were classified as positive (Familiar, Yes, Agree) and negative (Not Familiar, No, Disagree). This approach allowed for a clear assessment of existing competencies and the identification of specific areas in which capacity-building interventions are needed.

Table 1 Pre-assessment survey questions on knowledge, skills, and attitudes (KSA) for coffee nursery management for the two small-scale farming communities in Bukidnon, Philippines

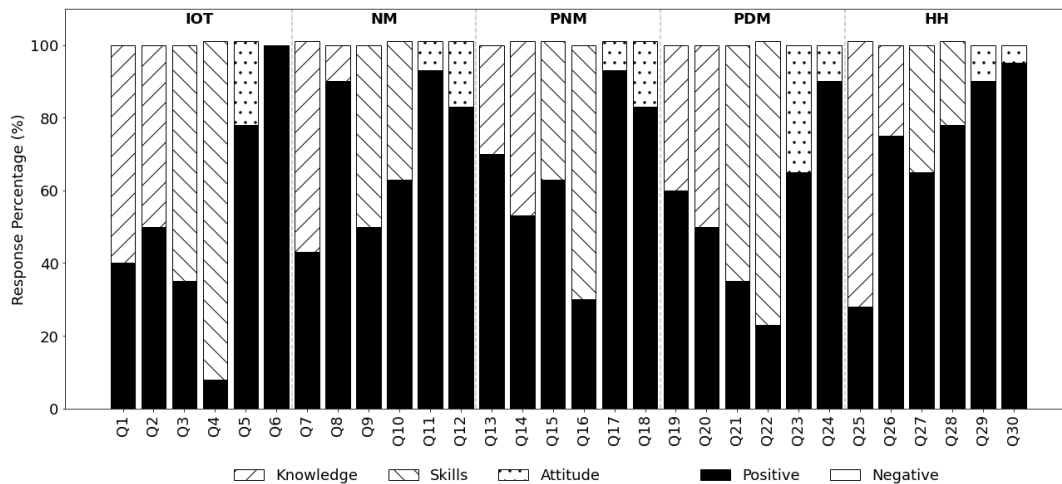
KSA	IoT familiarity	Nursery management	Plant nutrient management	Pest & disease management	Horticultural handling
Knowledge	1. How familiar are you with Internet of Things (IoT) devices used in agriculture?	7. How familiar are you with the practices of managing coffee seedling nurseries?	13. How well do you understand the importance of nutrient management for coffee seedlings?	19. How familiar are you with common pests and diseases affecting coffee seedlings?	25. Are you familiar with the hardening practices of coffee seedlings?
	2. Do you know how IoT devices can help monitor environmental factors such as temperature, humidity, and soil moisture?	8. Are you aware of how temperature, humidity, and light affect coffee seedlings in their early stages?	14. Are you familiar with the use of microbial fertilizers to improve nutrient levels in plants?	20. Do you know how to use technology and microbial fertilizers (e.g., Mykovam, Bio-N) to monitor and prevent pest or disease outbreaks?	26. Are you aware that hardening is a necessary preparation of coffee seedling before transplanting?
Skill	3. Have you ever used a mobile phone or SMS system to receive updates or information about your farm's activities and other crops?	9. Have you implemented practices such as proper spacing, watering schedules, or shading in your nursery?	15. Have you ever applied any nutrient recommendations for your coffee seedlings?	21. Have you used any traditional techniques, pest and disease prevention in your nursery?	27. Do you follow specific nursery practices to maintain the quality of coffee seedlings?
	4. Have you ever set up or operated digital devices (e.g., sensors) for agricultural purposes?	10. Have you been monitoring the environmental conditions in your nursery (e.g., temperature, humidity)?	16. Have you submitted any soil or leaf analysis to determine nutrient deficiencies?	22. Have you used any technology to monitor pest populations in your coffee nursery?	28. Have you used any interventions, solutions or techniques to improve coffee seedling production?
Attitude	5. How do you feel about using technology, such as IoT devices, to manage your farm's operations?	11. Do you feel that improving your seedling management practices will lead to better coffee production?	17. Do you think monitoring plant nutrient levels through technology can improve your seedling's growth?	23. Do you think that crop protection is needed on coffee nursery?	29. Do you believe that following proper nursery handling practices can improve the overall quality of coffee seedlings?
	6. Do you agree that adopting new technologies like IoT can improve the quality and speed of coffee seedling production?	12. Do you think that nursery should be accredited?	18. Do you believe that the use of microbial fertilizers (e.g., Mykovam, Bio-N) could improve production of coffee seedlings?	24. Do you agree that early detection of pests and disease is necessary?	30. How open are you to learning new techniques and practices to produce excellent quality coffee seedlings?

RESULTS AND DISCUSSION

Pre-assessment Survey (PAS) Results

The Pre-assessment Survey (PAS) revealed a significant gap in farmers' knowledge and skills while also showing a positive attitude towards sustainable agricultural practices and technologies, (Fig. 1). The results convey that 60% of the farmers are unfamiliar with (IoT) technologies. Despite 50% of the respondents being aware of IoT's potential in agriculture, 65% had never used mobile phones or SMS for agricultural activities, and only 7.5% had practical experience with devices such as sensors. This highlights the need for targeted interventions to improve technology adoption.

Similarly, while 90% of farmers understood the environmental factors affecting coffee seedlings, only 50% consistently applied best practices, such as proper spacing and shading, in their nursery management. In plant nutrient management, 70% of farmers acknowledged its importance, yet only 52.5% were familiar with microbial fertilizers, and 27.5% had never conducted soil or leaf analyses, demonstrating a disconnect between practical knowledge and implementation. Farmers also displayed familiarity with pests and diseases, with 60% recognizing common threats to coffee seedlings. However, only 15% regularly used technology and new practices to monitor pests and diseases in their crops. Moreover, 77.5% had never employed diagnostic tools, highlighting their reliance on traditional methods. In horticultural practices, 65% of the farmers applied interventions to improve the quality of coffee seedlings. In horticultural practices on coffee, 77.5% of the farmers knew that the hardening process was an important step in preparation before the transplantation of coffee seedlings. However, only 47.5% were very familiar with the process.



Notes: (IoT - IoT familiarity, NM - Nursery Management, PHM- Plant Nutrient, Management, PDM - Pest and Disease Management, HH - Horticulture Handling). Q1-Q30 corresponding to Questions

Fig. 1 Knowledge, skills, and attitudes of indigenous farmers gathered from PAS

The PAS shows a high attitude among farmers toward adopting new technologies, with 77.5% of them expressing strong willingness. The majority (92.5%) acknowledged that enhancing nursery management and monitoring plant health through technology could significantly boost productivity. Additionally, 65% recognized the importance of crop protection in seedling handling, and 95% expressed openness to learning new techniques and practices aimed at producing high-quality coffee seedlings.

These results underscore the need for enhanced training, access to resources, and promotion of smart agricultural technologies to bridge the gap between theoretical knowledge and practical application in the field. The gathered data indicate that while farmers possess foundational knowledge in key agricultural areas, practical application and technology adoption remain limited. Addressing these gaps through capacity-building programs, resource accessibility, and the demonstration of inventions is essential for promoting innovative and sustainable agricultural practices (Guevara and Tumague, 2023).

These findings illustrate a critical gap in the capacity of indigenous coffee farmers to adopt IoT technologies and sustainable agricultural practices. Similar studies, such as those by Deichmann et

al. (2016) and Aker (2017), highlight that access to technology alone is insufficient; knowledge and skill building are essential for effective utilization. The PAS provides baseline information to tailor a training program to develop the knowledge and skills of indigenous farmers to capacitate them to adopt IoT technologies and sustainable agricultural practices (Clark and Chopeta, 2004).

One of the effective models that empowers farmers to become local scientists and enables them to innovate and improve crop yield sustainability is Davide's Farmer-Scientist Program. The program's participatory approach fosters a deeper understanding of agronomic principles, which is crucial for addressing the unique challenges faced by indigenous farmers (Davide, 2001).

The findings of the PAS were used to design a tailored Farmer-Scientist Training Program (FSTP) based on Davide's model. The tailored FSTP seeks to bridge the gap between scientific knowledge and traditional agricultural practices by integrating a culturally sensitive, ritual-based approach. Tailored for indigenous coffee farmers, the program incorporates gamification elements to facilitate effective learning and ensure that training is accessible and engaging (Cayabyab et al., 2024). The gamification framework underpinning the FSTP is grounded in de Jesus' *Bahay-bahayan* Framework (Fig. 2), which emphasizes the use of culturally relevant interactive learning techniques to enhance knowledge retention and practical application (de Jesus et al., 2017).

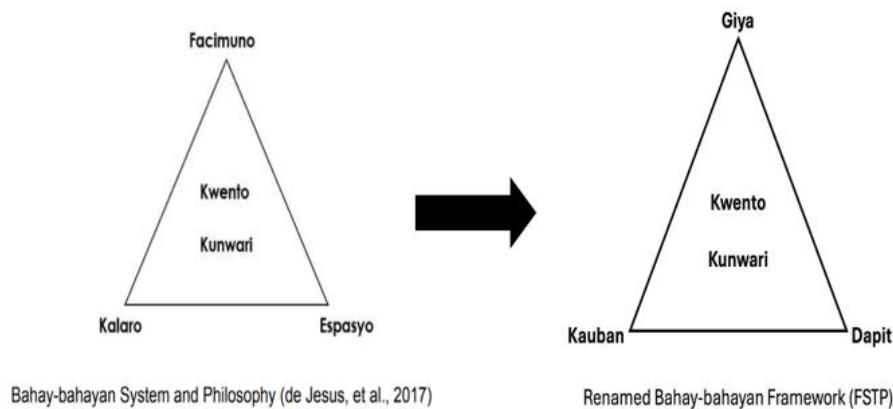


Fig. 2 Renamed *Bahay-bahayan* framework designed for FSTP

The results of the PAS, which revealed knowledge and skills gaps in IoT adoption for small-scale coffee farmers, were the focus of the tailored FSTP. It addresses a significant gap in rural agriculture, where technology is often underutilized because of a lack of understanding.

CONCLUSION

This study demonstrated the effectiveness of using a Pre-Assessment Survey (PAS) as a diagnostic tool to design a tailored Farmer-Scientist Training Program (FSTP) for indigenous small-scale coffee farmers in Bukidnon. The PAS successfully identified significant gaps in knowledge, skills, and practical applications related to IoT-based nursery management, despite a generally positive attitude toward adopting new technologies. By mapping the baseline competencies and learning needs of farmers across the cognitive, psychomotor, and affective domains, the survey informed the design of a culturally appropriate, gamified training program rooted in participatory learning.

The resulting FSTP, anchored in Davide's Farmer-Scientist model and the Bahay-bahayan framework, bridges traditional knowledge with scientific practices. It empowers farmers to become adaptive and innovative agents of sustainable agriculture, capable of enhancing productivity and resilience in the face of climate-related challenges. This approach not only supports technology adoption but also strengthens community-led capacity building, reinforcing the role of Indigenous farmers as stewards of knowledge and innovation.

Future research should focus on the long-term impacts of such programs on farmers' livelihoods, productivity, and resilience to climate risks. Additionally, exploring the scalability of this model to

other agricultural contexts can contribute to broader efforts to achieve sustainable and inclusive development.

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The authors express their profound gratitude to the BIMP-EAGA-KOREA Cooperation Fund (BKCF) under the Global Green Growth Institute (GGGI) for providing the financial support that made the Pre-assessment Survey (PAS) and Training Needs Analysis (TNA) possible. We also extend our sincere appreciation to the Local Government Unit (LGU) of Pangantucan, whose invaluable assistance in mobilizing resources and facilitating local engagement greatly contributed to the success of this project. Finally, we acknowledge the steadfast support of the Mindanao Development Authority (MinDA) for championing sustainable agricultural development in the region and for encouraging us throughout the process. This collective effort has significantly advanced our shared vision of empowering indigenous coffee farmers in Bukidnon through climate-smart, technology-driven innovations.

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Assessment of Agricultural Land-use/ Land-cover Change in the Diamphwe River Basin using Sentinel-2 Imageries

KENFORD A. B. LUWEYA

Graduate School of Agro-Environmental Science, Tokyo University of Agriculture, Japan

KE ZHANG

Japan International Research Center of Agricultural Sciences, Japan

LAMECK FIWA

Lilongwe University of Agriculture and Natural Resources, Malawi

SARVESH MASKEY

Faculty of Regional Environmental Science, Tokyo University of Agriculture, Japan

AYAKO SEKIYAMA

Faculty of Regional Environmental Science, Tokyo University of Agriculture, Japan

HIROMU OKAZAWA*

Faculty of Regional Environmental Science, Tokyo University of Agriculture, Japan

Email: h1okazaw@nodai.ac.jp

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Abstract Land use and land cover (LU/LC) classification is an important aspect of research in various sectors of society. With technological advancements, LU/LC classification is a catalyst to achieve set goals, including the Malawi 2063 agenda. Diamphwe Basin, with over 90% farmers, is in central Malawi on vastly flat land, with a lot of potential in both commercial and subsistence agriculture production. Using the September 2017 and 2022 Sentinel-2 images, supervised classification and change detection were performed to track LU/LC changes using the maximum likelihood algorithm. The classes used for this classification were dense vegetation, wetland vegetation, agricultural land, settlement land, and bare land. The results showed that dense vegetation land increased by 10%, mostly converted from wetlands in forest reserves, and agricultural land decreased by 15.5%, of which a large proportion was converted to settlement land, thus increasing settlement land (urbanization) by 11.7%. The increased dense forest is expected to have a cooling effect and can increase baseflow to river discharge, whereas decreased agricultural land is expected to have a heating effect on the land mass. However, owing to the proximity to agricultural land, people in the basin experience more heating effects than cooling effects. Urbanization can create a ready market and can be leveraged to increase agricultural production through irrigation in the basin, as seen in the case of the Ganges River Basin. An increase in dense forest area could lead to an increase in river discharge owing to an increase in basin storage in the form of a baseflow increase. Since almost all human developments occur on land, LU/LC change detection is the key to policymakers and other stakeholders in achieving the three pillars of the Malawi 2063 agenda, thus agricultural development, industrialization, and urbanization by keeping abreast of the changes on the land.

Keywords Sentinel-2, LU/LC, change detection, classification method, agricultural land

INTRODUCTION

Land use and land cover (LU/LC) changes are important topics in various societal sectors. It refers to changes in the surface covering of the Earth and the conversion of land utilization by humans from

one purpose to another. Land/canopy cover is a significant indicator of crop development (Zhang et al. 2021). LU/LC classification is vital for urban planning, resource management, environmental monitoring, and agriculture (Topaloğlu et al., 2016). The Diamphwe Basin's long-term hydrologic trend analysis showed a decreasing trend in river discharge between 1975 and 2010 (Luweya et al., 2024); however, a recent half-decade hydrological trend indicates an increase in river discharge. Changes in LU/LC, such as the shift from perennial to seasonal vegetation (row-cropping/agricultural expansion), lead to increased discharge (water yield) owing to an increase in baseflow (Schilling et al., 2010). In small, forested watersheds, an increase in forest cover increases the base flow by promoting infiltration (sink function enhancement) and recharging-discharging processes that increase the yield at the outlet (Zhou et al., 2010; Ouyang et al., 2013; Uwimana et al., 2017).

Limited point-based weather data from traditional stations hamper climate-change research. RS provides a continuous, high-resolution view of the Earth's climate using satellite, aircraft, or drone sensors (Wang, 2023). Satellite RS technology data provide observations of essential climate variables (ECVs), such as LU/LC, independent of in situ measurements, thus enhancing our understanding of climate change from space by validating climate models and improving their future projections and impacts (Wang 2023; Zhao et al. 2023). LU/LC conversion impacts the climate through temperature changes; any change in agricultural land cover induces localized cooling, similar to reforestation, but converting dense forests to agriculture induces warming (Nayak and Mandal, 2019; Sleeter et al., 2018). Several LU/LC classification studies have been conducted in Malawi, ranging from monitoring forest resources in both urban and forest reserves, all of which used satellite sensors other than high spatial and temporal resolution, to Sentinel-2, which offers free access, a convenient option for developing countries such as Malawi. Most of the previous RS research could not target agricultural watersheds such as the Diamphwe Basin, where climate change issues can be leveraged through LU/LC changes, especially in developing countries where point weather data are scarce.

OBJECTIVE

Hydrologic trends for river discharge indicate an increasing trend in the last seven years, despite long-term decreasing trends over the past 3.5 decades. To understand the cause of the recent increasing trend of river discharge, this study aimed to detect six years of LU/LC changes in the Diamphwe agricultural watershed using Sentinel-2 imagery.

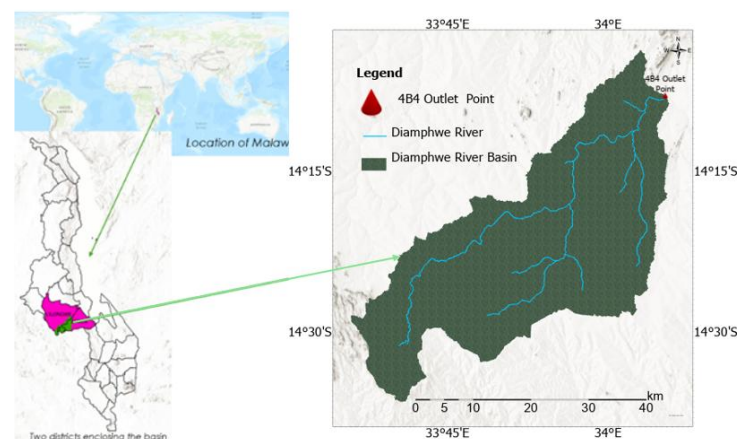


Fig. 1 Location of Diamphwe River basin

ETHODOLOGY

Study Site

The Diamphwe River Basin (Fig. 1) has vast wetlands (Dambos) along the perennial river with high irrigation potential that stakeholders have not yet fully utilized. It covers the Lilongwe and Dedza districts within the central region plains between 1,200 and 1,400 m above sea level. The basin has a warm tropical climate with temperatures ranging from 3.5°C to 39°C; generally, it has a rainy season (November to April) and a dry season (May to October) (Malawi Government, 2016). Similar to the rest of the country, rainfed agriculture is the main occupation of the basin, with over 90% of the farmers being small-scale (Malawi Government, 2019). The basin is located between 33.57°E and 34.13°E and 13.96°S and 14.72°S, enclosing an area of 1420.2 km². The Dzalanyama Forest Reserve partly occupies the basin within the river catchment area bordering Mozambique.

Data Collection and Pre-Processing

Earth observation (EO) Sentinel-2 and 12 band-based raw data images were downloaded from the Sentinel Hub website to assess LU/LC changes. The details of downloaded data are as follows.

Table 1 Sentinel-2 data details

Parameter	Details
Data source/format	Sentinel 2 EO browser/ TIFF (32-bit float)
Resolution/coordinate system	High (2500 x 1449px)/ WGS (EPSG 4326)
Resolution	Lat: 0.0006871 deg/px (2.5sec/px); Long : 0.0007086 deg/px (2.6sec/px)
Cloud cover	Atmospherically corrected (cloud cover < 5%)
Download/ recorded date	6 th August 2024/ 1 st September 2017 and 23 rd September 2022

After the data were downloaded, composite band combinations were prepared in ArcGIS Pro to produce RGB composites (true color → B04, B03, and B02, or false color → B05, B04, and B03). For clear vegetation identification, a Normalized Difference Vegetation Index (NDVI) composite raster was prepared (B04→ electromagnetic spectrum (EMS) portion that absorbs red energy and resampled to 10 m resolution B08→EMS portion that reflects NIR energy) for use with (RGB=Red, Green, Blue) composites. NDVI was computed (Rouse et al., 1973) as shown in Eq. (1).

$$NDVI = \frac{NIR - Red}{NIR + Red} \quad (1)$$

where NIR is the near-infrared energy reflected and Red is the energy absorbed within the EMS.

Image Classification and Method

Supervised image classification was used in this study, where the image analyst guided the pixel categorization process by providing numerical descriptors for different LU/LC types in the scene to a computer algorithm (Sivakumar et al., 2003). Using representative sample sites of known LU/LC types (training samples), a numerical interpretation key was created to outline the spectral attributes for each feature. In ArcGIS Pro, each pixel in the dataset was compared numerically to each category in the interpretation key and labelled with the name of the category it most closely resembled (Sivakumar, 2012). Table 2 describes the five classes utilized since the data were collected in September, the dry season.

Table 2 Class descriptions and codes

Code	Class	Description
1	Dense vegetation	Areas with thick vegetation, especially in natural forest reserves
2	Vegetation/wetlands	Areas with trees, shrubs and bushes, especially in dambos/forests
3	Agriculture/cultivated land	Land used for cultivation of crops, especially rainfed crops
4	Settlement/build-up land	Residential areas and trading centers with some buildings
5	Bare land	Areas with no vegetation and not used for cultivation, also in forest

GIS has three main methods for classifying satellite images: (1) maximum likelihood (ML), (2) Geoprocessing Tool-classified raster (GPT-CR), and (3) image classification wizard (ICW) with

three sub-methods: SVM, RT, and KNN. The GPT-CR classification method was used in this study after proving to be a better classifier for Sentinel-2 images than the other methods.

Accuracy Assessment and Change Detection

An accuracy assessment compares a classified image to a reference image, such as an aerial photograph or ground truth data, by matching pixels for pixels in scale, detail, categories, and projection (Parece et al., 2019). An accuracy assessment point raster was created and linked to Google Earth using a Keyhole Markup Language (KML) file. Google Earth uses more recent images as ground truth for study regions. Pixel mismatches in the RS are recorded as errors in an error matrix that compares the class code assigned during classification with the actual class from an aerial photo. The two key coefficients from the error matrix are (i) Cohen's kappa, which assesses the classification performance against random assignment, and (ii) overall accuracy, which indicates the ratio of matching points between the classified and reference images (Parece et al., 2019). Change detection in RS involves comparing multiple pairs of raster datasets from the same area at different times to identify the type, magnitude, timing, and location of changes due to environmental or climatic trends. Hence, the output is the difference between the raster in pixel changes (Parece et al., 2019). In this study, two classified rasters, 2017 and 2022 Sentinel-2, classified raster for the Diamphwe Basin, were used. Raster was first converted from the crf format to TIFF and then to a polygon raster. The dissolved polygon raster generated a 'from $\rightarrow$ to Table' through a pixel-by-pixel comparison to allow the assessment of the nature and magnitude of change, as shown in area and percentages in Table 6.

RESULTS AND DISCUSSION

The MK/Pettitt test for the 2010-2023 rainfall trend decreased (not significant) and river discharge trend increased 2018 as a transition year (at a 0.10 significance level) between a set of years with lower and a set of years with higher river discharge (Fig. 2, left); hence, diverged rainfall-river discharge trends. For the years with higher river discharges, 2016-2023, an increasing trend (MK trend analysis) was obtained (at a significance level of 0.01) (Fig. 2, right). However, rainfall showed no trend change in the two R-analyses, that is, the MK and Pettitt tests. To assess the linkages between increasing river discharge and basin characteristics, RS and ArcGIS methods and LU/LC changes were analyzed. Hence, LU/LC change detection was performed using Sentinel-2 images from 2017 and 2022. The classified rasters were assessed for accuracy, and the results are summarized in the accuracy assessment Tables 3 and 4.

The overall accuracy and kappa coefficients for 2022 were 77% and 69%, respectively, whereas those for 2017 were 81% and 74%, respectively. A higher kappa coefficient indicates a better classification process than the random assignment of values. However, a higher overall accuracy indicates a good match between the classified and reference images, such as those from Google Earth.

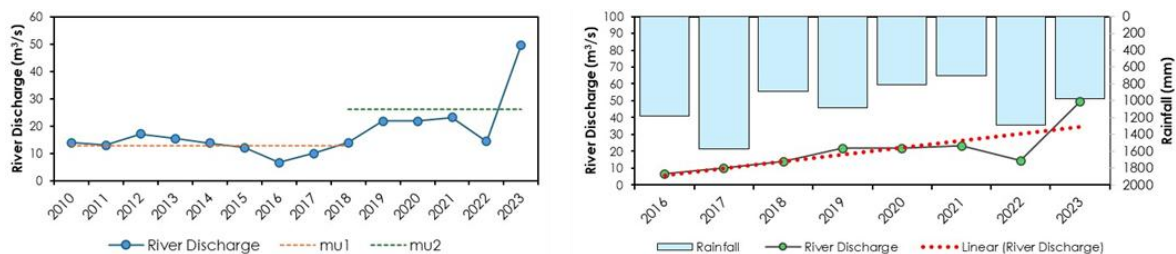


Fig. 2 Pettitt test for 2010-2023 (left) and MK trend for 2016-2023 (right)

Change Detection

Figure 3 shows the classified raster for 2017 and 2022, and Tables 5 and 6 show the changes detected in the area (km²) and percentage ratios over the six years, respectively. Dense vegetation increased by 10.03%, from 136.64 km² in 2017 to 150 km² in 2022. Notably, 12.6% of wetland vegetation (54.01 km²) was converted to dense vegetation between 2017 and 2022, representing 3.82% of the entire basin area (Table 5).

Table 3 Confusion matrix assessment for 2017

	Dense veg.	Wetlands	Agriculture	Settlement	Bare land	Total	P-accuracy	Kappa
Dense Veg.	11	0	0	0	0	11	1.00	0
Wetlands	0	32	1	0	0	33	0.97	0
Agriculture	3	3	38	1	0	45	0.84	0
Settlement	5	0	5	10	0	20	0.50	0
Bare land	0	1	4	0	5	10	0.50	0
Total	19	36	48	11	5	119	0.00	0
P-accuracy	0.58	0.89	0.79	0.91	1.00	0.00	0.81	0
Kappa	0	0	0	0	0	0	0	0.74

Table 4 Confusion matrix assessment for 2022

	Dense veg.	Wetlands	Agriculture	Settlement	Bare land	Total	P-accuracy	Kappa
Dense Veg.	8	3	0	0	0	11	0.73	0
Wetlands	0	32	1	0	0	33	0.97	0
Agriculture	0	3	32	0	0	35	0.91	0
Settlement	0	1	9	11	0	21	0.52	0
Bare land	0	8	0	0	2	10	0.20	0
Total	8	47	42	11	2	110	0.00	0
P-accuracy	1	0.68	0.76	1.00	1.00	0.00	0.77	0
Kappa	0	0	0	0	0	0	0.00	0.69

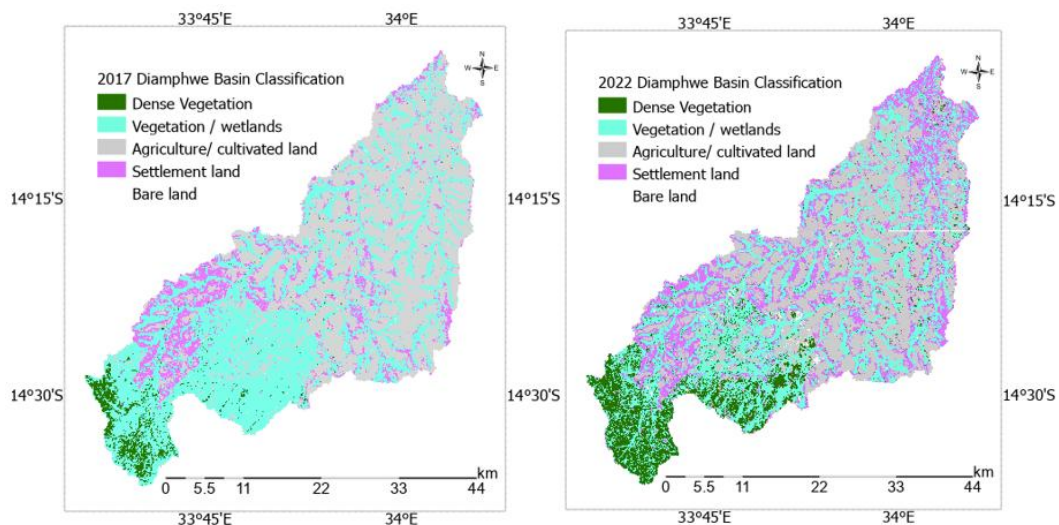


Fig. 3 2017 and 2022 classified raster for Diamphwe basin

Wetland (Dambo) vegetation increased by 11.14% from the initial area of 428.72 km² in 2017, specifically in the protected areas of the Dzalanyama and Chongoni forest reserves. An increase in dense forests leads to general cooling conditions (Sleeter et al., 2018). The increase in dense vegetation could have resulted from the intensified security of the Malawi Defense Forces (MDF) over the last decade, especially in areas far from people where security is tight.

Some areas with dense vegetation were possibly reclaimed land encroached upon from the late 1990s to the early 2000s. Agricultural land decreased by 15.49% (91.33 km²). Notably, 15.49% (91.31 km²) (Table 5) of agricultural land was converted to settlements, representing 6.45% of the basin area. The increase in dense vegetation in the interiors of the two forest reserves, Chongoni and

Dzalanyama, has less impact on land cooling because dense vegetation is far from where people live. People are more affected by warming owing to the decreased agricultural land.

Increased perennial dense vegetation can contribute to the river's baseflow due to the promotion of infiltration-recharge-discharge processes that increase basin storage, consequently redistributing water from the rainy season to the dry season. The conversion of agricultural land to settlement land can accelerate river sedimentation due to increased surface runoff (Schilling et al. 2010; Uwimana et al. 2017; Zhou et al. 2010).

Table 5 Detailed actual 2017-2022 changes detected in each class

Code	Class name	Initial area (km ²)	Initial % Δ	2022-2017 area Δ (km ²)	Basin% area Δ
1	Dense vegetation to wetlands	136.64	34.05	46.52	3.29
2	Dense vegetation to Agriculture land	136.64	7.99	10.92	0.77
3	Dense vegetation to Settlement land	136.64	2.57	3.51	0.25
4	Dense vegetation to Bare land	136.64	1.15	1.57	0.11
5	Wetlands to Dense vegetation	428.72	12.60	54.01	3.82
6	Wetlands to Agriculture land	428.72	6.61	28.35	2.00
7	Wetlands to Settlement land	428.72	7.42	31.80	2.25
8	Wetlands to Bare land	428.72	0.57	2.43	0.17
9	Agriculture land to Dense vegetation	589.64	3.10	18.25	1.29
10	Agriculture land to Wetlands	589.64	12.05	71.03	5.02
11	Agriculture land to Settlement land	589.64	15.49	91.31	6.45
12	Agriculture land to Bare land	589.64	0.44	2.61	0.18
13	Settlement land to Dense vegetation	256.96	1.76	4.53	0.32
14	Settlement land to Wetlands	256.96	15.91	40.88	2.89
15	Settlement land to Agriculture land	256.96	21.27	54.67	3.86
16	Settlement land to Bare land	256.96	0.42	1.09	0.08
17	Bare land to Dense vegetation	7.25	1.76	0.13	0.01
18	Bare land to Wetlands	7.25	18.67	1.35	0.10
19	Bare land to Agriculture land	7.25	6.89	0.50	0.04
20	Bare land to Settlement land	7.25	76.48	5.55	0.39
21	No change			944.79	66.73
Total Area				1415.82	100.00

Table 6 Area contribution per class for 2017 and 2022 classified raster

Class name/code	2017		2022		Area Δ	Percent Δ
	Area (km ²)	Percent	Area (km ²)	Percent		
Dense vegetation	136.64	9.63	150.35	10.59	13.71	10.03
Vegetation/ wetlands	428.72	30.21	476.47	33.57	47.75	11.14
Agriculture/ cultivated land	589.64	41.54	498.31	35.11	-91.33	-15.49
Settlement land	256.96	18.10	286.91	20.21	29.95	11.66
Bare land	7.25	0.51	7.35	0.52	0.09	1.31

CONCLUSION

RS and GIS are vital for classifying and detecting changes in satellite imagery. Using Sentinel-2, five classes were classified in the Diamphwe Basin: dense vegetation, wetland vegetation, agricultural land, settlement land, and bare land. The GPT-CR method was used for supervised classification during the 6-year study period from 2017 to 2022. A total of 66.7% of the basin land was not exposed to any changes in LU/LC. Agricultural land experienced a decrease of 15.5%, of which a large proportion was converted to settlement land, resulting in an increase in settlement land (urbanization) of 11.7%. Within the forest region, dense vegetation experienced an increase in area of 10.0%, largely converted from wetland vegetation. Cooling conditions are expected from an increase in dense vegetation in the forest; however, decreasing agricultural land has a heating effect on the basin. People in the basin experience a heating effect more than a cooling effect because they are closer to agricultural land than to dense vegetation land. Government land reclamation efforts through tight MDF security could have contributed to the increased density of vegetation in the forest. Increased

dense perennial vegetation can contribute to river baseflow, which can increase the river discharge. The decrease in farmland is a worrisome situation for the basin, as over 90% of the inhabitants are farmers. Increased urbanization can mean an expansion of the market for farm goods that can be leveraged by venturing into modern irrigation to increase production. Increased settlement land and decreased wetland vegetation accelerate sedimentation in rivers because of increased surface runoff. This research recommends a combined field and RS study of river ecotone (Dambos) analysis and watershed modelling to quantify the water yield and sediments. LU/LC change detection is key to policy-makers and stakeholders achieving the three pillars of the Malawi 2063 agenda by keeping abreast of land changes.

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Educational and Child Protection in Conflict-Affected Bangsamoro: A Case Study of PEACE-PRO

MA. JOSEPHINE THERESE EMILY G. TEVES

Department of Social Sciences, University of the Philippines Manila, Manila, Philippines

Email: mgteves@up.edu.ph

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Abstract This study examines the impact of the Provision of Expanded Access to Child Education and Protection in Conflict-Affected Areas (PEACE-PRO) project in the Bangsamoro Autonomous Region in Muslim Mindanao (BARMM), where ongoing armed conflict and the COVID-19 pandemic severely disrupted basic education. Conducted over five months (May–August 2024), this ethnographic case study employed semi-structured interviews and focus group discussions with learners, teachers, parents and project implementers. Using Maslow’s hierarchy of needs as a framework, this study analyzes how PEACE-PRO addressed both educational quality and child protection through the creation of safe learning spaces, provision of Water, Sanitation, and Hygiene (WASH) facilities, teacher training, and community-based education governance. The findings indicate that 100% of the parent participants gained a deeper understanding of child protection principles, while 65% recognized the value of educational sessions despite logistical barriers. Moreover, 95% expressed interest in integrating livelihood support into child-focused interventions. This study highlights the potential of private-sector initiatives to contribute meaningfully to rural development, child protection, and educational resilience in conflict-affected settings.

Keywords Maslow’s Hierarchy of Needs, PEACE-PRO, BARMM, rural development, sustainable education, conflict-affected areas

INTRODUCTION

The Provision of Expanded Access to Child Education and Protection in Conflict-Affected Areas (PEACE-PRO) is a private-sector initiative designed to address educational disruptions caused by ongoing armed conflict and the COVID-19 pandemic among basic education students in conflict-affected regions of the Bangsamoro Autonomous Region in Muslim Mindanao (BARMM). Implemented from September 1, 2021, to August 31, 2022, the project aimed to mitigate the negative impact of ongoing armed conflicts and the COVID-19 pandemic on education and child protection in the region. It focuses on enhancing access to safe, uninterrupted, and culturally appropriate educational opportunities while ensuring the physical, mental, and psychosocial well-being of learners in volatile regions.

OBJECTIVE

This study critically assessed the PEACE-PRO project, evaluating its impact on the quality of education and child protection in BARMM, as well as its implications for sustainable rural development in conflict zones.

METHODOLOGY

This study investigated the impact, perceptions, challenges, suggestions, and recommendations of project beneficiaries and stakeholders. It employs qualitative methods, including focus group

discussions (FGDs), semi-structured interviews, documentary analysis, and narratives of Most Significant Change (MSC). These methods were used to gain comprehensive insights into the project's implementation process. Drawing from Hesse-Biber's (2010) perspective, this approach facilitates a nuanced exploration of research paradigms, power dynamics, and authority. Through these qualitative methods, this study provides a detailed understanding of the PEACE-PRO project's contributions to rural development, sustainable education, child protection, and community-based governance in conflict-affected areas.

The research locale is BARMM, a region in the southern Philippines that has undergone significant political changes after decades of conflict. The region's challenges are compounded by limited resources, which further strain the capacity to provide essential services, such as education. Issues such as low participation rates, high dropout rates, and lack of infrastructure have severely affected the region's education system, leaving a significant portion of youth out of school (Lim, 2020).

The sample was purposefully selected to ensure that the perspectives of these groups, who are central to the project's objectives, were adequately represented. The sample included: (a) 71 parents from various schools across BARMM, selected for FGDs to assess their views on the project's impact, educational infrastructure, and challenges faced by their children. These parents were drawn from schools identified as part of the PEACE-PRO initiative, ensuring that the sample reflected a diversity of experiences related to the conflict and educational disruptions, (b) 61 teachers employed in partner schools, who are key participants in the implementation of the PEACE-PRO project. Teachers were selected to provide insights into their experiences with child protection measures, education delivery, and the integration of infrastructure improvements such as Water, Sanitation, and Hygiene (WASH) facilities and safe learning spaces. (c) 14 youth facilitators engaged in the project, who played a role in facilitating activities and offered support to their peers.

RESULTS AND DISCUSSION

The PEACE-PRO project has made significant contributions to rural development, infrastructure, sustainable education, child protection, and community-based governance. The findings align with the approaches of interdisciplinary development, particularly in rural and conflict-affected regions: **(a) Rural development and infrastructure:** The project successfully enhanced school infrastructure, directly contributing to rural development. Key improvements included the installation of WASH facilities and the establishment of Temporary Learning Spaces (TLS) in partner schools. These interventions played a critical role in ensuring the safe reopening of schools during the COVID-19 pandemic and facilitating the continuation of education. WASH facilities not only improve sanitation but also help mitigate the spread of the virus, ensuring a healthier environment for both learners and educators. Furthermore, TLS provide a safe and structured learning environment, enabling students to resume their education in conflict-affected areas where regular school buildings are damaged or repurposed for emergency use. Physical infrastructure improvements directly address the educational and health needs of communities, fostering rural development and helping build long-term resilience against future crises.

(b) Sustainable education: The PEACE-PRO project made a notable contribution to sustainable education, focusing on both accessibility and quality. One of the project's central goals was to improve literacy, numeracy, and social-emotional learning (SEL) skills among learners, which was achieved through the development and distribution of distance learning modules. The project also introduced community-based tutorials to ensure that learners in remote areas, where formal schooling had been disrupted, continued to receive education. The project aligns with the broader Sustainable Development Goals, ensuring that educational opportunities remain accessible, even in crisis situations.

(c) Child protection in rural contexts: A critical finding of this study was the significant impact of the PEACE-PRO project on child protection in rural and conflict-affected contexts. Through its focus on child protection policies, the project raised awareness among parents and teachers about children's rights, including those of marginalized groups, such as children with disabilities and those with

diverse gender identities. Teachers received specialized training in child protection, psychological first aid, and referral pathways for children experiencing abuse or trauma. This is particularly crucial in conflict zones, where children are often exposed to risks such as recruitment by armed groups, early marriage, and gender-based violence. The project also established monitoring and reporting mechanisms for grave child rights violations, which ensured that schools and madrasahs were equipped to address and report issues such as sexual and gender-based violence (Krupar, 2019). The promotion of International Humanitarian Law (IHL) and child protection standards in educational settings further emphasizes the importance of creating safe spaces for learning, where children can access education without fear of exploitation.

(d) Community-based governance: The study also highlighted the role of community-based governance in ensuring the success and sustainability of the PEACE-PRO project. Through local leadership and involvement, the project ensured that the interventions were culturally relevant and were supported by the communities they aimed to serve. Educational sessions for parents were tailored to the specific needs and contexts of the BARMM, empowering families to support their children's learning and wellbeing during the pandemic. Teachers, parents, and youth facilitators actively participated in the project, creating a sense of ownership and accountability within the community, and contributing to the sustainability of the project's educational initiatives. Local governance structures played an essential role in overseeing and supporting the implementation of child protection and educational strategies.

(e) Conflict-affected areas and resilience: The PEACE-PRO project's interventions also demonstrated its focus on resilience-building in conflict-affected areas. In addition to its infrastructure and educational improvements, the project's emphasis on mental health support and psychosocial services helped learners cope with the trauma of conflict and displacement. Capacity-building for teachers in crisis contexts, including training on teacher wellbeing and trauma-informed pedagogical practices, contributed to building resilience within the education system. Teachers were equipped to support learners emotionally and psychologically, which was particularly important in a region where prolonged conflict had led to significant emotional and mental health challenges for both students and educators alike.

Impact on Learners and the Education Sector

From the perspectives of parents and teachers, the PEACE-PRO project was viewed as a transformative intervention. Teachers reported that the training they received, particularly in inclusive practices and child protection, enabled them to better meet the needs of their students, especially those from marginalized groups. Parents also expressed gratitude for the support provided through educational materials and awareness campaigns, which helped them navigate the challenges of remote learning during the pandemic. Overall, the PEACE-PRO project was regarded as a vital initiative that addressed the physical, psychological, and educational needs of conflict-affected communities in BARMM, contributing to both short-term recovery and long-term development in the region.

Parental Engagement and Challenges in Child Protection Education

The PEACE-PRO project successfully engaged 806 parents (259 male, 547 female) in educational sessions focused on child protection, learners' rights, international humanitarian law (IHL), and reporting mechanisms. This high level of participation surpassed the project's target, demonstrating a strong community interest in addressing child protection issues in conflict-affected areas. One hundred percent of All parents reported a deeper understanding of child protection policies, including the importance of ensuring children's rights to safety, participation, and non-discrimination. Many expressed their readiness to attend further training sessions, emphasizing the significant role these programs play in protecting learners and fostering a safe learning environment for them. This highlights the importance of community-driven educational efforts in rural and conflict zones, which align with the strategies of sustainable rural development and ESD. Additionally, they acknowledged

that the provision of school kits addressed their learners' physiological needs. For example, one parent highlighted the benefits of attending sessions on child protection policies while receiving school kits.

Parents' Perceptions of the Value of Education

Sixty-five percent of parents, despite facing logistical barriers, valued educational sessions. This highlights the community's commitment to improving children's welfare and educational outcomes despite the challenges. Parents who attended the sessions felt empowered and motivated to participate in school governance, particularly in child protection committees. The project's ability to offer education that respects parents' diverse roles and responsibilities in rural settings is a model of sustainable education in conflict-affected areas.

Additionally, ninety-five percent of parents expressed a desire for more comprehensive support, including livelihood training alongside child protection education. The integration of livelihood support would address the economic challenges faced by parents, thereby contributing to more sustainable rural development and improved child protection practices. This aligns with Scoones' (2013) emphasis on the need for a holistic approach to rural development, where socio-economic development, including livelihood strategies, is integrated with educational and environmental interventions. Scoones argues that addressing these interconnected areas from a livelihoods' perspective is crucial for creating resilient communities that are better equipped to support both children's welfare and broader development goals.

Sustainability and Long-Term Impact

The PEACE-PRO project was successful in addressing higher-level needs, particularly safety and belonging, according to Maslow's hierarchy of needs. By integrating psychosocial support into school activities and child protection policies, the project contributed to a safer, more supportive learning environment. The positive impact on students and their families suggests that the interventions contribute to the long-term well-being of both learners and their communities. The dedication and motivation of the parents were remarkable. For example, many parents diligently attended educational sessions despite receiving minimal or no financial support from the project organizers. Some even covered their food and transportation expenses. However, for greater sustainability, it is important to continue supporting and expanding the capacity of local communities to independently maintain these initiatives.

The project successfully addressed learners' higher-level needs according to Maslow's hierarchy, particularly safety, belonging, and love. It achieved this by integrating psychosocial support into school activities, thereby addressing the emotional well-being of learners and educators, especially in conflict-affected areas. Furthermore, the project expanded workshops and learning sessions on child protection policies, ensuring accessibility and accommodating parents' and teachers' constraints, such as job schedules and domestic responsibilities.

Empowering Teachers for Child Protection and Development

In rural areas, where access to resources and infrastructure can be limited, teachers play a pivotal role in ensuring the safety and development of children, especially in conflict-affected contexts. However, teachers must possess the necessary knowledge and skills to effectively carry out this crucial responsibility. A comprehensive understanding of learners' rights empowers educators not only to assess whether these rights are respected in the classroom but also to extend this awareness to the broader community. With this knowledge, teachers can address harmful attitudes and behaviors that undermine learners' rights, including their right to safety, non-discrimination, and participation in their educational journey.

Through PEACE-PRO, teachers in both formal public schools and madrasahs experienced significant improvements in their professional development. One notable impact of this project was

the inclusion of training in international humanitarian law and psychosocial support, which is especially vital in conflict zones, such as Gaza. One educator highlighted how this training empowered her to recognize and address child protection issues, thereby ensuring her learners' safety and enabling them to thrive. The training enabled teachers to provide better support for their learners' safety and emotional well-being. Teachers also gained skills in inclusive education practices, preparing them to meet the diverse needs of learners, including those facing significant challenges due to ongoing conflicts or the COVID-19 pandemic itself. For example, one teacher from a Madrasah shared her gratitude for the training, noting how it helped her to better support and protect her learners, especially those in conflict areas. She emphasized the importance of such professional development, as Madrasah educators often lack institutional connections to access similar opportunities. Another educator highlighted the critical need for training in social-emotional learning (SEL) and distance learning strategies, especially given the challenges posed by the pandemic. These initiatives not only addressed learners' educational needs but also contributed to public health safety, which is especially important in rural schools, where resources are limited.

Additionally, teachers gained skills to address the psychosocial needs of students, particularly in the aftermath of crises such as the COVID-19 pandemic. Some teachers identified specific training sessions that they found particularly valuable while preparing for the resumption of face-to-face classes. One teacher mentioned the usefulness of the Psychological First Aid training, which she applied not only to her learners but also to a fellow teacher who faced difficulties during the pandemic. She advocated for expanding this training across the entire district office to benefit her colleagues and parents, who were also impacted by the pandemic. The project has therefore empowered teachers to play a critical role in both child protection and the broader educational development of children, especially in conflict-affected rural areas. Beyond addressing learners' fundamental physiological and safety needs, the project also focused on teachers' esteem needs. This is evidenced by the provision of comprehensive training for teachers in inclusive educational practices, psychological first aid and gender-based violence prevention. These initiatives underscore the critical role of teachers in establishing a supportive learning environment that upholds learners' rights and enhances their self-esteem.

The project's impact extends beyond teachers to include the wider community, such as parents, who play a vital role in supporting child-protection efforts. In the FGDs, some parents expressed their desire for more information about child protection policies and their role in ensuring their children's safety. This aligns with strategies aimed at achieving environmental and rural development, as it underscores the need for inclusive, community-based solutions to address educational challenges.

Impact of the PEACE-PRO Project

The PEACE-PRO project, implemented in conflict-affected rural areas, has had a notable impact on both educators and parents, fostering a deeper understanding of child protection policies and enhancing community engagement in safeguarding children's rights. The qualitative data from FGDs reflect substantial shifts in knowledge, attitudes, and practices among participants, particularly regarding child protection policies and practices. These findings highlight how the PEACE-PRO project contributes to rural development and sustainable education by strengthening the child protection systems and empowering local communities. These results demonstrate the project's success in addressing critical needs and advancing sustainable child protection measures. Specifically, the data show that.

(a) Enhanced child protection practices: Teachers and parents reported significant improvements in their knowledge of child protection, particularly concerning various forms of abuse, as defined by Philippine legislation. Participants noted that they were now better equipped to identify, report, and prevent abuse, thereby ensuring a safer learning environment for students.

(b) Increased awareness among educators: Teachers, particularly in Madrasah schools, which often lack access to formal professional development opportunities, expressed heightened awareness of the legal and ethical responsibilities surrounding child protection. This awareness not only improved

their practices but also empowered them to advocate for stronger protective measures within their schools and communities.

(c) Positive shifts in teachers' attitudes: Teachers reported positive changes in their attitudes toward child protection, emphasizing their commitment to upholding the rights of learners. These shifts were particularly evident in the increased adoption of inclusive education practices, psychosocial support for learners, and active participation in the child protection committees. These changes underscore the project's role in strengthening community-based governance and building a culture of child protection at the local level in the Philippines.

(d) Capacity building for rural educators: Through professional development initiatives, PEACE-PRO equipped teachers with new skills in humanitarian law, inclusive education, psychological first aid, and gender-based violence prevention. These skills are essential for addressing the diverse needs of learners, particularly in conflict-affected rural areas, where resources and training opportunities are limited. The project's focus on providing rural educators with the tools to foster safe, inclusive, and sustainable learning environments aligns with the overall goal of promoting rural development and community-driven solutions.

The results demonstrate that the PEACE-PRO project has significantly contributed to enhancing child protection measures in rural, conflict-affected areas by empowering teachers and parents with the knowledge and skills necessary to safeguard the rights of learners. By addressing both educational and protective needs, the project aligns with strategies for achieving sustainable education, rural development, and community-based governance.

CONCLUSION

The PEACE-PRO project exemplifies a holistic, evidence-based approach to improving educational quality and child protection in conflict-affected areas of the BARMM. Grounded in Maslow's hierarchy, the project addressed learners' basic and psychological needs while advancing their academic and social development. By the project's conclusion, students demonstrated measurable improvements in literacy and numeracy: endline assessments revealed a 34% increase in functional literacy and a 28% gain in numeracy skills. These outcomes were assessed using tools adapted from the early grade reading assessment and early grade Mathematics assessment, contextualized for the Bangsamoro setting and administered by trained facilitators.

Child protection mechanisms were also significantly enhanced, with a 65% increase in the number of identified and resolved cases owing to improved referral systems, psychosocial support, and school-community collaboration. Teacher capacity building was central to these outcomes, with 87% of educators completing training in child-centered pedagogy and protection protocols. The project's multisectoral approach not only improved learning outcomes but also laid the foundation for sustainable, community-led development. In alignment with Redding (2023) and Ahmad et al. (2023), PEACE-PRO confirms that education, when inclusive and protective, is a powerful catalyst for empowerment and long-term social resilience.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA ACCESS STATEMENT

The data supporting the findings of this study are available from the corresponding author upon reasonable requests.

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Assessing Determinants and Adoption Patterns of Sustainable Rice Cultivation in Central Northeast Thailand

ORAWAN SRISOMPUN*

Maharakham University, Maha Sarakham, Thailand

Email: orawan.s@msu.ac.th

HO THANH TAM

Ritsumeikan University, Kyoto, Japan

TRAN QUOC THINH

Ritsumeikan University, Kyoto, Japan

KOJI SHIMADA

Ritsumeikan University, Kyoto, Japan

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Abstract This study evaluated the determinants and adoption patterns associated with sustainable rice farming practices in Central Northeast Thailand. A sample of 109 farmers was selected using multistage sampling, targeting regions with a high number of GAP-certified or organic rice farmers. Data were collected through structured interviews and analyzed using descriptive statistics and stepwise regression. The findings revealed that the most widely adopted sustainable rice farming practice was manure application (89.91%), whereas more advanced practices, such as climate-smart or precision agriculture, exhibited low adoption rates (9.17%). Participation in farmer groups played a crucial role in promoting sustainable practices, with 93.75% of high adopters engaging in farmer groups, underscoring the importance of local institutions in facilitating adoption. Risk attitude also influenced adoption, with risk-tolerant farmers more likely to embrace sustainable practices, particularly among the high-adoption group (56.25%). Economic awareness was significantly correlated with higher adoption levels, with an average Likert score of 4.41 among high adopters. The regression analysis confirmed that farmer group participation and economic awareness had statistically significant positive effects on adoption, whereas risk aversion had a statistically significant negative effect. Additionally, challenges related to pest and weed management have encouraged farmers to seek more effective solutions, thereby facilitating the adoption of sustainable practices. These results indicate that enhancing local institutional support and promoting superior rice varieties are crucial for increasing sustainable rice farming practices in this region.

Keywords sustainable rice farming, adoption patterns, Central Northeast Thailand, farmer group participation, agronomic challenges

INTRODUCTION

Rice farming, a crucial component of Thailand's economy, is an enduring cultural and social fixture. Apart from its economic significance, rice is the national food of the Thai people. Rice is a symbol of food security and prosperity, and it plays an integral role in Thai traditions, rituals, and daily life. (Suebpongsang et al., 2020). Thailand's agriculture and economy revolve around rice production. Rice cultivation remains the cornerstone of Thai agriculture, with roughly 45-50% of the national agricultural land consistently devoted to it (FAO, 2025). Rice is Thailand's number one agricultural product, accounting for 15% of the agricultural gross domestic product (GDP). Rice is Thailand's second most valuable agricultural export. However, rice cultivation faces increasing challenges as it strives to balance productivity and sustainability. Climate change, fluctuating market demand, and

increasing global market competition exacerbate the vulnerability of Thailand's rice farmers (IPCC, 2021). These challenges necessitate a shift toward more resilient and sustainable agricultural practices that can safeguard the future livelihoods of farmers and ensure the nation's food security. This transition is crucial for maintaining Thailand's competitive edge in the international rice market while addressing environmental concerns and meeting global sustainability targets (Connor et al., 2023).

Conventional rice farming practices worldwide, including dependence on synthetic fertilizers and chemical pesticides, have led to environmental and economic challenges. These practices are significant sources of greenhouse gases, such as methane and nitrous oxide, and thus lead to the worsening of climate change (Sari et al., 2023). In addition, the rapid development of intensive rice production systems has intensified soil degradation, water pollution, and ecological risks, particularly in developing regions of the world. These deleterious effects are mainly related to the overuse of agrochemicals to achieve high yields (Tran et al., 2024).

In response, sustainable agriculture has received growing attention as an option to reduce the rate of environmental degradation while continuing to guarantee food security and support rural farmers and communities. Rice production in particular is a resource-demanding and environmentally relevant crop. Rice paddy growing alone substantially contributes, both in terms of total yearly global methane emissions and water use (IPCC, 2021). For example, research in Northeast Thailand found that rice has significantly lower water productivity than other crops, such as field corn, highlighting its high-water demands (Promkhambut et al., 2014). As one of the world's leading rice producers, Thailand faces mounting pressure to transition toward more sustainable agricultural practices to address environmental and economic vulnerabilities.

This heightened awareness and the trade-offs between productivity and natural resource degradation have contributed to Thailand's promotion of sustainable farming practices, such as organic matter addition, crop rotation, and water-saving methods, such as alternate wetting and drying (AWD). These practices are increasingly recognized globally as achieving a good balance between high production and environmental sustainability (FAO, 2023). In the context of the most recent Food and Agriculture Organization (FAO) policy framework, sustainable rice systems and cultivation practices should improve productivity while conserving ecosystems, contributing to climate adaptation and mitigation (FAO, 2021). Likewise, the IPCC (2022) indicated that climate-resilient technologies, including reduced agrochemical use, AWD irrigation, and improved rice varieties, are crucial for reducing emissions and enhancing food security.

Despite the increased recognition of the benefits of sustainable agriculture by policymakers, researchers, and development organizations, the adoption rates of these practices among smallholder farmers remain limited (Pierrette et al., 2021). The adoption of sustainable methods is influenced by financial resources, attitudes towards risks, and knowledge of the economy of farmers (Pannell et al., 2006). This study aims to fill these knowledge gaps by analyzing the determinants and major drivers of the adoption patterns of sustainability-related practices for rice cultivation in Central Northeast Thailand. Utilizing descriptive statistics and stepwise regression analysis, this study identified key drivers of adoption, including farmer group affiliation, economic knowledge, and agronomic challenges, offering valuable insights for the development of future sustainability policies in Thailand.

OBJECTIVE

This study aimed to explore the socioeconomic, agronomic, and institutional factors influencing the adoption of sustainable rice farming practices. The research findings will provide insights for policymakers and stakeholders to design targeted interventions that promote sustainable rice farming and enhance farmers' resilience to environmental and economic challenges in the region.

METHODOLOGY

Study Areas, Data Collection, and Sampling Method

This study was conducted in the Maha Sarakham and Khon Kaen provinces in Central Northeastern Thailand, which are major rice-producing provinces. To provide broad data, Maha Sarakham Province was selected because of its primary irrigation reliance on a rain-fed ecosystem and the variable and unpredictable seasonal rainfall, and Khon Kaen Province was selected because of its access to a well-established irrigation system, including reservoirs and canal networks, that supports double-cropping.

This study utilized cross-sectional data collected through structured interviews with 109 rice farmers. The data encompassed household, demographic, and socioeconomic characteristics, land use, cultivation practices, input use, labor practices, production costs, organizational membership, agricultural experience, and farmer awareness of sustainable farming practices. Additional information included challenges in rice cultivation, problem-solving strategies, production goals, and participation in training and field visits.

The population for this study comprised rice farmers from the Central Northeastern region of Thailand who practiced sustainable rice production, including biocontrol and natural extraction methods. Given the absence of precise statistical data regarding the population, the sample size was estimated using a standard formula for sample size determination based on the proportions. Using a 95% confidence level ($Z = 1.96$), 5% margin of error (E), and estimated adoption proportion (p) of 7.63% (based on GAP and organic rice farming statistics) (Srisompun et al., 2019), the calculated sample size was 108.23. The sample size was rounded up to 109 farmers for the analysis.

A multistage sampling technique was used to ensure a representative sample of rice farmers who adopted sustainable practices. Farmers were purposively selected from Maha Sarakham and Khon Kaen provinces of Thailand. In each province, districts with the highest concentrations of GAP-certified or organic rice farmers were identified. From these districts, one sub-district per province was purposively sampled, and the farming households were listed. Finally, farmers were randomly selected using simple random sampling to ensure equal representation within the sub-districts.

Data Analysis and Model

Descriptive statistics and stepwise regression were used to analyze the data collected. The sustainable rice farming practice adoption patterns were summarised using descriptive statistics, describing these practices' frequencies compared with other planting practices, such as resource use. We used stepwise regression to investigate the determinants influencing the adoption of sustainable practices. The number of sustainable practices adopted was the dependent variable in the model, with independent variables being a combination of farmer characteristics (age, education, farm size, and income), institutional factors (farmer group participation and access to extension services), and agronomic challenges (pest and weed problems). Economic awareness was also included as a variable and was measured on a Likert scale ranging from 1 (very low) to 5 (very high). This method ensured that only the most impactful variables related to adoption were retained, as non-significant variables were removed (Frost, 2020).

RESULTS AND DISCUSSION

The study of the rates and scales of adaptation to recommended rice management practices by rice farmers in central northeastern Thailand reflects a varied picture of agricultural practices in the region. According to Table 1, the highest adoption level was for manure application, which was practiced by 89.91% of the farmers, indicating that it is widely accepted and perceived to be effective. On the other hand, modern techniques like Climate Smart or Precision Agriculture remained less adopted, at only 9.17%. The adoption rate of organic rice cultivation is moderate and is used by more than half (59.63%) of the farmers. Biocontrol and water-efficient rice varieties, although increasingly heavily promoted, still face limited adoption at 32.11% and 22.94%, respectively.

The rightmost columns in Table 1 present the adoption distribution of farmers by the 15 sustainable practices studied. These data demonstrate that some farmers applied only a few practices (13.89% applied four), while a smaller proportion adopted a wide range of sustainable practices.

Table 1 Adoption rates and patterns of sustainable rice practices among farmers

Sustainable rice practice	Number of farmers	% Adoption	Number of practices adopted	Number of farmers	% Adoption
Organic rice	65.00	59.63	0.00	1.00	0.93
System of rice intensification (SRI)	24.00	22.02	1.00	6.00	5.56
Apply manure	98.00	89.91	2.00	7.00	6.48
Reduce chemical fertilizers	81.00	74.31	3.00	4.00	3.7
Reduce pesticide	56.00	51.38	4.00	15.00	13.89
Crop rotation	51.00	46.79	5.00	14.00	12.96
Cover crop	33.00	30.28	6.00	10.00	9.26
Alternate wetting and drying	30.00	27.52	7.00	14.00	12.96
Direct seeding	8.00	7.34	8.00	6.00	5.56
Water conservation	28.00	25.69	9.00	8.00	7.41
Water-efficient rice varieties	25.00	22.94	10.00	8.00	7.41
Biocontrol	35.00	32.11	11.00	2.00	1.85
Natural extracts	33.00	30.28	12.00	8.00	7.41
Native rice varieties	25.00	22.94	13.00	1.00	0.93
Climate-smart/Precision agriculture	10.00	9.17	14.00	3.00	2.78
			15.00	1.00	0.93

Source: Authors survey. Note: The left side presents the adoption rates of individual practices; the right side presents the distribution of farmers by the total number of sustainable practices they adopted.

The analysis presented in Table 2 provides illuminating insights into the adoption levels across different farmer groups and their associated risk attitudes and economic indicators. The farmers were classified into three categories based on the number of sustainable practices adopted: minimal adoption (1–5 practices), medium adoption (6–10 practices), and high adoption (more than ten practices). A key observation was the significantly higher participation in farmer groups among the high adoption group (93.75%) than the low (57.45%) and medium (69.57%) groups. This suggests that group membership plays a vital role in promoting the adoption of sustainable practices, as farmer groups offer improved access to extension services and technical information (Mtega, 2021) and serve as effective channels for knowledge dissemination (Rahmadanih et al., 2018). This trend is paralleled by an increase in risk tolerance attitudes among the high adoption group (56.25%), suggesting a potential correlation between a farmer's willingness to embrace risk and their engagement in sustainable practices. Additionally, adoption levels increased with increased economic awareness, with the high adoption group scoring an average of 4.41 on a Likert scale, compared to 3.92 and 3.99 in the low and medium groups, respectively. This suggests that greater awareness of economic impacts may be linked to higher adoption rates. Furthermore, the high adoption group experienced the most substantial challenges with weed issues (62.5%), indicating that while these farmers are willing to adopt sustainable practices, they also face significant agronomic challenges in doing so.

The results of the stepwise regression analysis, presented in Table 3, highlight the critical factors influencing the adoption of sustainable agricultural practices. Of particular interest is that participation in farmer groups was a positive predictor (Beta = 1.557, $p = 0.011$). The results support earlier work underlining the importance of social networks and collective learning in increasing the adoption of innovative practices (Pretty, 2003; Bandiera and Rasul 2006). Farmer groups frequently operate as knowledge-sharing centers, where individuals gain insight from their peers and can efficiently connect to extension services, thereby alleviating the uncertainty surrounding sustainable adoption of new practices. However, risk attitude was negatively correlated with adopting sustainable practices (coefficient = -0.262 ; $p = 0.027$). This seems to indicate that risk-averse individuals do not adopt sustainable practices, as they perceive higher levels of uncertainty and lower short-term returns compared to existing conventional practices. This finding corresponds with that of Marra et al. (2023), who suggested that risk aversion may largely suppress the adoption of agricultural innovations, as they typically impose high switching costs in terms of either disruption to routine farming practices or upfront investments.

Table 2 Adoption levels of sustainable rice farming practices and associated risk and economic indicators

Variables	Group of adoption level ^{1/}			Overall
	Low	Medium	High	
Farmer group participation (%)	57.45	69.57	93.75	67.89
Risk attitude score				
- Risk lover (%)	23.40	23.91	56.25	28.44
- Medium risk (%)	55.32	63.04	43.75	56.88
- Risk aversion (%)	21.28	13.04	0	14.68
Issues faced (%)				
- Pest issues	2.13	13.04	25.00	10.09
- Weed issues	17.02	17.78	62.50	24.07
- Labour cost issues	2.13	28.26	18.75	15.60
Economic awareness (Likert 1–5) ^{2/}	3.92	3.99	4.41	4.02

Source: Author's Calculation

Note: ^{1/}Group of Adoption Level defined as: Minimal (<5 practices), Medium (6-10 practices), High (>10 practices).

^{2/} Economic Awareness Scale: 1 = Very Low, 2 = Low, 3 = Medium, 4 = High, 5 = Very High.

Table 3 Stepwise regression results for factors influencing sustainable agriculture adoption

Variable	Coefficient	Std. error	t-statistic	p-value ^{1/}	
Farmer group participation	1.557	0.600	2.590	0.011	***
Risk attitude	- 0.262	0.117	- 2.240	0.027	**
Economic awareness	0.727	0.347	2.100	0.039	**
Pest issues	3.112	0.924	3.370	0.001	***
Weed issues	2.324	0.642	3.620	0.001	***
Labor cost issues	2.716	0.730	3.720	0.001	***
Constant	2.430	1.638	1.480	0.141	

Source: Author's Calculation

Note: ^{1/} ** statistically significant at p-value ≤ 0.05 ; *** statistically significant at p-value ≤ 0.01

The results indicate that economic awareness significantly and positively influences the adoption of sustainable agricultural practices, with a coefficient value of 0.727 ($p = 0.039$). This highlights how important economic incentives are in shaping farmer behavior. More precisely, when farmers recognize the economic benefits of sustainable practices such as lower input costs, increased efficiency, and access to premium markets they are more likely to adopt these practices. This is in line with the basic principles of the Diffusion of Innovation Theory (Xia et al., 2022), which states that innovation adoption is determined by its relative advantages. One of the most important components of relative advantage is economic benefit, which strongly influences decisions. For example, farmers who are aware of the cost savings associated with decreased chemical usage or higher selling prices for sustainable or certified products are more likely to adopt sustainable farming systems. In addition, economic incentives play a prominent role in adopting innovative processes in the agricultural sector. Taylor and Bhasme (2024) noted that farmers tend to abandon or reject innovations when the sustained economic benefits are not clear-cut, particularly if they do not match the socioecological context of those who could benefit from adopting new practices. They observed that farm and ranch sustainability is required to maintain the long-term adoption of agricultural innovations.

The analysis revealed that pest and weed management challenges significantly limited the adoption of sustainable agricultural methods, with coefficients of 3.112 and 2.324, respectively, and p-values of less than 0.001. These findings underscore the critical role of effective pest and weed control in crop performance and farm profitability. Farmers may perceive sustainable practices as less reliable in managing these issues than conventional methods, leading to adoption hesitancy. Farmers often view sustainable practices as inadequate for addressing pest and weed problems because they directly affect crop yields and economic returns. This perception creates a substantial barrier to the widespread implementation of sustainable methods (Finger et al., 2024). Conventional methods are often regarded as more efficient and reliable by farmers, particularly in pest and weed management, because of the quick and bio-efficient effects of spraying chemicals. In contrast,

sustainable approaches, such as integrated pest management (IPM) or cover cropping, require more time, labor, and knowledge, with benefits that are less immediate or more difficult to quantify (Pretty, 2008). Such perceptions add to the resistance to alternative approaches, especially among farmers with a short-term financial outlook. It is essential to respond to these challenges with integrated and diverse strategies. Increasing extension services to deliver more specific training and local support may provide farmers with the skills, knowledge, and experience required to efficiently implement integrated management practices. Moreover, governments should provide financial incentives to facilitate the transition to more sustainable methods. Potential amendments to pricing schemes could include tiered pricing for biocontrol products to improve affordability, as well as subsidies or cost-sharing programs that reduce the economic burden associated with typically labor-intensive sustainable practices (Pannell et al., 2006).

Additionally, labor costs have emerged as a pivotal factor influencing the adoption of sustainable agricultural practices, as evidenced by a coefficient value of 2.716 ($p < 0.001$). In many sustainable practices, the labor-intensive nature often discourages their adoption, especially in locations with scarce and/or expensive labor availability. If farmers recognize a decrease in the total amount of labor required, they are more likely to adopt these practices. This agrees with previous studies, such as that by Silva and Ratnaweera (2020), who indicated that labor shortages and the high cost of labor are major obstacles to the adoption of input-intensive agricultural technology. Because the economic benefits of transitioning to sustainable practices are, in many cases, not immediate, the need for additional labor inputs further exacerbates farmers' reluctance to use sustainable methods. This calls for the development and diffusion of labor-saving technologies and working practices. To solve this challenge, mechanization, precision agriculture tools, and better management practices should all play an important role in decreasing the labor intensity of sustainable farming-type systems to make them more appealing to farmers. Chindasombatcharoen et al. (2024) argued that the adoption of such labor-saving innovations is crucial for the broader implementation of sustainable agricultural systems. By alleviating labor constraints, these technologies can not only improve efficiency but also foster greater resilience in agricultural systems, particularly in labor-constrained environments.

CONCLUSION

This study focused on the determinants of adoption of sustainable rice farming practices in the Maha Sarakham and Khon Kaen provinces in Central Northeast Thailand. The findings confirm that farmer group participation and economic awareness are key drivers of adoption, underlining the critical role of social networks and financial considerations in facilitating the transition to sustainable agriculture. Despite these benefits, the adoption of sustainable practices is uneven, as risk-averse farmers may be reluctant to adopt them because of perceived risks and short-term costs. There are also major challenges with agronomics, mainly weed and pest management and high labor requirements. Sustainable practices are often perceived as more labor-intensive and less effective for pest control than conventional methods, limiting their adoption in areas with labor constraints. To address these challenges and promote wider adoption, we propose the following recommendations.

1. Local institutions should be empowered by motivating farmer groups and cooperatives to improve learning, collective decision-making, and technical assistance to build trust, facilitate learning and evolution, and make sustainable practice adoption ready.
2. Encourage economic incentives, such as subsidizing sustainable inputs, market access, and premium pricing of certified sustainably produced rice. Such rewards lower financial risks and enhance the attractiveness of sustainable practices.
3. Government agencies, research institutions, and development partners should invest in appropriate technologies, such as labor-saving equipment, precision farming tools, and integrated pest management (IPM) solutions. This could reduce the physical effort required for sustainable farming, making such methods more effective and scalable.
4. Strengthening and updating extension services or their development, and the combination of sustainable agriculture in rural development programs with recurring analysis and feedback,

capacity building, and credit or crop insurance. Extension officers should be trained to address risk perception and help farmers build long-term resilience.

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ETHICAL STATEMENT

This study was conducted in accordance with the institutional ethical guidelines. Ethical approval was obtained from the Human Research Ethics Committee of Mahasarakham University (Approval No. [487-459/2567]). Prior to the interviews, all participants were informed about the purpose of the study, assured of the confidentiality of their responses, and provided written or verbal consent to participate voluntarily.

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Feasibility of Low Water Level Management in Irrigation Ponds: Focusing on Baseflow and Water Storage Recovery Periods in Oro River Basin, Tottori

REN NISHIURA

Graduate School of Sustainability Science, Tottori University, Tottori, Japan

YURI YAMAZAKI

Faculty of Agriculture, Tottori University, Tottori, Japan

KATSUYUKI SHIMIZU*

Faculty of Agriculture, Tottori University, Tottori, Japan

Email: shimizu@tottori-u.ac.jp

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Abstract Japan has about 150,000 irrigation ponds, primarily located in areas with low rainfall and regions lacking nearby rivers. These ponds primarily supply irrigation water for paddy fields and serve as year-round sources of domestic and fire-fighting water. In recent years, Japan has experienced an intensification and increase in the frequency of heavy rainfall events from summer to autumn (July to September), leading to an increase in the number of water-related disasters. These irrigation ponds have also suffered an increase in disasters caused by heavy rainfall. To address this issue, one of the flood control methods for irrigation ponds is “low-water-level management”. By maintaining lower water levels, it is expected that the risks of dike breaches due to overtopping will be minimized, and peak flow from the spillway will also be mitigated. However, implementing low-water-level management may lead to the potential risk of not being able to secure a sufficient water supply for irrigation. This study evaluated the feasibility of implementing low-water-level management across 52 irrigation ponds in the Oro River Basin in Tottori City, Tottori Prefecture. We calculated the recovery period for water storage using only baseflow to determine whether it is possible to maintain low water levels without compromising the necessary water supply. The results indicate that low-water-level management can be implemented in many ponds without significant concerns regarding water availability, supporting its potential as a flood control measure.

Keywords low-water level management, baseflow, hydrological observation, flood mitigation

INTRODUCTION

Japan's landscape is dotted with approximately 150,000 irrigation ponds, primarily in areas with low precipitation or lacking large rivers. These ponds are mainly used for irrigating rice paddies in the region. Some ponds also serve other roles, such as irrigating upland crops and fruit trees, providing domestic water supply, and preventing fires in downstream villages.

The increasing intensity of heavy rain, a direct consequence of climate change, has wreaked havoc on Japan's irrigation ponds in recent years. The Ministry of Agriculture, Forestry and Fisheries, Japan (MAFF) reports that from 2013 to 2023 (MAFF 2024), heavy rains have damaged a staggering 6,040 irrigation ponds, with 320 collapsing under the onslaught.

Failures in irrigation ponds caused by heavy rainfall can be broadly classified into three categories: seepage, embankment sliding, and overflow (Hori et al., 2002). Overflow failure occurs when the water level in an irrigation pond rises rapidly during heavy rainfall, causing water to

overflow the embankment and leading to erosion. The risk of overflow failure is expected to increase with an increase in heavy rainfall events owing to global warming (Mihara et al., 2023).

As a preventative method to mitigate the risk of overflow failure, the Japanese government has set a design standard requiring irrigation pond spillways to safely pass a 200-year flood event. However, renovating a large number of irrigation ponds is time-consuming and costly. To address this issue, a low-cost emergency discharge device was developed to prevent or mitigate flooding (Shimizu et al., 2016).

In recent years, low-water-level management has attracted attention as a cost-effective and efficient method for mitigating the risk of overflow failure. This approach includes two main strategies: (1) pre-release before rainfall, where water levels are temporarily lowered in anticipation of heavy rainfall, and (2) scheduled water level control, where water levels are managed at specific values according to a predefined plan for different periods of time. Both methods aim to enhance the effectiveness of irrigation ponds in terms of flood mitigation by maintaining an adequate capacity to accommodate heavy rainfall.

However, the primary function of irrigation ponds is to maximize water storage. Implementing low-water-level management would defeat the original purpose of irrigation ponds and may lead to insufficient water availability for irrigation. Additionally, irrigation managers often hesitate to adopt pre-release strategies before rainfall because of uncertainty regarding the time required for water levels to return to their original state after release.

OBJECTIVE

This study aimed to quantify the monthly baseflow from hydrological observations at two irrigation ponds in the Oro River Basin, Tottori, and to estimate the water storage recovery period in 52 irrigation ponds using observed baseflow rates.

METHODOLOGY

Target Area

In this study, we selected irrigation ponds in the Oro River Basin in Tottori City. Various efforts have been made for watershed flood control in the area because flood damage due to heavy rainfall has been frequent in the past. Most of these irrigation ponds are created by filling valleys. Their total storage volume ranges from 200 to 260,000 m³, catchment area from 0.004 to 1.483 km², and full water area from 60 to 40,000 m². Data for each irrigation pond were obtained from the irrigation pond registry owned by Tottori Prefecture.

In this region, the irrigation season for paddy fields is from May to September (Harasawa et al., 2023; Shimizu et al., 2015). This season coincides with the season (August and September) when heavy rainfall events such as typhoons are most frequent.

Hydrological Observation

Precipitation: Precipitation was measured at the Tottori Observatory by the Japan Meteorological Agency (JMA). Data were collected from the Internet (JMA, 2024). The collection interval was 1 h, and the period was from August 1, 2023, to December 31, 2023.

Runoff volume: The runoff volume from the catchment area into the irrigation ponds must be determined. However, directly capturing the discharge from irrigation ponds in the catchment area is difficult. Therefore, we selected irrigation ponds with few water withdrawal operations and relatively stable near-full water levels and measured the overflow from the spillways of these irrigation ponds by flow observation in the canal immediately below the irrigation ponds and assumed that this was the discharge from the catchment area into each irrigation pond. Table 1 shows the characteristics of the irrigation ponds where hydrological observations were made.

Table 1 Specifications of the ponds where hydrological observations were conducted

	Storage capacity (m ³)	Catchment area (km ²)	Water area (m ²)
Pond 1	3,100	0.131	2,400
Pond 2	3,200	0.029	800

We conducted water level and flow observations in the downstream canal of two irrigation ponds. Water levels were observed at 15 min intervals using a capacitance water level meter. The observation period was from August 1 to December 31, 2023. The average flow velocity at different water levels was measured five times in both irrigation ponds using a current meter. The values were multiplied by the cross-sectional area of the canal to obtain the flow rate. A water level-flow curve was prepared from the canal water level and flow rate through flow observations.

The lowest stable water level for each month was extracted from the observed water levels. The values were substituted into the water level-flow curve, and the calculated flow rate was used as the base-flow rate. Eq. (1) was used to convert the flow rate into the baseflow height.

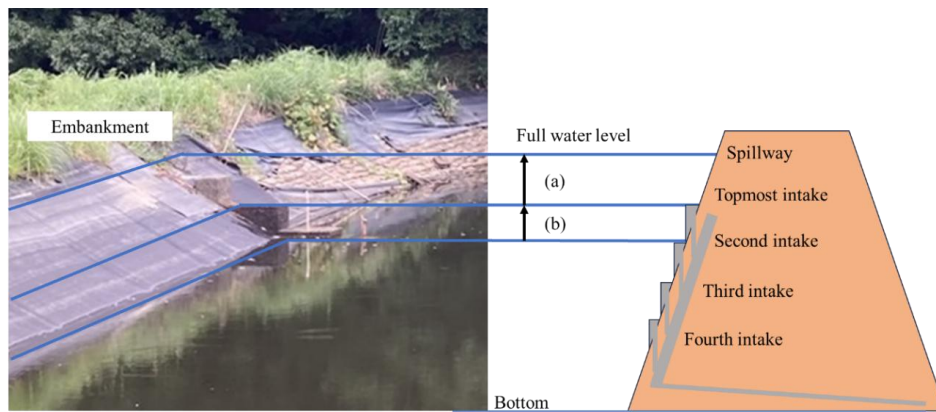
$$q_b = \frac{0.0864Q}{CA} \quad (1)$$

Where q_b is baseflow height (mm/d), Q is flow rate (L/s), CA is catchment area (km²).

Water storage Recovery Period

We selected 52 of the 72 ponds in the Oro River Basin to estimate the water storage recovery period based on the following criteria: (1) irrigation ponds that store water only from runoff from the catchment area without any water supply from the river and (2) irrigation ponds with available data on total storage, basin catchment area, and full-water area.

Here, we estimated water storage recovery periods for two types of water level differences in each pond (Fig. 1). (a) Water level difference from the topmost intake level to the full-water level. (b) Water level difference from the second intake level to the topmost intake level.

**Fig. 1 Water level difference (a) and (b)**

Both periods were calculated for the late summer season, when most damage from heavy rainfall or typhoons is expected. However, September is the end of the irrigation season; therefore, water demand is relatively low, and pre-release is unlikely to cause serious problems. Furthermore, by the end of the irrigation period, water levels are usually low, so pre-release is unnecessary. Therefore, this study did not consider the case of September. The respective recovery periods for each irrigation pond were calculated using Eq. (2).

$$T = \frac{V}{1000 \cdot q_b \cdot CA} \quad (2)$$

Where T is water level recovery period (d), V is storage capacity (m³), q_b is baseflow height (mm/d), and CA is catchment area (km²).

V was defined as the full-water area multiplied by the measured intake spacing ((a) or (b) in Fig. 1). For irrigation ponds where the intake spacing could not be measured, an average value of 30 cm was used for both (a) and (b).

RESULTS AND DISCUSSION

Monthly Baseflow Height

The monthly baseflow heights of ponds 1 and 2 and the precipitation during the month are shown in Table 2.

Table 2 Monthly basal run-off heights and precipitation in Ponds 1 and 2

	Baseflow height at Pond 1 (mm/d)	Baseflow height at Pond 2 (mm/d)	Precipitation (mm/m)
August	3.03	4.43	266.0
September	0.97	1.66	133.5
October	0.73	1.91	101.5
November	1.03	2.71	166.0
December	2.28	2.71	102.0

The monthly baseflow height for each pond ranged from 0.73 to 3.03 mm/d for Pond 1 and from 1.66 to 4.43 mm/d for Pond 2. The baseflow heights of ponds 1 and 2 in the same month differed by 0.4-1.4 mm/d. In both ponds, baseflow heights were high in August, when rainfall was high, while baseflow heights were low when rainfall was low. In contrast, baseflow heights were higher in December, despite the low precipitation.

We calculated the correlation coefficients between the monthly base runoff height and the total precipitation one month before the day the base runoff was observed. The correlation coefficients were 0.73 for Pond 1 and 0.81 for Pond 2, indicating a strong correlation between the two irrigation ponds. A high correlation between the monthly base runoff height and the total precipitation the month before the day indicates that the previous rainfall greatly affects the baseflow rate in a small catchment area, such as an irrigation pond. In August, the baseflow heights used to estimate the water storage recovery period during the irrigation period were set at a minimum of 3.03 and a maximum of 4.43 m.

Water Storage Recovery Period

Figure 2 shows the top 20 ponds with the longest water storage recovery periods among the 52 ponds. Almost all irrigation ponds (ponds A to M in Fig. 2) recovered the water level to the maximum within a week, regardless of the water storage recovery period of (a) and (b). Among the remaining 32 irrigation ponds not included in Fig. 2, the water storage levels recovered quickly, with recovery periods ranging from 0.1 days to a maximum of 3 days. Therefore, the possibility of a water shortage is low. In this region, rice paddy irrigation is generally completed by mid-August. While some paddies with longer growing periods may continue irrigation into September, they represent a small minority of the total. In light of this situation, by August, which marks the final stage of the irrigation period, if the irrigation pond is at full capacity or reaches the level of the first intake valve, then even if the water level is reduced by one intake valve, the risk of water shortage is considered low, provided that the level can recover within approximately one week without rain. Therefore, the irrigation manager can pre-release water before rainfall during the irrigation season. In addition, these are the water storage recovery periods considering only the baseflow rate, and the actual recovery period is expected to be shorter than this. In addition, because the baseflow heights of ponds 1 and 2 were applied to all irrigation ponds in the Oro River Basin in this study, the actual results may differ from these.

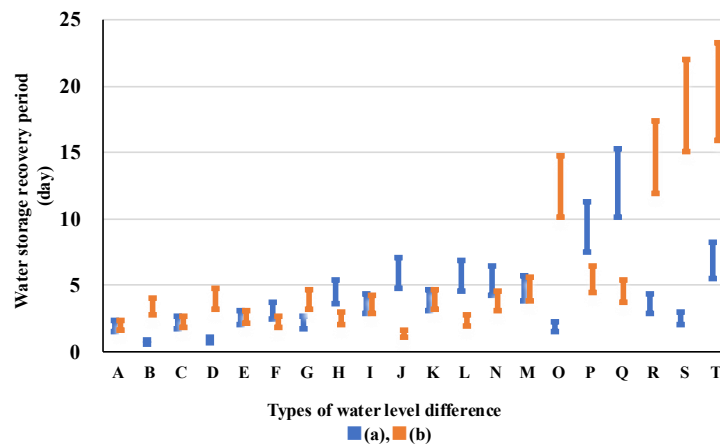


Fig. 2 Water storage recovery period

CONCLUSION

We found that the amount of baseflow into the irrigation ponds varied greatly from period to period, which was strongly influenced by rainfall. The differences in flow rates, despite the irrigation ponds being in the same area, suggest that observations should also be conducted in other irrigation ponds.

Low-water-level management during the irrigation season can also be implemented without worrying about water shortages due to quick recovery. The actual water storage rate recovery period is expected to be shorter than estimated because only the baseflow rate was used as inflow for the calculation.

To accurately calculate the water storage recovery period, the following issues need to be addressed: water level monitoring throughout the year, accurate irrigation pond storage capacity measurement methods, and the development of runoff analysis models that can be adapted to small catchment areas.

In addition, it is necessary to estimate the water requirements of the beneficiary areas and evaluate the flood control function of low-water-level management in irrigation ponds.

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Effect of Seasons on the Quality of Fresh Semen in Thai Native Chickens: Deang Dok Koon and Pradu Hang Dam

YUPIN PHASUK*

Faculty of Agriculture, Khon Kaen University, Khon Kaen, Thailand
Email: yuplua@kku.ac.th

NATNAREE KANTASON

Faculty of Veterinary Medicine, Khon Kaen University, Khon Kaen, Thailand

SAJEE KUNHAREANG

Faculty of Agriculture, Khon Kaen University, Khon Kaen, Thailand

THEVIN VONGPRALUB

Faculty of Agriculture, Khon Kaen University, Khon Kaen, Thailand

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Abstract This study investigated the impact of seasonal variations on the quality of fresh semen in two Thai Native chicken breeds: Deang Dok Koon (DDK) and Pradu Hang Dam (PD). A 3×2 factorial experiment was conducted using a completely randomized design (CRD). The factors considered were season (summer, rainy, and winter) and breed (DDK and PD) of the cows. Twelve roosters per breed (aged 1 year) and 40 commercial laying hens were housed in open-air conditions. Semen was collected twice a week for 24 weeks (48 total collections). Semen volume, mass movement, sperm progressive motility, sperm concentration, total sperm count, sperm viability, sperm morphology, and fertility were evaluated. No significant interaction was found between season and breed. While the season did not affect mass movement, sperm progressive motility, and total sperm count, it significantly influenced semen volume, sperm concentration, sperm viability, sperm morphology, and fertility. Winter had the highest sperm concentration (4.51×10^9 sperm/mL), followed by summer (4.16×10^9 sperm/mL) and the rainy season (3.82×10^9 sperm/mL). Summer had the lowest sperm viability (93.45%), whereas rainy (95.49%) and winter (95.22%) seasons were similar. Sperm morphology was higher in summer (6.79%) than in the rainy season (5.66%) and winter (5.18%); however, the rainy season and winter were not significantly different. Fertility rates were highest in winter (86.81%) and the rainy season (85.88%), with summer (77.99%) being the lowest. Breed significantly affected mass movement, sperm progressive motility, sperm concentration, and sperm viability, but not fertility. The PD breed showed superior semen quality compared to DDK. Overall, seasonal variations significantly impacted fresh semen quality, with winter providing optimal conditions compared to summer and rainy seasons.

Keywords semen quality, sperm motility, fertility, seasonal variation, Thai native chicken

INTRODUCTION

The Deang Dok Koon (DDK) chicken, a novel synthetic breed developed in Thailand, presents a viable pathway for enhancing employment opportunities in small-scale agricultural sectors. This dual-purpose breed, meticulously selected for meat and egg production, demonstrates exceptional adaptability to free-range environments and exhibits remarkable resilience in high-temperature conditions. With an annual egg output ranging from 220 to 240 eggs per hen (Kunhareang et al., 2023), the DDK breed has garnered significant demand among farmers, necessitating a concerted effort to augment the breeding stock. Artificial insemination (AI) is a highly efficient breeding technique that is contingent on the availability of superior-quality semen. Global warming elevates

the Earth's surface and atmospheric temperatures, exacerbating climate variability. This phenomenon can induce significant stress in animals, including poultry. The temperature-humidity index (THI) quantifies heat stress by considering temperature and humidity. Although THI thresholds vary across species, elevated temperatures compromise avian immune function and male reproductive health, affecting semen quality (McDaniel et al., 2008; McDaniel et al., 1996). Thailand's tropical climate, characterized by high temperatures and humidity, presents significant heat stress challenges for poultry. In Thai native PD chickens, a THI of 74 marks the onset of heat stress, which impacts egg production (Loengbudnark et al., 2023). However, the influence of environmental factors on semen quality in Thai native roosters remains uncertain (Sonseeda et al., 2013), potentially due to breed-specific heat tolerance and interannual climatic variations. Given the dearth of research on DDK semen quality concerning environmental conditions, this study investigated the impact of seasonal temperature and humidity variations on semen quality. These findings provide crucial insights for optimizing DDK breeding programs under Thailand's challenging climatic conditions.

OBJECTIVE

This study aimed to investigate the impact of seasonal variations in temperature and relative humidity on the quality of fresh semen from DDK and PD roosters. This study aimed to establish baseline semen quality data for both breeds, with PD serving as a reference standard for the semen quality of native Thai chickens. These findings will inform future efforts to enhance semen quality in both DDK and PD roosters.

METHODOLOGY

Animals and Management

This study was approved by the Institutional Animal Care and Use Committee of Khon Kaen University (Thailand) (approval no. IACUC-KKU-81/66), adhering to the ethical guidelines for animal experimentation established by the National Research Council of Thailand. The study utilized 12 roosters per breed (DDK and PD), aged 52 weeks and weighing 2.5-3 kg. In addition, 40 commercial laying hens were used for AI evaluations.

Semen Collection and Evaluation

Semen was collected from individual roosters twice weekly over a period of 24 weeks, encompassing three distinct seasons: summer (April-May 2023; 8 weeks), rainy (July-August 2023; 8 weeks), and winter (December-January 2023; 8 weeks). A data logger (GSP-6, Elitech, UK) recorded ambient temperature (AT; °C), and relative humidity (RH, %). The THI was subsequently calculated using the equation: $THI = (0.8 \times AT) + (RH / 100) \times (AT - 14.4) + 46.4$, as developed by Mader and Davis (2013).

Fresh semen was evaluated for volume, mass movement, sperm progressive motility, concentration, total sperm count, viability, and morphology according to the methods described by Bakst et al. (1991) and Sonseeda et al. (2013). Artificial insemination (AI) was performed between 4:00 and 5:00 PM. Eggs were collected daily from days 2 to 15 post-AI. Fertility was determined by candling eggs on day 10 of incubation and calculated as the percentage of fertile eggs among the total number of eggs collected (Thananurak et al., 2022).

Statistical Analysis

The experiment employed a 3×2 factorial design within a completely randomized design (CRD). Data analysis was performed using analysis of variance (ANOVA) to assess mean differences, implemented using the Statistical Analysis System (SAS) software (SAS Institute, 1996).

RESULTS AND DISCUSSION

Data collected at the experimental site revealed significant seasonal variations in temperature, relative humidity, and THI. Specifically, the average THI during the summer and rainy seasons was 81.41 and 80.34, respectively (Table 1). These values fall within the "emergency" zone for heat stress in laying hens, indicating a severe level of heat stress (Kim et al., 2021). Based on studies examining the impact of THI on egg production and physiological responses in laying hens, four distinct heat stress zones have been defined: no stress (THI < 70), alert (THI 70-75), danger (THI 76-81), and emergency (THI > 81).

Effect of Seasons on Quality of Fresh Semen

An evaluation of fresh semen quality in two breeds revealed significant seasonal variations in several key parameters. Specifically, semen volume, sperm concentration, sperm viability, sperm morphology, and fertility were influenced by the season ($p < 0.05$), as shown in Table 2. In contrast, no seasonal effects were observed for mass movement, sperm progressive motility, or total sperm count ($p > 0.05$). No significant interaction was observed between the breed and season ($p > 0.05$). Elevated ambient temperatures, particularly during the summer and rainy seasons, contribute to elevated THI values, leading to heat stress in livestock. This stress adversely affects the male reproductive function. Studies have demonstrated that heat stress can damage Sertoli cells, resulting in decreased semen volume (Guo et al., 2021), sperm concentration, and increased sperm mortality (Telangana et al., 2021). Consistent with these findings, Elagib et al. (2012) observed a negative correlation between sperm concentration and increasing temperature in White Leghorn chickens in Sudan. Similarly, Adamu et al. (2019) reported a decrease in semen concentration in indigenous Nigerian chickens during the late rainy season, which was characterized by lighter semen color. Furthermore, Pimprasert et al. (2023) observed the highest sperm concentration during winter and the lowest during the rainy season in Thailand.

Table 1 Maximum, minimum and average temperature, relative humidity, and THI for each season at the experimental location

Observations	Maximum	Minimum	Average	SD
Temperature (°C)				
Summer	39.20	22.40	30.28	1.99
Rainy	34.20	23.30	28.02	1.07
Winter	32.80	14.19	24.18	1.89
Relative humidity (%)				
Summer	98.80	39.90	67.77	9.48
Rainy	99.70	57.00	84.73	4.58
Winter	96.70	40.20	74.66	4.44
THI				
Summer	90.50	70.74	81.41	1.78
Rainy	86.78	72.25	80.34	1.25
Winter	84.81	56.06	73.43	3.18

Note) Data were collected from the Integrated Farm of the Department of Animal Science, Faculty of Agriculture, Khon Kaen University.

Heat stress induces oxidative stress, leading to increased lipid peroxidation and the generation of reactive oxygen species (Yongjie, 2020). These reactive species damage cell membranes, increase sperm mortality (Tselutin et al., 1999), and disrupt the spermatogenesis process, increasing abnormal sperm morphology (Fouad et al., 2016). However, these findings contrast with those of Sonseeda et al. (2013), who reported no significant seasonal effects on the semen quality. This discrepancy may be attributed to differences in experimental conditions, including a lower range of average temperatures (20.6-31.2°C) and relative humidity (53.5-82.2%) in the Sonseeda et al. (2013) study compared to the present study (average temperature: 24.18-30.28°C; average relative humidity: 67.77-84.73%). It is also important to consider that, despite being of the same breed (PD), the genetic

makeup of these animals may have evolved to prioritize their productivity. High-yielding animals often exhibit reduced fertility (Walsh et al., 2011), which can manifest as a lower semen quality.

This study observed significant seasonal variations in fertility rates, with the lowest fertility rate (77.99%) recorded during the summer season compared to the rainy (85.88%) and winter (86.81%) seasons. The summer season, characterized by the highest THI, induces the greatest heat stress in chickens. While spermatogenesis continues during heat stress, leading to the production of viable sperm, these spermatozoa may exhibit DNA damage (Banks et al., 2005). This damage can compromise sperm integrity and reduce their lifespan within the hen reproductive tract (Wang et al., 2014), thereby limiting the availability of sperm for fertilization (King et al., 2002). These findings align with those of McDaniel et al. (1996), who demonstrated a 42% reduction in fertility in broilers exposed to 32°C compared with those maintained at 21°C. Moreover, McDaniel et al. (1995) observed a reduced ability of sperm from heat-stressed roosters to penetrate the perivitelline layer of the egg. The current study, with an average summer temperature of 30.28°C, further emphasizes the sensitivity of rooster fertility to elevated temperatures. These results suggest that temperatures below 32°C can induce heat stress and adversely affect semen quality in roosters.

Table 2 Effect of seasons and breeds on the quality of fresh semen in DDK and PD.

Factors	Semen volume (ml)	Mass movement (scores)	Sperm progressive motility (%)	Sperm concentration (x10 ⁹ sperm/ml)	Total sperm count (x10 ⁹ /ejaculate)	Sperm viability (%)	Sperm morphology (%)	Fertility (%)
Seasons								
Summer	0.45±0.08 ^b	4.24±0.37	59.58±11.04	4.16±1 ^{ab}	1.56±1.56	93.45±1.91 ^b	6.79±1.57 ^a	77.99±6.78 ^b
Rainy	0.47±0.05 ^{ab}	4.34±0.30	60.44±4.64	3.82±0.56 ^b	1.63±1.63	95.49±1.72 ^a	5.66±1.21 ^b	85.88±3.96 ^a
Winter	0.49±0.05 ^a	4.36±0.25	62.69±4.44	4.51±0.60 ^a	1.60±1.60	95.22±3.20 ^a	5.18±0.60 ^b	86.81±5.89 ^a
p-value	0.046	0.37	0.41	0.0064	0.99	0.02	0.001	0.003
Breeds								
DDK	0.44±0.05 ^b	4.14±0.33 ^b	57.96±7.47 ^b	3.84±1 ^b	1.33±1.33 ^b	93.64±2.84 ^b	6.17±1.49	82.19±6.94
PD	0.50±0.05 ^a	4.48±0.17 ^a	63.85±6.28 ^a	4.48±1 ^a	1.87±1.87 ^a	95.80±1.47 ^a	5.58±1.15	84.92±6.59
p-value	0.01	0.01	0.004	0.004	0.001	0.004	0.89	0.13
Seasons	0.96	0.32	0.13	0.59	0.44	0.30	0.45	0.71
*Breeds								
SEM	0.04	0.09	1.07	0.36	0.48	0.36	0.20	1.05

^{a, b} different superscript letters within columns indicate significant differences ($p < 0.05$).

Effect of Breeds on Quality of Fresh Semen

Breed significantly influenced semen volume, sperm mass movement, sperm progressive motility, sperm concentration, and sperm viability ($p < 0.05$), whereas no significant breed effects were observed on sperm morphology and fertility rate ($p > 0.05$), as shown in Table 2. The effect of breed on semen quality in this study showed that the semen quality of PD was higher than that of DDK. Although DDK has a bloodline of Thai native chickens, being raised in Thailand's environment impacts the semen quality of DDK. The overall quality of DDK is lower than PD, which is consistent with the study of Peters et al. (2008) in Nigeria, who found that seven different breeds, namely Black Nera, White Leghorn, Giriraja, Naked necked, Frizzled, Normal Feathered, and hybrid breed, had different semen volume and sperm concentration. This is due to genetic differences between regions, resulting in different abilities to adapt to the environment of the region.

Tabatabaei et al. (2009) reported that Iranian native chickens had lower sperm concentration and abnormal sperm percentage than Ross-308 but had higher sperm motility and sperm viability than Ross-308. In India, a study was conducted on the semen quality of Naked neck and Bantam chickens and found that the semen quality of the two breeds was different, except for sperm concentration, indicating that the genetic structure of chickens was different, resulting in different semen qualities (Shanmugam et al., 2012). In Thailand, the study by Sonseeda et al. (2013) on Thai native chickens (Lueng hang kaow, Pradoo hang dam, and Chee) reported that the influence of breeds did not significantly affect semen quality. This may be because all three breeds are genetically similar Thai native chickens, resulting in minimal differences in semen quality (Choomee and Worananthakij, 2017).

In this experiment, breed did not affect the fertility rate ($p > 0.05$), with the average fertility rates of DDK and PD being 82.19 ± 6.94 and $84.92 \pm 6.59\%$, respectively (*Table 2*). Although the semen quality of DDK and PD differed, the fertility rate did not, indicating that the fresh semen quality of DDK was still viable and did not affect fertility rate. Semen quality does not affect the conception rate as long as certain thresholds are met, including a semen volume of not less than 0.2 ml, mass movement of not less than score 2, sperm progressive motility of not less than 60% (Iswati et al., 2018), sperm concentration of not less than 150×10^6 sperm/dose (Kheawkanha et al., 2024), sperm viability of not less than 70% (Iswati et al., 2018), and sperm morphology of not exceeding 20-25% abnormality (Vongpralub, 2016). Therefore, fresh DDK semen is still considered good quality and adaptable to Thailand's environment, and it does not affect fertility rate.

CONCLUSION

A study on the effects of season and breed on the quality of fresh semen in DDK and PD revealed that the summer season resulted in the lowest quality of fresh semen, while the winter season resulted in the highest quality. However, although seasons and breeds affect semen quality, DDK and PD remain within the range of good-quality semen and do not affect the fertility rate, indicating that these chicken breeds can tolerate the environment in Thailand.

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Watermelon Peels and Rinds as a Food Preservative and Additive in Pork *Longganisa* (Sausage)

DANICA MARIE B. APOSAGA*

College of Industrial Technology, University of Antique, Sibalom, Antique, Philippines

Email: danicamarie.aposaga@antiquespride.edu.ph

JESSEBEL V. GADOT

College of Arts and Sciences, University of Antique, Sibalom, Antique, Philippines

JEMAICA S. LABUS

Integrated Research Centers, University of Antique, Sibalom, Antique, Philippines

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Abstract Food products in the Philippines mostly use synthetic preservatives, including the curing powder for pork *longganisa* (sausages) (PL), a widely consumed cured meat. Currently, there is an emerging trend to look for natural alternatives to increase the nutritional value of food while ensuring its stability during storage. In Sibalom, Antique, 41.9% or 11,250pcs. of watermelons are surveyed to be rejected and left on the field to rot after harvest. The development of these rejects as food preservatives and additives from the rinds and peels of red-fleshed “Sweet 16” (RF16) and yellow-fleshed “Sweet Gold” (YFSG) watermelons was conducted. The peels and rinds were oven-dried at 60°C were powdered and added at 6% to the PL. A positive control using Prague powder (PRP) and a negative control (NC) were used alongside the treatments. The sensory evaluation results showed a significant difference in odor among the PRP, RF16, and YFSG samples on day 16. Meanwhile, no significant differences were found between the color, texture, and flavor of all samples. The free fatty acid content of PRP and NC increased on day 27, whereas it decreased for RF16 and YFSG, suggesting better shelf-life stability. When analyzing the nutritional content, no significant differences were observed in the moisture content of all samples, whereas the crude fat content did not differ between YFSG and PRP. Crude protein was highest in PRP, whereas the crude fiber content of YFSG and RF16 was significantly higher and even increased on day 27. The use of watermelon peels and rind powders from the rejects was comparable to that of the commercial preservative, as it further improved the nutritional content and shelf-life stability of pork *longganisa*, promoting a circular food system that can also be introduced to a wide variety of food products.

Keywords food preservative, food additive, watermelon rejects, peels and rinds, food losses

INTRODUCTION

In the Philippines, synthetic preservatives are used in a wide variety of food products to increase shelf-life stability, prevent microbial spoilage, reduce lipid oxidation, and maintain sensory properties. Despite its popular use, there is growing concern regarding the use of synthetic preservatives, such as curing powder, locally referred to as *Prague powder*, as it contains nitrates and nitrites that can be converted to carcinogenic nitrosamines, causing adverse health effects to consumers (Shi et al., 2024). Due to this concern, natural preservatives are being explored from plant extracts that can potentially replace the synthetic preservatives in the market. One of these is the use of watermelon waste. Kumar et al. (2018) assessed the lipid peroxidation of pork patties with watermelon rinds (WMR) and found results comparable to those of the positive control (treated with 0.02% butylated hydroxytoluene). The results also showed a significant reduction in lipid peroxidation compared to that in the untreated samples, indicating its effectiveness as a preservative. Currently, there are no studies in the Philippines applying watermelon waste in food products or its

use as a natural preservative and additive, as most studies are geared toward the extraction of its pectin, candying rinds, and its use as a rejuvenating agent (Lo et al., 2019; Back et al., 2016).

The annual production of watermelon in 2021 was estimated at 135, 845.60 tons in the Philippines (FAO, 2024), with Western Visayas being the highest producer in the country at 51, 781 tons, comprising 41.5% of the total watermelon production (Philippine Statistics Authority, 2023). Due to higher watermelon production, great watermelon waste is also generated, as observed in a surveyed site in Cubay-Napultan, Sibalom, Antique, wherein almost half of the watermelons are considered waste (41.9% or 11,250 pcs), and are left in the field to rot (Aposaga et al., 2025). The use of watermelon waste in the form of its peels and rinds as a natural food preservative and value additive has potential, especially in Western Visayas, the highest watermelon producer in the Philippines. In this study, the use of watermelon powder (WamPow) from the top two grown cultivars of the red-fleshed Sweet 16 (RF16) and yellow-fleshed Sweet Gold (YFSG) watermelons as a potential replacement for synthetic preservatives was evaluated in pork longganisa (sausage).

OBJECTIVE

This study aimed to determine the potential of watermelon peel and rind from watermelon rejects left on the field after harvest in Cubay-Napultan, Sibalom, Antique, Philippines, to be used as a natural food preservative and additive when added to pork *longganisa*.

METHODOLOGY

Around 100 pcs. of RF16 and YFSG were collected in Cubay-Napultan, Sibalom, Antique, in February 2023. Only the watermelons that were considered rejects and left in the field but were still in good condition were collected as samples. The watermelons were washed with potable water, dipped in 100ppm ppm chlorine solution for 5 min, rinsed with potable water, air-dried, and stored in a well-ventilated area before preparation. The peels and rinds were thoroughly separated from the flesh and cut into 1x1cm³. The two cultivars of YFSG and RF16, labeled YFSG 60°C and RF16 60°C, respectively, were dried at 60°C and powdered.

In formulating the pork *longganisa* with WamPow, the percentage of WamPow added to pork *longganisa* was examined through a preliminary test ranging from 3%, 6%, and 9%, wherein the most acceptable result came from pork *longganisa* treated with 6% WamPow and was used in the final formulation. Controls were also prepared alongside the treatments using Prague powder and one without any preservatives or additives. The samples were then analyzed for *Escherichia coli*, *Staphylococcus aureus*, and Aerobic Plate Count for microbial quality, sensory evaluation using the 7-point hedonic scale from seven trained panelists, free fatty acid content based on the modified method from the AOAC 41.121 for crude and refined oils, and proximate nutrient content (AOAC International, 2019). In analyzing the results, the two-way analysis of variance (ANOVA) was performed, with Fisher's least significant difference (LSD) as the post-hoc using the StatPlus software (Build 8.0.3/Core v7.8.11). The level of significance was set at $P < 0.05$.

RESULTS AND DISCUSSION

Microbiological Analysis

Over 27 days, the APC test was conducted to monitor the progress of bacterial growth in the cooked *longganisa*, as shown in Fig. 1. Analysis on Day 0 showed a high count for RF16 60°C samples; however, it was still within the set limit for ready-to-eat (RTE) food. The sudden drop in count in all samples on Day 7 was mainly due to the longer storage period at -2°C to -5°C, which affected the metabolic activity and nutrient uptake of the microorganisms, leading to a partial reduction in the microbial population. From days 14 to 27, the increase in APC may be associated with the increased resistance of the remaining bacterial population to the frozen conditions and may have multiplied

once heated due to its longer storage period. Despite the increase in microbial count, all samples passed the microbiological test during the 27-day storage period and were within the limit. This indicates the safety of watermelon rejects when added to food.

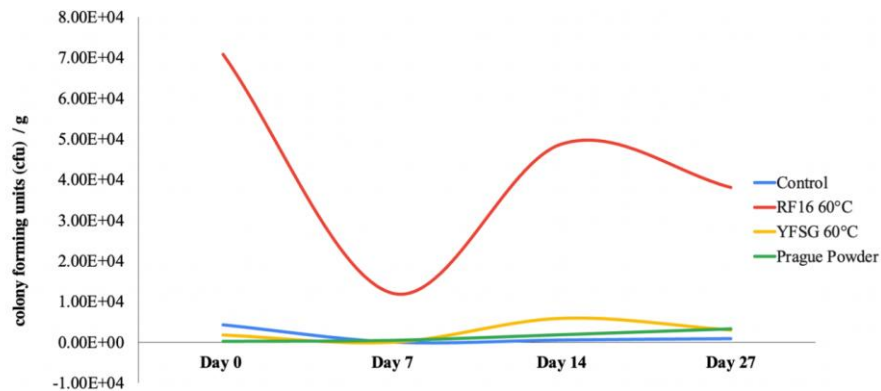


Fig. 1 APC monitoring of cooked pork Longganisa

Further microbiological tests were conducted through the assessment of the indicator organisms, *E.coli* and *S. aureus*. All samples tested showed negative growth for *E.coli*, while monitoring for *S. aureus* showed growth, but all within the acceptable limit, with the lowest recorded at ≤ 25 cfu/g for pork longganisa mixed with RF16 60°C and the highest at 9×10^1 cfu/g from the Prague powder. The maximum limits of the indicator organisms were based on the Food Standards Australia New Zealand (2025). The results indicate how WamPow was able to reduce the growth of *S. aureus* compared to the synthetic preservative.

Sensory Evaluation

The sensory characteristics of the pork longganisa with WamPow, Prague powder, and those without any preservatives or additives did not significantly vary in terms of its color, texture, odor, and flavor during the storage at days 1, 7, and 16.

Effect of the Treatments on the Color of the Pork Longganisa

The color, as seen in Table 1 of the samples remained stable throughout the storage period, with Prague powder exhibiting the highest acceptability due to its distinct red color in the pork longganisa. The color of the sample treated with RF16 at 60°C had the highest acceptability the longer it was stored. On the 7th and 16th days of storage, the pork longganisa with WamPow did not significantly differ from that with Prague powder. The green color in the pork longganisa from the WamPow was still considered new, and uncommon for pork products by the panelists. Green is mostly associated with non-meat products, which still serves as an area for improvement during product development.

Effect of the Treatments on the Texture of the Pork Longganisa

The texture of each sample during the whole storage period from day 1, 7, and 16 did not significantly differ. However, for the control, its texture was found to be highly acceptable at the end of its storage period, as seen in Table 1. Based on the comments of the panelists, the texture of the RF16 60°C pork longganisa on day 1 was quite dry but improved the longer its storage period, similar to YFSG 60°C. The texture of the WamPow-treated pork longganisa on day 1 was less juicy and moist due to the observed high absorbency of the WamPow, which soaked up the water, oils, and juices in the pork longganisa, resulting in lower scores for its texture. Over time, the texture of the WamPow improved when stored longer and became comparable with the control and Prague powder on days 7 and 16.

Effect of the Treatments on the Odor of the Pork *Longganisa*

The odor, as shown in Table 1 of the samples, did not significantly differ during the whole storage period, with the highest rating given to the control and the Prague powder. YFSG 60°C had the most acceptable score among the WamPow-treated samples on days 7 and 16. The odor of the WamPow-treated pork *longganisa* was generally similar to one other, having leafy and grassy notes described as having an interesting odor when incorporated into the meat. Since the addition of WamPow has not yet been previously explored in the Philippines, the combination of its odor with meat was considered new and predominantly different. However, higher acceptability values were noted as the duration of storage increased, as the smell became less distinct compared to day 1.

Table 1 Sensory evaluation results of the cooked pork *Longganisa*

Sample	Color attribute during storage		
	Day 1	Day 7	Day 16
Control	6.67±1.94 ^{a,A,B}	5.00±2.52 ^{a,A}	4.43±2.07 ^{a,B}
RF16 60°C	5.22±1.30 ^{a,B}	5.86±1.21 ^{a,A}	6.86±1.07 ^{a,A}
YFSG 60°C	4.89±1.05 ^{a,B}	5.43±2.07 ^{a,A}	5.29±1.50 ^{a,A,B}
Prague powder	7.11±1.9 ^{a,A}	6.57±2.64 ^{a,A}	7.29±1.60 ^{a,A}
Sample	Texture attribute during storage		
	Day 1	Day 7	Day 16
Control	7.44±1.67 ^{a,A}	6.86±2.19 ^{b,A}	7.14±1.21 ^{a,b,A}
RF16 60°C	4.67±1.00 ^{a,C}	6.57±1.13 ^{a,A}	5.71±2.06 ^{a,A}
YFSG 60°C	5.44±1.42 ^{a,B,C}	6.14±1.77 ^{a,A}	5.71±1.89 ^{a,A}
Prague powder	7.33±1.58 ^{a,A}	5.14±2.41 ^{a,A}	7.00±1.91 ^{a,A}
Sample	Odor attribute during storage		
	Day 1	Day 7	Day 16
Control	5.78±1.92 ^{a,A}	4.86±2.12 ^{a,A}	6.29±1.60 ^{a,A,B}
RF16 60°C	4.33±1.66 ^{a,A}	4.14±2.04 ^{a,A}	5.29±1.70 ^{a,B}
YFSG 60°C	4.33±1.58 ^{a,A}	5.43±1.62 ^{a,A}	5.57±1.5 ^{a,A,B}
Prague powder	6.11±1.83 ^{a,A}	5.57±2.44 ^{a,A}	7.71±1.60 ^{a,A}
Sample	Flavor attribute during storage		
	Day 1	Day 7	Day 16
Control	6.67±2.24 ^{a,A}	7.14±2.40 ^{a,A}	6.00±2.52 ^{a,A}
RF16 60°C	4.56±1.24 ^{a,A}	4.86±1.95 ^{a,A}	6.00±2.08 ^{a,A}
YFSG 60°C	6.11±1.96 ^{a,A}	6.14±2.34 ^{a,A}	5.71±2.14 ^{a,A}
Prague powder	5.89±2.76 ^{a,A}	5.57±2.88 ^{a,A}	6.71±2.81 ^{a,A}

Data are presented as mean ± standard deviation (n=9 for day 1, and n=7 for days 7 and 16). Mean values in the same row per attribute, with similar superscript small letters (a-b), are not significantly different at $p < 0.05$. Mean values in the same column per attribute, with similar superscript capital letters (A-D), are significantly different at $p < 0.05$.

Effect of the Treatments on the Flavor of the Pork *Longganisa*

Flavor is considered an important sensory characteristic of a food product, as it is a major determinant factor in terms of food preference. The sensory evaluation results showed the flavor profile of the samples during the storage period, and when compared with one another, did not generally significantly differ at days 7 and 16, indicating that the taste of WamPow-treated pork *longganisa* can be compared with that of Prague powder-treated samples. The WamPow samples were noted to have an improved flavor, from a strong leafy taste that became faint the longer its storage, which was noted by the panelists as the reason for its higher rating at day 7. This indicates that a longer storage period aids in enhancing the overall flavor profile of pork *longganisa* treated with WamPow, as it was able to compete with the controls, as detailed in Table 1.

Free Fatty Acid (FFA)

FFA are prone to oxidation and are indicators of rancidity. The %FFA from Day 0 to Day 27, as shown in Table 2, increased for the control and Prague powder-treated samples, while the FFA of RF16 60°C and YFSG 60°C decreased over time. The lower %FFA value of WamPow-treated pork *longganisa* indicates the pork is less rancid, and implies a slower degradation process, making the samples shelf-stable. Based on the results, WamPow can act as a natural preservative and enables the reduction of %FFA values during its storage period, indicating the influence of the WamPow on lowering lipid oxidation. The RF16 60°C contributed to a much lower FFA.

Table 2 Free fatty acid (FFA) values of cooked pork *Longganisa* samples

Sample	Day of storage (FFA (%), cooked samples)			
	0	7	16	27
Control	0.33±0.1 ^{a,B}	0.50±0.06 ^{a,C}	0.59±0.15 ^{a,B}	0.70±0.10 ^{a,A,B}
RF16 60°C	0.86±0.21 ^{a,A}	0.72±0.15 ^{a,A,B,C}	0.77±0.08 ^{a,A,B}	0.61±0.05 ^{a,B}
YFSG 60°C	0.71±0.28 ^{a,A,B}	1.05±0.10 ^{a,A}	0.93±0.17 ^{a,A,B}	0.70±0.02 ^{a,A,B}
Prague powder	0.42±0.31 ^{a,A,B}	0.55±0.14 ^{a,B,C}	0.65±0.09 ^{a,B}	0.84±0.31 ^{a,A,B}

Data are presented as mean ± standard deviation (n=3). Mean values in the same row with similar superscript small letters (a-b) are not significantly different at $p < 0.05$. Mean values in the same column with similar superscript capital letters (A-B) are significantly different at $p < 0.05$.

Nutritional Composition of Cooked Pork *Longganisa*

The proximate nutrients of the cooked pork *longganisa* were evaluated on days 0 and 27.

Moisture Content (MC)

The %MC of the pork *longganisa* samples, as shown in Table 3, did not significantly vary among the treatments and between the storage times (Day 0 and 27). This indicates that WamPow does not significantly affect the %MC of pork *longganisa*.

Ash Content

The %Ash of pork *longganisa* for all treatments decreased by day 27. The highest value of ash was reported to be RF16 at 60°C, with a value of 8.68% on day 0. The lowest ash value was recorded for the control at 5.51% on day 27. The higher ash values of pork *longganisa* with WamPow may be due to the number of inorganic compounds, such as minerals, present in the dried watermelon peels and rinds, as detailed in Table 3.

Crude Protein (CP)

The %CP of pork *longganisa* decreased with storage period, except for YFSG 60°C, which increased on day 27 (Table 3). On day 0, the highest %CP was recorded for Prague powder at 32.62%, and the lowest %CP was recorded for YFSG 60°C at 24.44%. The %CP of Prague powder was significantly higher than that of the WamPow-treated pork *longganisa* at days 0 and 27 due to the presence of nitrates and nitrites. For the control, the %CP by day 27 was not significantly different from that of the Prague powder-treated samples and YFSG 60°C. The results show that the RF16 cultivar at 60 °C may have affected the %CP of the pork *longganisa* samples during the storage period.

Crude Fat (CFt)

The %CFt of pork *longganisa* did not significantly differ over the storage period from day 0 to day 27, except for the control, which significantly decreased by day 27, as shown in Table 3. As preservatives were not added to the control, the fat may have oxidized, resulting in a much lower value. No significant differences were found in the reduced %CFt of the other samples by day 27,

indicating the effect of minimizing fat oxidation through the addition of Prague powder and WamPow to pork *longganisa*.

Crude Fiber

Higher crude fiber values were found in the YFSG treated at 60°C. The WamPow-treated pork *longganisa* was significantly higher and even increased by day 27 compared to Prague powder and control. This indicates the ability of WamPow to add value to pork *longganisa* and other food products. The significant increase in the crude fiber at day 27 for YFSG 60°C by 1.33% shows the positive interaction of WamPow with the nutrient matrix of the pork *longganisa*. No significant increase in the crude fiber of the Prague powder and control by the end of its 27-day storage period was observed as presented in Table 3. The results show that the addition of WamPow can further increase the marketability of pork products, which were previously low in fiber.

Table 3 Proximate nutrient results of the cooked pork *Longganisa*

Sample	Moisture content (%) during storage, cooked samples	
	Day 0	Day 27
Control	3.86±0.01 ^{a,A}	3.84±0.03 ^{a,A}
RF16 60°C	3.85±0.02 ^{a,A}	3.87±0.01 ^{a,A}
YFSG 60°C	3.87±0.01 ^{a,A}	3.83±0.02 ^{a,A}
Prague powder	3.83±0.05 ^{a,A}	3.84±0.01 ^{a,A}
Sample	Ash content (%) during storage, cooked samples	
	Day 0	Day 27
Control	5.67±0.09 ^{a,E}	5.51±0.16 ^{a,E}
RF16 60°C	8.68±0.08 ^{a,A}	8.63±0.11 ^{a,A}
YFSG 60°C	6.88±0.05 ^{a,C}	6.71±0.01 ^{a,C}
Prague powder	6.54±0.05 ^{a,D}	6.35±0.10 ^{a,D}
Sample	Crude protein (%) during storage, cooked samples	
	Day 0	Day 27
Control	29.78±0.85 ^{a,B}	29.33±2.17 ^{a,A,B}
RF16 60°C	30.36±2.80 ^{a,B}	26.76±0.59 ^{b,B,C}
YFSG 60°C	24.44±0.20 ^{a,B}	25.14±1.69 ^{a,C}
Prague powder	32.62±3.01 ^{a,A}	32.55±1.13 ^{a,A}
Sample	Crude fat (%) during storage, cooked samples	
	Day 0	Day 27
Control	45.44±1.44 ^{a,A}	39.50±2.93 ^{b,A,B}
RF16 60°C	37.95±2.80 ^{a,B}	36.58±5.5 ^{a,B}
YFSG 60°C	43.71±2.21 ^{a,A}	41.80±2.30 ^{a,A}
Prague powder	42.48±0.23 ^{a,A,B}	42.33±1.21 ^{a,A}
Sample	Crude fiber (%) during storage, cooked samples	
	Day 0	Day 27
Control	0.30±0.08 ^{a,B}	0.51±0.07 ^{a,B}
RF16 60°C	3.52±0.13 ^{a,A}	3.78±0.04 ^{a,A}
YFSG 60°C	3.32±0.16 ^{b,A}	4.65±0.16 ^{a,A}
Prague powder	0.39±0.01 ^{a,B}	0.58±0.04 ^{a,B}

Data are presented as mean ± standard deviation (n=3). Mean values in the same row per test, with similar superscript small letters (a), are not significantly different at p<0.05. Mean values in the same column per test, with similar superscript capital letters (A), are significantly different at p<0.05.

CONCLUSION

The production of watermelon powders (WamPow) from the red-fleshed *Sweet 16* and yellow-fleshed *Sweet Gold* in the province of Antique, Philippines, has great potential for commercialization and use in a wide variety of food products as a natural food preservative and value additive, as it performs similarly to synthetic preservatives in reducing the production of free fatty acids during

storage and even adding fiber to pork *longganisa*. In comparing the WamPow powders, RF16 60°C had higher values of color, crude ash, and crude protein, and lower FFA, while YFSG 60°C had higher results for odor, flavor, crude fat, and crude fiber.

This study addresses the research gaps in utilizing watermelon peels and rinds as natural preservatives and value additives for potential use in a wide variety of food products. Overall, the results of the study produced a technology that adds economic value and addresses the problems of watermelon losses and waste during watermelon harvests in the Philippines, while simultaneously increasing the marketability of pork *longganisa*.

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Sustainable Palm Oil Downstream Value Chain in Industrial Zones: A Case Study in Riau Province, Indonesia

PRIMA GANDHI*

*Graduate School of International Food and Agricultural Studies,
Tokyo University of Agriculture, Japan /
Agribusiness Management, College of Vocational Studies, IPB University, Bogor, Indonesia
Email: 13623001@nodai.ac.jp*

FUMIE TAKANASHI

Faculty of International Agriculture and Food Studie, Tokyo University of Agriculture, Japan

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Abstract Indonesia, the world's top palm oil producer, yielded 46.99 million tons in 2023. The province of Riau, which leads in both production and plantation area, has initiated three industrial zones focused on palm oil cultivation. Of all the industrial estates, only the Dumai Industrial Estate (DIE) is implementing downstream processing by 2025, potentially enhancing the sector's value-added contribution. Although numerous studies have been conducted on the palm oil value chain in Indonesia, no research has focused on specific regions or examined the relationships between the entities within those regions. This study examines the structure and governance of the value chain in DIE. DIE has four distinct value chains: Wilmar International Group (WIG), First Resources Group (FRG), Permata Hijau Group (PHG), and Sumber Jaya Oleo Group (SJIOLEO). These four supply chains function independently with no horizontal integration. DIE specializes in palm oil-based products, including oleofood, oleochemicals, and oleofuel (biodiesel). Notably, only the WIG chain, through PT Wilmar Nabati Indonesia, employs RSPO-certified CPO for its export products. PT Wilmar Bioenergi Indonesia, operating within the WIG, FRG, PHG, and SJIOLEO chains, does not procure RSPO-certified CPO because its production of biofuels and oleochemicals primarily serves the domestic market. In DIE, not all downstream palm oil activities focus on exports, and value chain governance, whether based on RSPO or non-RSPO certification, follows a hierarchy type.

Keywords downstream, governance, industrial zones, palm oil industry, value chain

INTRODUCTION

Over the last ten years, palm oil has become the most widely produced vegetable oil globally. Valued for its high vitamin E content (Kuppithayanant et al., 2014), it represents around 40% of the global vegetable oil market (Gandhi and Takanashi, 2025). Southeast Asia leads the sector, producing over 80% of palm oil and nearly one-third of all vegetable oils (OECD/FAO, 2024). Over the past five years, Indonesia has established itself as the world's largest palm oil producer. In 2023, Indonesia produced 47.08 million tons of Crude Palm Oil (CPO) (BPS, 2024), sourced from 16.83 million hectares of palm oil plantations. Domestic palm oil consumption reached 23.13 million tons in 2023, an increase from 21.24 million tons in 2022 (GAPKI, 2024). This increase was largely attributed to the implementation of the biodiesel (B35) policy, which significantly increased domestic palm oil demand for biodiesel production. Conversely, Indonesian palm oil exports have steadily declined in the past five years. In 2023, exports totaled 38.23 million metric tons, with a value of USD 25.61 billion (Ministry of Agriculture, 2024). The palm oil industry is a vital component of Indonesia's economic development. However, growing international concerns regarding the environmental and social sustainability of its supply chain have intensified in recent years (Carmagnac et al., 2022). In

particular, regulatory and consumer pressures from the EU have compelled the industry to enhance transparency and align its operations with globally recognized sustainability standards. Few sectors actively promote certification participation among their members as strongly as the palm oil industry, particularly with schemes such as the Indonesian Sustainable Palm Oil (ISPO) and the Roundtable on Sustainable Palm Oil (RSPO). These initiatives play a significant role in shaping industry practices, as certification for product safety and differentiation has been shown to influence entire value chains across various sectors (Gereffi and Lee, 2009). Riau Province is a leading palm oil producer in Indonesia, with a total production of 8.79 million tons from 2.87 million hectares of plantations. As a key province in palm oil production, the Riau Provincial Government has established three industrial zones focused on the palm oil sector: Dumai Industrial Estate (DIE), Tanjung Buton Industrial Estate (TBIE), and Tenayan Industrial Estate (TIE). Among these, only DIE currently accommodates downstream palm oil industry. Although several studies have examined Riau's palm oil value chain, its structure and governance palm oil value chain remain largely unexplored.

OBJECTIVE

This study analyzes the structure and governance of the palm oil industry value chain in the DIE.

METHODOLOGY

The value chain describes the entire product creation chain (Porter, 1985). In a broader sense, value chain analysis refers to the activities within a single company to bring a product to market. Meanwhile, in a broad sense, the value chain looks at a series of vertically and horizontally complex activities carried out by various actors to bring raw materials and final products through the chain to the sales. Lazzarini developed the net chain concept, a critical theoretical framework in this study, to show vertical and horizontal value chain linkages (Lazzarini et al., 2001). Vertical integration reflects the flow of products and services from primary producers to final consumers (i.e., value chain or supply chain). The horizontal dimension represents the relationships between actors in the same chain. Gereffi and Fernandez-Stark (2016) identified five types (market, modular, relational, captive and hierarchy) of global value chain (GVC) governance: high to low levels of explicit coordination and power asymmetry between buyers and suppliers. The governance type is determined by four key variables: complexity of transactions, ability to codify transactions, capabilities in the supply base, and degree of explicit coordination and power asymmetry.



Source: Modified from PT KID by authors (2024).

Fig. 1 Research area

Understanding GVC governance is crucial as it reveals power dynamics, affects risk and reward distribution, improves labor and environmental standards, and enables value chain upgrading. This study adopted a comprehensive case study approach. The chain analysis steps carried out in this study were data collection, value chain, and governance analysis. The researcher collected secondary data

from documents, statistical records, research studies, and reports related to the DIE. This data was analyzed by reviewing relevant documents in the study. This holistic approach ensures a comprehensive understanding of the subject matter. Primary data were collected through semi-structured interviews conducted during the field survey to examine the profiles of actors operating in DIE. DIE is located at Jl. P.Sumatera No.1, Dumai Industrial Area, Pelintung, Medang Kampai, Dumai City (Fig. 1). Dumai City is in Riau Province, Indonesia, on the East Coast of Sumatra Island. Dumai officially became a city on April 20, 1999, after being part of Bengkalis Regency. Dumai has an area of approximately 2,065.59 km² with 7-36 villages. In 2023, the population of Dumai is estimated to reach 338,064 people. Dumai is known as the "Oil City" because it has a rapidly growing oil and gas industry and serves as a center for palm oil processing. Dumai has a strategic port for international trade, especially with Malaysia and Singapore. The DIE plays a major role in Dumai's regional economic growth, with observable positive impacts on the GRDP and industrial diversification (Sumarno et al., 2001). The author conducted a study on DIE in September 2024.

RESULTS AND DISCUSSION

Entities Operating in Dumai Industrial Estate

DIE is the largest industrial area in the Riau Province, with a total land area of 1,792 ha. The basis of the Industrial Estate Policy regulation is Presidential Decree No. 53 of 1989. DIE was officially recognized as a National Vital Object in the Industrial Sector under Ministerial Decree No. 805/M-IND/Kep/12/2017. Eligible investors receive incentives such as reduced income tax, VAT exemption, and import duty reliefs. In addition to these fiscal benefits, non-fiscal incentives are available, including support for constructing and managing power plants. Regional tax incentives may include reductions, reliefs, or exemptions from land ownership taxes and street-lighting levies.

Table 1 List of companies invested in Dumai industrial estate

No	Company	Established	Product	Activity	Land area (ha)	Country
1	PT Sentana Adi Daya Pratama	1999	KCl (potassium chloride) crown fertilizer, Peruvian rock phosphate crown fertilizer, ZA (ammonium sulfate) crown fertilizer, TSP (triple super phosphate) crown fertilizer	Fertilizer production	16.63	Singapore
2	PT Murini Sam Sam II	2006	Palm kernel and CPO	Palm oil mill	7.18	Singapore
3	PT Wilmar Nabati Indonesia	2008	Olein, stearin and PFAD	Refinery, fractionation, oleochemical and flour mill	53.43	Singapore
4	PT Wilmar Bioenergi Indonesia	2008	Fatty acid methyl esters	Refinery for biodiesel	11.50	Singapore
5	PT Petro Andalan Nusantara	2008	Oil	Fuel oil trading	2.71	Singapore
6	PT Wilmar Chemical Indonesia	2008	Methanol	Methanol trading	1.81	Singapore
7	PT Ciliandra Perkasa	2009	FAME, PFAD, crude glycerine, fatty mater	Refinery for biodiesel	5.08	Singapore
8	PT Bumi Karyatama Raharja	2014	Activated clay/ bleaching earth	Chemical industry for mining	9.20	Singapore
9	PT Samator Indo Gas	2015	Nitogen	Nitrogen (N ₂) plant	3.01	Indonesia
10	PT Pelita Agung Industry	2019	FAME, PFAD, crude glycerine, fatty mater, palm kernel expeller	Refinery for biodiesel	21.20	Indonesia
11	PT Perusahaan Listrik Negara	2020	Electricity	Powerplant	40.60	Indonesia
12	PT Sumber Jaya Industri Oleo	2022	RBDO (refined, bleached, deodorized oil), PFAD, RBDPO (refined, bleached, deodorized palm olein)	Refinery	4.57	Indonesia

Source: Authors' field survey and document review (2024).

On August 31, 2010, the Indonesian Government designated DIE as a Palm Oil Industry Cluster, although it is also open to various other types of industries. In 2024, there are 12 tenants, four from Indonesia and eight from Singapore. Seven of the 12 companies are subsidiaries of the Wilmar International Group. The 12 tenants employ 9,524 permanent and 176 outsourcing workers. DIE is managed by PT Kawasan Industri Dumai (KID), a subsidiary of the Wilmar International Group Ltd.

Palm Oil Value Chain and Governance in Dumai Industrial Estate

1. The Wilmar International Group (WIG): The WIG, founded on April 1, 1991, has grown from a small trading company into Asia's leading agribusiness group. Today, WIG is a global leader in agribusiness with over 500 manufacturing plants worldwide and a diverse portfolio including oil palm cultivation, edible oils refining, oilseeds crushing, consumer products, specialty fats, oleochemicals, biodiesel manufacturing, sugar milling, and refining with its headquarter in Singapore. The WIG Value Chain involves four companies located in the DIE. Three companies, PT Murini Sam Sam II (POM), PT Wilmar Nabati Indonesia (Refinery), and PT Wilmar Bioenergi Indonesia (Refinery) are in the downstream palm oil industry. Meanwhile, PT Sentana Adi Daya Pratama (PT SADP) is involved upstream as a supplier of agricultural inputs in the form of fertilizers for oil palm plantations owned by WIG outside the DIE. POM PT Murini Sam-Sam II (PT MSSII) obtains RSPO-certified Fresh Fruit Bunches (FFB) from Wilmar plantations and non-RSPO-certified FFB from private plantations and smallholders. PT MSSII produces RSPO-certified CPO for PT Wilmar Nabati Indonesia (PT WNI), which is used as a raw material for oleofood production. PT MSSII also produces non-RSPO-certified CPO for PT Wilmar Bioenergi Indonesia (PT WBI), which is used as a raw material for oleofuels. To meet its production needs, in addition to PT MSSII, PT WBI and PT WNI also obtain CPO supplies from WIG's POMs located outside the DIE. In DIE, PT WBI produces Fatty Acid Methyl Ester (FAME), which is sold domestically to PT Pertamina as biodiesel. PT WNI produces Olein, Stearin, and Palm Fatty Acid Distillate (PFAD), which are exported to WIG subsidiaries in Singapore, Malaysia, Germany, and China. In the WIG value chain, there are no horizontal or vertical relationships with tenants outside the WIG, indicating that Wilmar International manages its transactions independently from upstream to downstream.

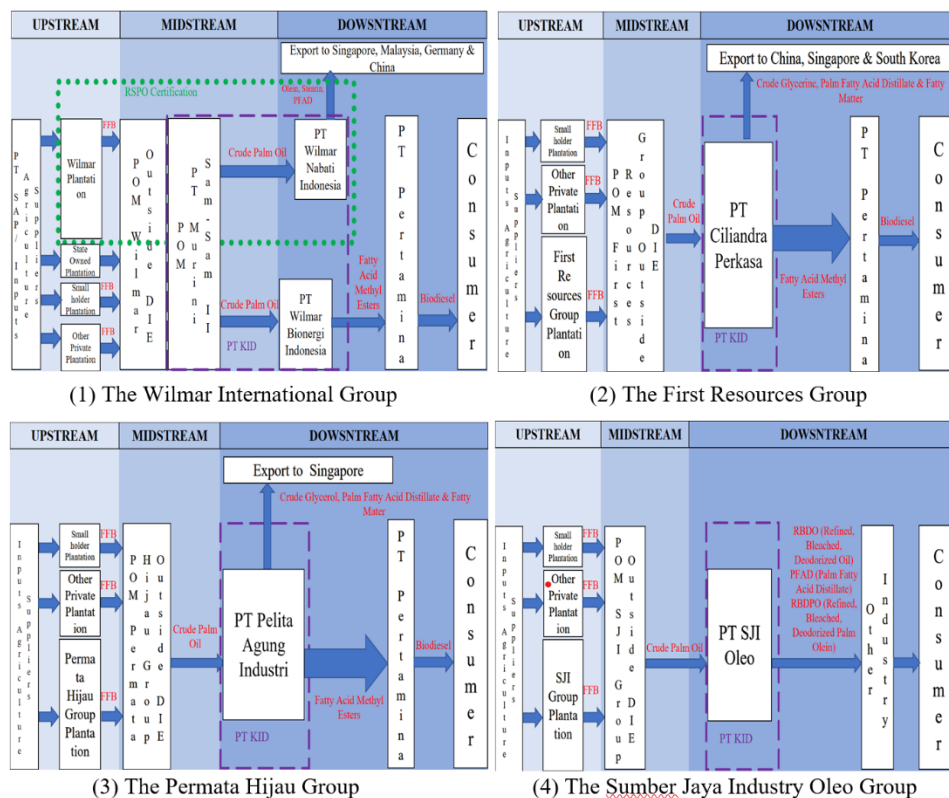
2. The First Resources Group (FRG): The FRG was established in 1992 and has been listed on the Singapore Exchange since 2007. FRG is a leading palm oil producer in Southeast Asia, headquartered in Singapore. The company manages over 200,000 hectares of oil palm plantations across Indonesia's Riau, East Kalimantan, and West Kalimantan Provinces. The core business activities include oil palm cultivation, harvesting, and CPO and PK processing. The FRG has one DIE refinery company, PT Ciliandra Perkasa (PT CP). PT CP obtains its CPO supply from POM FRG, which is located outside the DIE. PT CP produces Crude Glycerine, PFAD, and Fatty Mater, which are exported to China, Singapore, and Korea. In addition, PT CP produces FAME, which is sold domestically to PT PERTAMINA as a biodiesel. PT CP (FRG Value Chain) does not utilize RSPO-certified raw materials and has no horizontal or vertical relationships with other tenants in the DIE.

3. The Permata Hijau Group (PHG): PHG is a fully integrated palm oil corporation founded in 1984, with its headquarters in Medan. The company's core business is palm oil plantations, and it has since expanded to cover the entire palm oil value chain. PHG's operations span from upstream plantation to midstream and downstream industries and produce value-added products. PHG manages a total land area of 24,500 ha for oil palm cultivation. PHG operates six POMs, six refineries, five palm kernel oil mills, three biodiesel plants, two oleochemical plants, and a specialty fat plant, all of which are located in Indonesia. PHG has a refinery company located in DIE, PT Pelita Agung Industri (PT PAI). PT PAI obtains its raw material supply as CPO from POM PHG outside the DIE. PT PAI produces Crude Glycerine, PFAD, Fatty Mater, and Palm Kernel Expeller (PKE), which are exported to Singapore. In addition, PT PAI produces FAME, which is sold domestically to PT PERTAMINA as a biodiesel. The PT PAI (PHG Value Chain) does not utilize RSPO-certified raw materials and has no horizontal or vertical relationships with other tenants in the DIE.

4. The Sumber Jaya Industry Oleo Group (SJIOLEO): SJIOLEO is an Indonesian-based fully

integrated palm oil company focusing on downstream operations, with its head office in Jakarta. The company's scope ranges from producing, sourcing, refining, and trading palm oil and its products. SJIOLEO has a refinery company located in DIE, PT Sumber Jaya Industri Oleo (PT SJIOLEO). PT SJIOLEO is the newest company to operate in DIE in 2022. PT SJIOLEO obtains its raw materials from POM PT SJIOLEO outside the DIE. PT SJIOLEO produces Refined, Bleached, Deodorized Oil (RBDO), PFAD, and Refined, Bleached, Deodorized Palm Olein (RBDPO), which are sold to the domestic oleochemical and oleo food industries. PT SJIOLEO does not utilize RSPO-certified raw materials and has no horizontal or vertical relationships with other tenants of DIE.

Based on the four palm oil value chains in DIE (Fig.2), value chain governance in DIE can be divided into two types: governance with RSPO certification and without RSPO certification (Fig. 3). The majority of industries in DIE use non-RSPO certification (ISPO) because they are domestically oriented. The types of interactions between actors in RSPO and non-RSPO palm oil value chain governance vary significantly at the upstream, midstream and downstream levels. Overall, at the upstream and downstream levels, these two types of value chain governance differ. However, at the midstream level, both follow a hierarchical structure. The discussion primarily focuses on midstream value chain governance because this study was conducted in DIE.



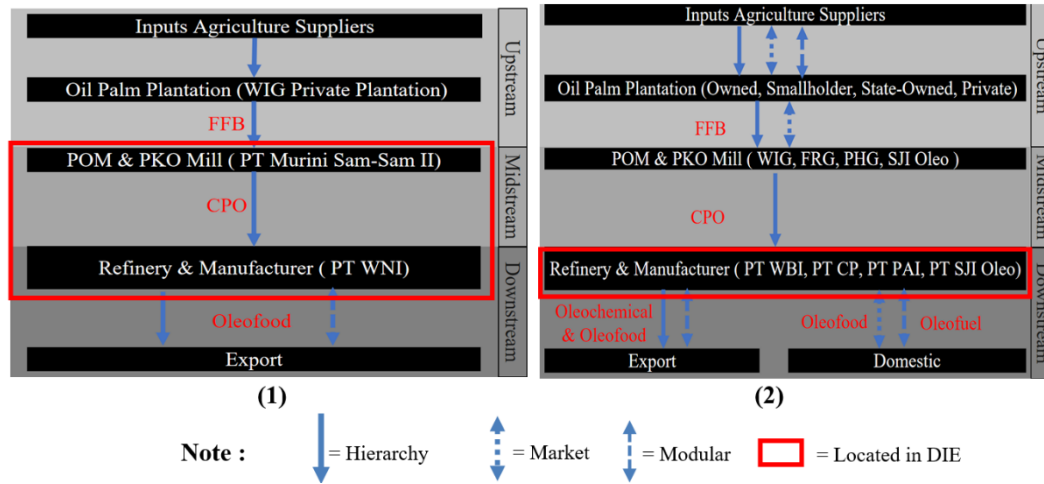
Source: Authors' field survey and document review (2024).

Fig. 2 Four palm oil value chains in DIE

RSPO Certification Value Chain Governance at DIE

At DIE, the interaction between PT MSSII and PT WNI involves the transaction of RSPO-certified CPO as a raw material for producing RSPO-certified oleofood ingredients. The production process must comply with seven RSPO sustainability requirements, necessitating actors with specialized capabilities. This leads to high transaction complexity in terms of linkages, capabilities, codification and product/process specifications. However, because the commodities already meet RSPO standards, the ability to codify transactions is low. Both companies are subsidiaries of Wimar International (WI), with top management control exercised through WI's head office in Singapore,

resulting in high explicit coordination and significant power asymmetry. Consequently, their supply base management capabilities are low, and the governance structure between PT MSSII and PT WNI is hierarchical owing to high transaction complexity, low codification ability, low supply management capabilities, and a high degree of explicit coordination and power asymmetry.



Source: Authors' field survey and document review (2024).

Fig. 3 RSPO (1) and non-RSPO (2) certification governance value chains

Non-RSPO Certification Value Chain Governance at DIE

Non-RSPO certification governance occurs within the WIG value chain (PT WBI), the FRG value chain (PT CP), the PHG value chain (PT PAI), and the SJIOLEO value chain (PT SJIOLEO). In the interactions between PT MSSII and PT WBI, PT CP and POM FRG, PT PAI and POM PHG, and PT SJIOLEO and POM SJIOLEO at DIE, the transacted product is non-RSPO CPO. As the production of non-RSPO CPO does not require raw materials and production processes that comply with the seven RSPO sustainability requirements, actors with specialized capabilities are not necessary. Based on this explanation, the transaction complexity—including linkages, actors' capabilities, codification, and product and process specifications—for commodities transacted in these interactions is low. PT MSSII and PT WBI are subsidiaries of WI, PT CP and POM FRG are subsidiaries of FRG, PT PAI and POM PHG are subsidiaries of PHG, and PT SJIOLEO and POM SJIOLEO are subsidiaries of SJIOLEO. The top management of PT MSSII, PT WBI, PT CP, POM FRG, PT PAI, POM PHG, PT SJIOLEO, and POM SJIOLEO can only exercise direct administrative control through the head offices of each group (WIG, FRG, PHG, and SJIOLEO). The top management at the head office holds authority over subordinates in the company's vertically integrated subsidiaries or affiliates. Direct control by the head office management implies a high level of explicit coordination and significant power asymmetry. Consequently, the capabilities of PT MSSII, PT WBI, PT CP, POM FRG, PT PAI, POM PHG, PT SJIOLEO, and POM SJIOLEO in managing the supply base, including the exchange of relevant information, buyer input, monitoring and intervention, switching costs, and explicit coordination with buyers, are low. Although the transacted commodities do not adhere to standards such as RSPO, the ability to codify transactions between PT MSSII and PT WBI, PT CP and POM FRG, PT PAI and POM PHG, and PT SJIOLEO and POM SJIOLEO remains low because administrative control, including transaction codification, requires approval from the head office of PT WBI. Based on the description above, it can be concluded that the governance value chain between PT MSSII and PT WBI, PT CP and POM FRG, PT PAI and POM PHG, and PT SJIOLEO and POM SJIOLEO is hierarchical because it meets three out of the four hierarchy requirements: low ability to codify transactions, low capabilities in supply base management, and a high degree of explicit coordination and power asymmetry. The only unmet requirement is low transaction complexity.

CONCLUSION

Based on the results and discussion, it is known: Firstly, DIE has four distinct value chains: WIG, FRG, PHG, and SJIOLEO. These four chains operate independently and are not horizontally integrated into each other. Secondly, only PT WNI in the WIG chain uses RSPO-certified CPO. PT WBI in the WIG, PT CP in the FRG, PT FAI in the PHG, and PT SJIOLEO in the SJIOLEO group chain do not use RSPO-certified CPO because they produce biofuels and oleochemicals that are primarily used domestically. Not all downstream palm oil activities in the DIE are export-oriented. Thirdly, the value chain governance type that uses RSPO or non-RSPO certification in DIE is hierarchical.

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Field-Based Insights into the Challenges of Sustainable Forest Management in Cambodia

KEIKO AOKI*

Headquarters, Institute of Environmental Rehabilitation and Conservation, Tokyo, Japan
Email: hq-erecon@nifty.com

MOSTAFA AHMATH

Cambodia Branch, Institute of Environmental Rehabilitation and Conservation, Phnom Penh, Cambodia

SREYLEN VA

Cambodia Branch, Institute of Environmental Rehabilitation and Conservation, Phnom Penh, Cambodia

MACHITO MIHARA

Headquarters, Institute of Environmental Rehabilitation and Conservation, Tokyo, Japan /
Tokyo University of Agriculture, Tokyo, Japan

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Abstract In Cambodia, forest cover decreased from 73% in the 1960s to 41% in 2020. The causes of deforestation and forest degradation include forest clearing and agricultural expansion, large-scale illegal logging, and timber trade following the issuance of Economic Land Concessions (ELCs). The impact of deforestation continues due to the overexploitation of forest resources by the growing population and unofficial ELCs. The massive forest loss in Cambodia has increased the risk of natural disasters, decreased the biological and genetic diversity of indigenous trees, and jeopardized local livelihoods where residents have traditionally relied on forest resources. Therefore, the Institute of Environmental Rehabilitation and Conservation (ERECON) has been addressing the challenges of forest loss with the aim of sustainable community development across Cambodian provinces. Initiatives are formed by integrating all three organizational programs, including: 1. Environmental Rehabilitation and Conservation – We recommend promoting participatory reforestation and management activities, enhancing carbon sequestration through agroforestry, conserving biodiversity through mixed planting of native tree species, and promoting genetic diversity through the propagation of seedlings. 2. Utilization of Natural Resources: Enhancing natural resource circulation through agroforestry, compost making using locally available organic resources, and promoting sustainable forest resource utilization. 3. Environmental Education: Promoting capacity building of local communities through workshops, training sessions, and participatory rural appraisal methods; formulating management groups that play a central role in managing planted seedlings; strengthening the capacity of schoolteachers; and promoting environmental education in elementary schools. In the program year of 2024, the project on promoting school environment greening, aiming for forest environmental education in Tboung Khmum Province, as well as the project on promoting reforestation and education for sustainable development in Siem Reap Province, were implemented. Based on the cases implemented in both provinces, the achievements and challenges of sustainable forest management in Cambodia are discussed.

Keywords reforestation, forest conservation, natural resource management, environmental education, Cambodia

INTRODUCTION

In Cambodia, forest cover declined from 73% in the 1960s (FA Cambodia, 2006) to 41% in 2020 (FAO, 2020). The first major deforestation phase occurred between the 1970s and the 1990s during the Khmer Rouge regime and the subsequent activities of its remnants, reducing forest cover by 59% by the year 2000 (FAO, 2020). The main factors contributing to deforestation include the forced relocation of residents to rural areas, agricultural collectivization, overexploitation of forest resources, and war-related forest destruction. From the early 2000s to the early 2010s, the expansion of agricultural land through Economic Land Concessions (ELCs) in Cambodia became full-scale. Since 2014, some ELCs have been reclaimed and returned to residents; however, illegal logging and unofficial ELCs remain significant threats. The decrease in forest resources increases the risk of natural disasters, decreases the biological and genetic diversity of forests, and jeopardizes the local livelihoods of residents who have traditionally relied on forest resources. As deforestation has become one of the most critical threats to ecological, social, and economic systems, the sustainable management and utilization of forest resources to meet current and future needs is one of the important sustainable development goals elucidated by the Royal Government of Cambodia (RGC).

Additionally, rural residents in Cambodia often have limited educational opportunities, resulting in limited knowledge of sustainable natural resource utilization, and a lack of awareness can jeopardize their livelihoods through unplanned forest consumption. Therefore, it is crucial to improve their environmental knowledge and awareness, paving the way for the development of a society that promotes sustainable forest resource management.

Education for Sustainable Development (ESD) empowers individuals and communities by promoting the knowledge, skills, attitudes, and values necessary for creating a more sustainable and equitable society. It also supports countries in achieving their sustainable development goals (SDGs). UNESCO's Green Education Partnership has advanced the 'Green School' as a whole-institution approach to ESD, enabling schools to empower learners as active citizens engaged in promoting sustainable lifestyles and climate action (UNESCO, 2023).

The Institute of Environmental Rehabilitation and Conservation (ERECON) has promoted various projects to create harmony between agricultural and urban development and the natural environment. Since 2021, the organization has expanded its reforestation efforts as part of environmental conservation and Education for Sustainable Development (ESD), leading to the creation of new initiatives across provinces in Cambodia.

PROGRAM AIMS

New initiatives are formed by integrating all three organizational programs, including:

1. Environmental Rehabilitation and Conservation

We recommend promoting participatory reforestation and management activities, enhancing carbon sequestration through agroforestry, conserving biodiversity through mixed planting of native tree species, and promoting genetic diversity through seedling propagation.

2. Utilization of Natural Resources

Enhancing natural resource circulation through agroforestry, composting local organic materials, and promoting sustainable forest resource utilization.

3. Environmental Education

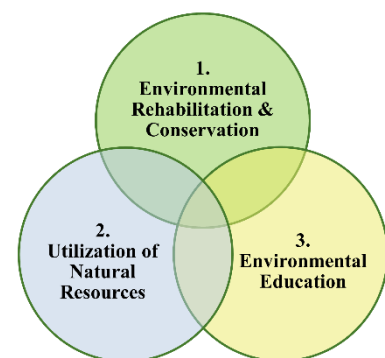


Fig. 1 ERECON's programs

Promoting training and participatory workshops for the capacity building of local communities, forming management groups by residents, strengthening the capacity of school teachers, and promoting environmental education in schools.

PROJECT SITES

The new projects were promoted across three provinces in Cambodia in collaboration with the Provincial Department of Agriculture, Forestry, and Fisheries of each province and local communities. The Project on Promoting Reforestation for Rehabilitating Rural Environment in Kampong Cham Province, Cambodia, was conducted to promote participatory reforestation and management activities across all ten districts in the province. The Project on Promoting School Environment Greening, aiming for Forest Environmental Education in Tboung Khmum Province, Cambodia, promoted forest environmental education in primary schools in the province.

Lastly, “The Project on Promoting Reforestation and Education for Sustainable Development in Siem Reap Province, Cambodia” was implemented for promoting agroforestry, seedling propagation, and compost making, as well as participatory extension activities in Siem Reap Province.

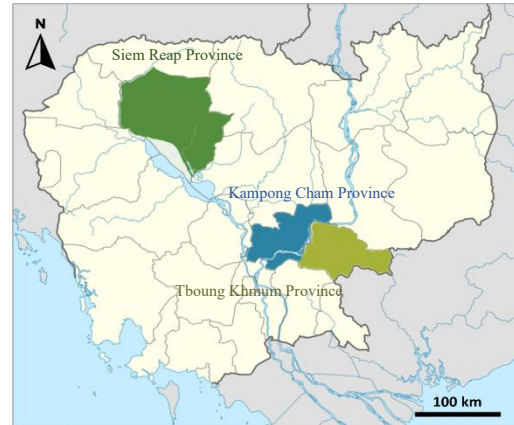


Fig. 2 Project sites in Cambodia

ACHIEVEMENTS

The achievements of each project are shown in Table 1, including restoration approaches, the number of active participants, and extension approaches.

Table 1 The achievements of each project

Project title	Project year	Restoration approaches	Number of active participants	Extension approaches
Promoting Reforestation for Rehabilitating the Rural Environment in Kampong Cham Province	2021-2023	- Community greening at 39 sites in the common area of 30 ha	1,585	- Form management groups at 39 sites - Conduct workshops on the importance of forest conservation
Promoting School Environment Greening, aiming for Forest Environmental Education in Tboung Khmum Province	2022-2024	- School greening at 26 local schools and lake sides in 18 ha - Produce 6,000 local tree seedlings at model schools - Utilize the planting site as an education platform	1,560	- Form teachers' groups at 26 schools - Promote competition among schools on the management practices as a part of environmental education - Facilitated teachers in creating nature games and in developing an environmental education guidebook.
Promoting Reforestation and Education for Sustainable Development in Siem Reap Province	2024	- Promote Agroforestry with local trees and cash crops in 15 ha - Produce 10,000 local tree seedlings - Make compost using organic materials collected from communities	136	- Promote a series of ESD workshops through Participatory Rural Appraisal (PRA), which facilitated the residents to 1) be aware of current situations caused by forest loss, 2) identify the issues to be tackled, and 3) plan for the future greening initiative.

1. Project on Promoting Reforestation for Rehabilitating Rural Environment in Kampong Cham Province, Cambodia (2021-2023)

The project promoted reforestation activities across all ten districts in Kampong Cham Province, focusing on the common areas such as pagodas, schools, and along the roads. In total, 30,000 native tree seedlings were planted at more than 30 sites in collaboration with over 1,700 active participants, aiming to restore the environment of rural areas for future generations. In addition, workshops on the “Importance of Forest and Biodiversity Conservation” were conducted to raise the environmental awareness of the residents. The planting sites are being managed by Forest Management Groups formed by residents at each site, who play a central role in management practices to maintain the tree survival rate.

Based on the questionnaire survey conducted among residents after the workshop, approximately 65% of residents understood what they learned in the workshop, and more than 90% were aware of the importance of being involved in management practices after planting by themselves. The results highlight the importance of continuing awareness programs through tree planting activities at the grassroots level.



Fig. 3 Planting activity in Kampong Cham Province

2. Project on Promoting School Environment Greening aiming for Forest Environmental Education in Tboung Khmum Province, Cambodia (2022-2024)

The project promotes a green environment in primary schools and forest environmental education at local schools in Tboung Khmum Province. Various environmental conservation activities were practiced across schools as part of environmental education by promoting planting sites as a nature-based learning platform at schools. In Phases 1 and 2 (2022-2023) of the project, school greening activities engaged more than 1,300 students and teachers from 26 primary schools across districts. In addition to the workshop on “The Importance of Forest and Biodiversity Conservation,” each school held a competition on “Seedling Management” to enhance students’ active participation in watering and weeding activities, leading to a higher tree survival rate at most of the schools. In Phase 3 (2024), the greening initiative was expanded to include lake conservation around Chitheang Lake, where local farmers and fishers depend on its natural resources for their livelihood. Primary school students and their families participated in planting activities on their own land.

Additionally, two model schools practiced seedling propagation under the supervision of the Forestry Administration, producing 6,000 native tree seedlings that were used for replanting in the communities. Moreover, the capacity building of the school teachers was further strengthened through workshops, where 16 school teachers from three schools developed their original Nature Games, and performed them for their students at the planting sites of Chitheang Lake. At the end of the project, these three schools were awarded under the title of “Excellence in Forest Environmental Education” in recognition of their greater engagement in promoting forest environmental education in Cambodia, acknowledged by the Tboung Khmum Provincial Department of Education, Youth and



Fig. 5 Nature game workshop facilitated by school teachers in Tboung Khmum Province

Sport (TBK DoEYS), the Tboung Khmum Provincial Department of Agriculture, Forestry, and Fisheries (PDAFF), and the Institute of Environmental Rehabilitation and Conservation (ERECN).

During the project period, monitoring and evaluation practices were conducted to assess the project's impact. The results identified factors in students' awareness and attitudes that showed positive correlations with their active participation in management practices, leading to higher tree survival rates (Aoki et al., 2024). Additionally, the study indicated that comprehensive awareness of the diverse benefits of trees may be positively connected to students' awareness of the importance of forest conservation, which is further connected to their responsible environmental actions (Aoki et al., 2024). This finding could contribute to the development of strategic environmental education to effectively address students' awareness and attitudes toward environmental issues.

3. Project on Promoting Reforestation and Education for Sustainable Development in Siem Reap Province, Cambodia (2024)

The project targeted a rural area of Siem Reap Province, which experienced severe deforestation due to infrastructure and agricultural land development after 2000. To rehabilitate the deforested area in the Banteay Srei District, an agroforestry-based reforestation approach was promoted in a 15-ha plot, subdivided into 15 blocks, where 9,000 native trees of four local species were planted alongside cash crops such as upland rice. A nursery was established to enable the annual propagation of over 10,000 native seedlings, ensuring genetic diversity for future reforestation efforts in the region. Additionally, organic materials were recycled to produce compost, which is used for maintaining the agroforestry site and seedling propagation. Based on a survey of the survival rate conducted in November 2024, it was confirmed to be 79%, and replanting activity was conducted to maintain forest cover.

To foster local engagement, a series of ESD workshops was conducted through participatory approaches in Kna Krao Village in Svay Leu District. The activities included a workshop on “Sustainable Land Management through Agroforestry,” a participatory planting activity, and participatory rural appraisal (PRA) with a gender-sensitive evaluation method. The participatory planting site in a common area became an agroforestry demonstration site, initiated voluntarily by residents.

In addition, another workshop on PRA encouraged participants to create PRA tools such as a forest resource map, a scoring table for forest resource utilization, and a timeline for land use changes, enabling them to be aware of issues and challenges resulting from the forest loss in their community. The community further developed conservation strategies by creating another PRA tool, the “Future Resource Map for Greening Plan,” which served as a valuable opportunity to collect meaningful information on the community's needs for reforestation. It also highlights the risk of losing traditional practices rooted in forest resources due to ongoing forest loss. Through these activities, local awareness of deforestation has significantly improved.

Through the analysis of qualitative and quantitative data acquired through the observation of the workshops, PRA tools, and questionnaire surveys, the key deforestation drivers and their impacts on local communities were identified. The findings highlight the urgent need to develop a forest resource management system and long-term capacity-building programs in the community. Participatory Rural Appraisal (PRA) has been proven to be an effective approach that contributes to raising



Fig. 6 Reforestation activity under agroforestry system in Siem Reap Province



Fig. 7 Participatory rural appraisal for discussing on a greening plan in Siem Reap Province

environmental awareness among local people while enabling outsiders to gather the overall real information of the local context. Moving forward, we will continue to collaborate with stakeholders to enhance forest conservation efforts and strengthen sustainable development strategies in Siem Reap Province.

FUTURE CHALLENGES

International NGOs play a vital role in addressing environmental conservation and human resource development challenges in Cambodia. To respond to the urgent need for greater stakeholder engagement in sustainable practices, promoting a comprehensive approach centered on education is essential. In line with international frameworks, our initiative aims to promote community-based and context-specific agroforestry, as advocated by the Center for International Forestry Research (CIFOR, 2020), as well as Education for Sustainable Development (ESD), promoted by the United Nations Educational, Scientific and Cultural Organization (UNESCO, 2014). As part of this effort, we are integrating agroforestry models into various land types, including farmlands, schoolyards, common areas, and residential spaces, to develop practical and localized solutions that reflect the needs of local communities. Moreover, we recognize the critical role of traditional knowledge in these processes, which not only contributes to sustainable resource use but also supports biodiversity through the preservation of cultural practices. Furthermore, by embedding environmental education into school curricula, we are investing in long-term human resource development, which is essential for achieving sustainable development in Cambodia.

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Enhancing Participative Community Development through School Construction and Renovation in Cambodia

KUMIKO KAWABE*

Headquarters, Institute of Environmental Rehabilitation and Conservation, Tokyo, Japan

Email: hq-erecon@nifty.com

KIMYEE ORNG

Cambodia Branch, Institute of Environmental Rehabilitation and Conservation, Phnom Penh, Cambodia

VIREAM RORNG

Cambodia Branch, Institute of Environmental Rehabilitation and Conservation, Phnom Penh, Cambodia

THYDALAK KOEUT

Cambodia Branch, Institute of Environmental Rehabilitation and Conservation, Phnom Penh, Cambodia

MACHITO MIHARA

Headquarters, Institute of Environmental Rehabilitation and Conservation, Tokyo, Japan / Tokyo University of Agriculture, Tokyo, Japan

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Abstract In rural Cambodia, inadequate school facilities and a shortage of classrooms continue to constrain children's access to education, despite increasing parental demand for schooling. Equally critically, the legacy of the Pol Pot era disrupted traditional forms of cooperation, eroded trust among villagers, and left many communities with limited experience in collective action. These conditions have made the concept of 'community' fragile and underdeveloped, posing significant challenges for rural development. To address both the educational and social dimensions, this project introduced school construction not as an end, but as a strategic entry point for community development. In the fiscal year 2024, the project was implemented in four primary schools in Tboung Khmum Province. At each site, school construction committees composed of local residents and teachers mobilized donations and labor, supervised construction progress, and practiced joint decision-making and accountability. Through these processes, residents began to rebuild trust and recognize the value of working together for a shared public good. After construction, contributions were reinvested into community development funds, which initiated small-scale businesses, such as community loans, chicken raising, fertilizer sales, and agricultural product collection. The profits from these activities are intended to be reinvested in education as revenue grows, reinforcing a cycle that links improved learning environments with community-led economic activities. The results suggest that school construction, when strategically positioned as a driver, can not only improve educational infrastructure but also foster cooperation, ownership, and self-reliance among rural Cambodian communities that have historically lacked strong traditions of collective action.

Keywords community development, school construction and renovation, self-sustaining community, importance of education

BACKGROUNDS AND OBJECTIVE

In rural Cambodia, the educational environment remains inadequate, with shortages of classrooms, limited school facilities, and insufficient hygiene infrastructure. Although parental demand for

children's education has been rising, these structural constraints continue to hinder access to quality learning opportunities. Meanwhile, the legacy of the Pol Pot era has severely disrupted community life: traditional forms of mutual support were dismantled, trust among villagers was eroded, and opportunities for collective action have remained limited. Consequently, the concept of "community" has become fragile, posing significant challenges for rural development.

This project was therefore designed to address both educational and social challenges by integrating school construction with community development. School construction was introduced not as an end in itself, but as a practical entry point for fostering cooperation, accountability, and ownership among local residents. By engaging community members in school construction committees, mobilizing local contributions of funds and labor, and subsequently reinvesting these resources into community development funds, the project aimed to create a cycle in which improvements in the educational environment stimulate community-led initiatives, while the benefits of those initiatives are reinvested into education. The ultimate objective was to promote self-reliance and sustainable development within rural Cambodian communities.

Accordingly, this report explores the factors that influence the enhancement of local self-help efforts by creating a sustainable educational environment to improve the livelihoods of local residents and promote sustainable rural development.

STRATEGIES FOR PROJECT IMPLEMENTATION

The project was undertaken in four primary school communities in Tboung Khmum Province, Cambodia (Fig. 1). Its implementation was structured in three interrelated phases, each designed to situate school construction as a driver of community development.

In the first phase, school construction committees were constituted at each site, comprising local residents and teachers. These committees assumed responsibility for mobilizing financial and labor contributions, liaising with construction companies, and ensuring procedural transparency through systematic reporting. The committees were intended to enhance local capacity in collective decision-making, accountability, and negotiation.

In the second phase, new physical infrastructure, including school buildings, toilet blocks, and handwashing stations, was constructed under the oversight of the committees. This phase not only addressed the shortage of educational facilities but also provided an opportunity for community members to engage in collective action directed toward a public good. Simultaneously, hygiene education initiatives were introduced, thereby linking the provision of physical facilities with behavioral improvements in school health practices.

In the third phase, community development fund committees were established. These bodies were trained in bookkeeping and financial management and were tasked with planning and implementing small-scale community businesses adapted to local contexts. Initiatives included community loan schemes, poultry raising, fertilizer sales, and the collection and marketing of agricultural products. The revenues generated from these activities were intended to be reinvested in education, establishing a feedback loop in which improved educational infrastructure and community-driven economic activities mutually reinforced one another. For example, loan schemes were prioritized in Damril Primary School, while cashew nut collection was initiated in Chhuk Sandal, reflecting the adaptation of business activities to local conditions.

Through this sequenced approach, the project sought to demonstrate that school construction could transcend its immediate function of infrastructure provision and operate as an entry point for cultivating community organization, participation, and self-reliance.

ACHIEVEMENTS OF THE PROJECT

The project produced notable achievements in terms of educational infrastructure, community awareness, and the initiation of community businesses. At the same time, it also revealed challenges and limitations that are instructive for future activities. These outcomes are presented in three main domains.

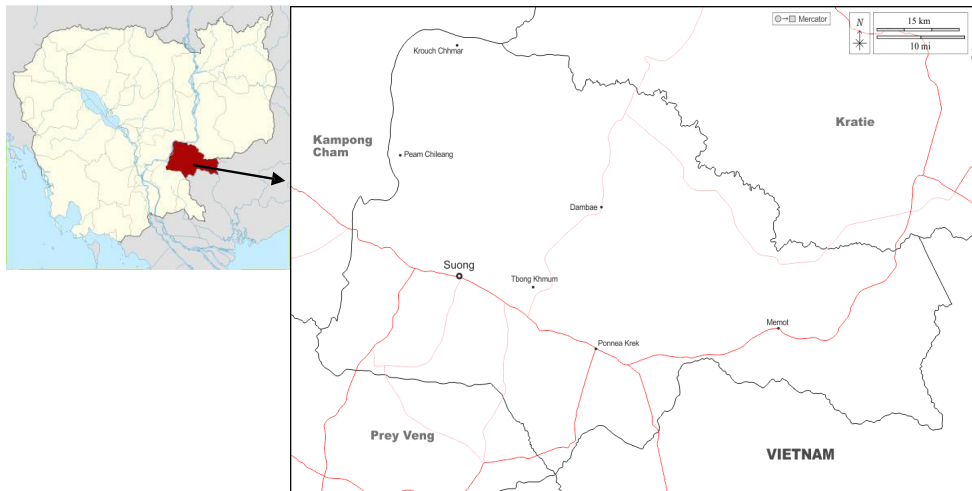


Fig. 1 Project sites for community development through school construction in Tboung Khmum Province, Cambodia

1. Establishment of School Construction Committees

Committees were successfully established in all four target schools. The members organized fundraising, mobilized labor, and monitored construction in collaboration with contractors. Weekly progress reports were produced to ensure transparency and accountability. Committee activities strengthened local capacity in negotiation and management; for example, signing a memorandum of agreement (MoA) with construction companies demonstrated enhanced procedural formality. Residents increasingly recognized that schools were being “built by themselves,” rather than externally provided, indicating an emerging sense of ownership. Nevertheless, participation levels varied across schools, with weaker engagement observed in sites where household constraints limited contributions of time and resources (Fig. 2).



Fig. 2 Meetings between the Trapeang Russey Primary School committee and the constructor for MoA signing

2. Improvement of Educational Infrastructure and Environment

The project resulted in the construction of one school building, one toilet block, and one handwashing facility at each site. Specific outcomes included six new classrooms at the Damril Primary School, a staff room and library at Chhuk Sandal (rare in rural contexts), improved space allocation and office functions at Trapeang Russey, and the introduction of afternoon classes at Chimoan, which increased facility utilization. These improvements contributed to compliance with the Ministry of Education,

Youth, and Sport (MoEYS) standards, which recommend class sizes of 35-45 students in the lower grades and 40-50 students in the upper grades. Prior to the project, some classes had more than 50 students (Fig. 3).

Hygiene education was also institutionalized. Although MoEYS promoted handwashing during the COVID-19 pandemic, these practices were not consistently sustained. With the installation of new toilets and handwashing stations, hygiene education was reintroduced in a systematic manner. Teachers were trained to deliver lessons on handwashing and toilet cleaning using posters and practical demonstrations, thereby linking new facilities with daily practices and reinforcing continuity (Fig. 4).

In addition to the above, teacher surveys revealed differences in involvement and perceptions of the project. At Chhuk Sandal and Trapeang Russey, all teachers participated in the project, whereas only 64% were involved at Damril and 67% at Chimoan. Moreover, variations were evident in the perceived importance of the project for improving educational quality and community development: 88% of teachers at Chhuk Sandal regarded the project as “very important” or “important,” compared to 68% at Damril, 68% at Chimoan, and 60% at Trapeang Russey. These findings indicate differing levels of teacher engagement and recognition of the project’s significance across sites (Table 1).



Fig. 3 Inauguration ceremonies at Trapeang Russey Primary School (left) and Chimoan Primary School (right)



Fig. 4 Hygiene workshops at primary schools of Damril (left) and Chimoan (right)

Table 1 Teachers’ involvement in, and perceptions of the school construction project

Primary school	Teacher involvement (%)	Perceived importance for educational and community development (%)
Damril Primary School	64%	68%
Chhuk Sandal Primary School	100%	88%
Trapeang Russey Primary School	100%	60%
Chimoan Primary School	67%	68%

3. Establishment of Community Development Funds and Businesses

Community development fund committees were created in all four sites, although business activities commenced only in Damril and Chhuk Sandal within the fiscal year. In Damril, where many households rely on migrant labor and are often composed of grandparents and grandchildren, a community loan project was selected as it required less intensive labor input. This scheme offered lower interest rates than microfinance institutions, thereby reducing household financial burdens.

At Chhuk Sandal, agricultural marketing initiatives were prioritized under the strong leadership of the school principal and village chief. Their capacity to mobilize and coordinate the community enabled the committee to explore multiple business ideas. During the 2025 harvest season, the committee collected and sold 18,871 kg of cashew nuts, generating a profit of USD 152.78. In contrast, an attempt to establish a rice collection scheme faced major difficulties. Insufficient initial communication with villagers and opportunistic selling to external wholesalers offering higher prices undermined the system. This outcome highlighted the importance of early consensus-building, transparent information-sharing, and incentive alignment with community members. Learning from this setback, the committee adjusted its approach in subsequent initiatives, placing greater emphasis on trust and communication, which contributed to the success of the cashew nut project.

Plans for fertilizer sales were also launched, and pilot production of organic compost was initiated to address declining cassava yields, marking an initial step toward sustainable agriculture. However, the labor-intensive nature of compost production poses potential barriers to adoption, and sustained community commitment will be required to ensure its viability.

In Trapeang Russey and Chimoan, where school completion occurred later in the fiscal year, business activities had not yet started, although discussions on potential initiatives were underway.

As the community businesses had only recently been initiated, the revenues generated from these activities remained modest and had not yet been reinvested into education. At this stage, committees were expected to develop clear plans, in consultation with schools, on how future profits could be allocated for educational purposes. For example, in Damril, the committee identified the installation of an incinerator as a priority for improving the school environment. Such initiatives illustrate the process through which schools and committees are expected to work together to shape concrete plans for educational improvement. Thus, the feedback loop between community businesses and educational development was still in the process of formation.



Fig. 5 Cashew nut collection in Chhuk Sandal Primary School community

Summary of Outcomes

Taken together, the results demonstrate that the project improved the educational environment through infrastructure provision, fostered new practices of transparency and collective action, and initiated community businesses that connected local economic activity with educational sustainability. At the same time, the challenges encountered—including limited teacher engagement in some schools, household constraints on participation, and the failure of the rice collection scheme—underscore that successful community development depends on local leadership, communication strategies, and the alignment of activities with community capacities. The variations across sites offer valuable lessons for scaling up community development efforts in rural Cambodia.

CONCLUSIONS AND FUTURE PERSPECTIVES

In fiscal year 2024, the project engaged four primary school communities in Tboung Khmum Province to improve educational environments and foster community development through the integrated processes of school construction and committee management. The outcomes demonstrated that school construction can function as more than an infrastructure intervention; it served as an entry point for cultivating collective action, transparency, and ownership among local residents. Teacher surveys further indicated that, although levels of involvement and perceived importance varied, the project contributed to greater awareness of the link between education and community development. Several challenges also emerged. In some communities, household structures, such as reliance on migrant labor or elderly caregivers, constrained active participation. Variations in leadership capacity also influenced outcomes, with Chhuk Sandal's strong village chief and school principal enabling diverse business initiatives, while other sites faced difficulties in mobilization. The unsuccessful rice collection scheme further highlighted the risks of inadequate communication and the need for consensus-building prior to launching community businesses. These experiences underscore that school construction alone cannot guarantee community empowerment; rather, the quality of facilitation, leadership, and participation strongly conditions the results.

Looking ahead, the project provides useful insights for scaling up community development through educational infrastructure. First, continued support for committee capacity building—especially in bookkeeping, communication, and negotiation—will be critical to sustaining both educational and business activities. Second, tailoring community projects to the specific socioeconomic contexts of each community is essential, as demonstrated by the appropriateness of the loan scheme in Damril and the cashew nut initiative in Chhuk Sandal. Third, building mechanisms for continuous monitoring and reflection will help communities learn from both successes and setbacks, thereby reinforcing self-reliance. These findings also have practical implications for policy, suggesting that school construction initiatives should be integrated with capacity-building and community engagement strategies to maximize their developmental impact.

In conclusion, this project aims to improve the sustainability of local communities through the integration of school construction with community development. The outcomes of this project are expected to contribute not only to improved educational infrastructure but also to the long-term formation of self-sustaining and resilient rural communities in Cambodia. Increasing local residents and governmental officers' understanding of ESD is indispensable for scaling up and replication in other areas.

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International Society of Environmental and Rural Development

Cooperative science and research body of the *Science Council of Japan*

Philosophy of ISERD:

Recently, in developing countries, subsistence agriculture is being converted to export-oriented mono-culture, and the amount of agricultural chemicals applied to the farmland is increasing every year. The applied chemicals in farmland cause serious environmental problems downstream such as eutrophication, unusual growth of aquatic plants, decrease in dissolved oxygen and accumulation of bottom mud in water resources. Also, there seem to be many cases in which people apply agricultural chemicals without understanding their impact on health and food safety. Therefore, it is necessary to promote and enhance understanding of sustainable rural development among local stakeholders, including farmers.

Sustainable rural development aims to meet human needs while preserving the natural environment. As it should cover not only social and economic development but also environmental conservation, no single organization can sufficiently achieve the aspirations of sustainable rural development. Collaboration among international, governmental and non-governmental organizations, together with the academic and scientific sector, is indispensable.

The knowledge and intelligence accumulated in universities and research institutions are also expected to make the programs facilitated by the international, governmental and non-governmental organizations more adequately implemented and meaningful to societal development. However, such cases, especially those implemented locally, have been scattered without having been summarized well or recorded in the annals of academic or scientific societies.

As such, the International Society of Environmental and Rural Development, founded in 2010, aims to discuss and develop suitable and effective processes and strategies on sustainable rural development, focusing on agricultural and environmental aspects in developing countries. The ultimate goals of the society are to contribute to sustainable rural development through social and economic development in harmony with the natural environment, and to support the potential and capacity building of local institutions and stakeholders in the rural areas with academic background.

Purposes of ISERD:

The primary purposes of ISERD are to contribute to sustainable rural development through social and economic development in harmony with the natural environment and to support the potential and capacity building of local institutions and stakeholders in the rural areas with academic background.

In order to enhance the realization of the primary purposes of ISERD, the secondary purposes are;

- to facilitate interaction among international, governmental, non-governmental organizations and local communities,
- to hold conferences or symposia on environmental and rural development,
- to edit the International Journal of Environmental and Rural Development (IJERD),
- to confer various awards based on scientific achievement, sustainability promotion, research paper or poster presentation, and
- to encourage and develop local awareness concerning sustainable rural development.

Membership:

There shall be two categories of membership.

- (a) Individual
- (b) Organizational

An application for membership of ISERD shall be submitted to the secretariat of ISERD, where is located in the Research Center at Institute of Environmental Rehabilitation and Conservation (Japan) by writing or by other appropriate means.

Also, all presenters who attended the International Conference on Environmental and Rural Development (ICERD) are registered as Individual Members of ISERD.

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Research Center, Institute of Environmental Rehabilitation and Conservation (ERECON)

2987-1 Onoji Machida-shi, Tokyo 195-0064, Japan
Tel/Fax: +81-42736-8972
E-mail: iserd.secretariat@gmail.com
Webpage: www.iserd.net

Collaborated with

Association of Environmental and Rural Development (AERD)

93/64 Moo.3, Sinsab Village 2, Bungyeetho Sub-District, Thanyaburi District,
Pathum Thani 12130, Thailand
Tel/Fax: +66-2957-8064
E-mail: iserd.secretariat@gmail.com
Webpage: www.iserd.net

