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HOUSEHOLD RESILIENCE AND IMPACT OF UNEMPLOYMENT, CLIMATE, AND PRICE SHOCKS ON FOOD SECURITY: EMPIRICAL EVIDENCE FROM THE PHILIPPINES

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ABSTRACT

Given the recent global shocks, it has become increasingly relevant to enhance resilience to food insecurity to cushion households amidst its adverse impacts and allow them to at least maintain their current level of food security. Using the 2003 to 2009 panel data from the Philippines, this paper explored the direct and indirect impacts of unemployment, climatological, and price shocks on real per capita food expenditure and household dietary diversity through its impacts on household resilience. Utilizing the Resilience Index Measurement and Analysis II (RIMA-II) and Two-Stage Least Squares (2SLS) approaches, it was found that shocks may have multiplier negative effects on future food security outcomes. However, a higher level of household resilience significantly improves future food expenditure, although it does not necessarily translate into a higher current level of household dietary diversity. Household resilience is also a significant factor for recovery from the loss induced by shocks in real per capita food expenditure and dietary diversity. Overall, it was found that strengthening household resilience, especially its most relevant pillars such as the use of basic services, social safety net, and adaptive capacity, is crucial in improving the long-term household food security status of Filipino households.

Key words: 2SLS, dietary diversity**,** food expenditure

INTRODUCTION

In the continuing fight against poverty, numerous studies have been conducted to characterize the vulnerable populations to reduce their risk of falling into poverty (ex-ante studies) (Bayudan-Dacuycuy and Lim 2013; Mina and Imai 2017; Ouadika 2020) and to assess which anti-poverty programs have been effective (ex-post studies) (Davis et al. 2005; Do et al. 2013). However, given the recent shocks in the economy (i.e., COVID-19 pandemic, rising oil prices, etc.), it has also become necessary to improve the resilience of the vulnerable households amidst these shocks. This is important because while uplifting the economic conditions of the vulnerable groups usually takes time, at the very least, their condition should not worsen even amid stressors, or the adverse impacts should not be long-lasting.

Food insecurity is one of the faces of poverty that is especially exacerbated in times of crisis. Between 2019 and 2020, there was a sharp increase in the incidence of food insecurity from 25 to 29 percent under the shadow of the COVID-19 pandemic, and the figures remain almost unchanged even after three years, with 2.33 billion people in the world experiencing moderate or severe food insecurity (FAO et al. 2024) making it harder to achieve the zero hunger target by 2030. Sociodemographic factors and asset ownership influence both the recurrent and episodic food insecurity of smallholder farmers, highlighting the need for policies and programs that will improve food security and resilience to extreme weather shocks (Alpizar et al. 2020). This was also supported by a previous study, which pointed out that the major reasons why rural households are vulnerable are the neglect to food security and food system management, and sustainability and resiliency (Nahid et al. 2021). An attempt to address this call is to examine how household resilience capacity affects food security outcomes.

This study sought to assess how household resilience affects food security outcomes amidst shocks, specifically unemployment, extreme rainfall and temperature, and price shocks, in the Philippine context, and to determine the separate impact of these shocks on household resilience and food security outcomes. While a growing number of studies have reviewed the link between household resilience and food security outcomes in the presence of shocks (Ansah et al. 2019; D'Errico et al. 2018; Haile et al. 2022), to the authors' knowledge, this paper is among the few to study household resilience as a causal pathway to food security which implies formulating policies that can address short-term and long-term food insecurity. Most studies measured resilience as an indicator of food security, making it difficult to differentiate the two concepts (Ansah et al. 2019). By studying household resilience as a pathway to food security, this paper addresses the gap in the existing literature and provides substantiation on the possible synergies and trade-offs that may exist between the two concepts in the presence of shocks. Further, using evidence from the Philippines, this paper also offers a perspective from Southeast Asia, as African perspectives dominate the existing literature. The Philippines had the second highest prevalence of food insecurity in Southeastern Asia (about 45%) next to Cambodia (51% prevalence) (FAO et al. 2024) and has topped the World Risk Index due to its frequent exposure to natural calamities and high vulnerability (Bündnis Entwicklung Hilft/ IFHV 2023) in 2023. By understanding the dimensions of household resilience of Filipino households, the results of this study also provide inputs to policymakers in identifying priority areas to focus on to increase households' resilience to shocks and indirectly resolve food insecurity problems.

MATERIALS AND METHODS

Data. The household-level panel data from the merged triennial Family Income and Expenditure Survey (FIES) and quarterly Labor Force Survey (LFS) conducted by the Philippine Statistics Authority (PSA) covering the periods: 2003, 2006, and 2009 were used. While more recent FIES datasets are available (i.e., 2012, 2015, and 2018), the respondents covered in the more recent rounds are different at each round as the PSA employed a repeated cross-sectional survey from 2012 onwards, in contrast to the panel survey employed from 2003 to 2009. Nevertheless, the experience of the households in response to the shocks that occurred from 2003 to 2009 may provide important insight into how household resilience can influence food security outcomes and how it can act as a pathway to achieve long-term food security. It is important to note that during the periods of 2003 to 2009, the Philippines has experienced extreme weather events (four El Niño and three La Niña episodes) that brought devastating typhoons, extreme flooding, and prolonged droughts; 2007/2008 global financial crisis which has also surged up rice prices; and other macroeconomic shocks (Mina and Imai 2017). These shock occurrences were presumed to have affected the resilience of the households and their food security status. Around this time, poverty and food and nutrition insecurities were already critical problems in the Philippines, citing both adults and children suffering from its consequences (Angeles-Agdeppa 2002; Fernandez-San Valentin and Berja Jr. 2012).

The 2003-2006-2009 panel dataset comprised a total of 6,253 households but after data cleaning, 6,251 households were retained in the sample. The FIES contains annual information on the households' socio-economic characteristics, detailed sources of income and expenditure, asset ownership, private transfers, and other household characteristics. On the other hand, LFS provides detailed information on the employment status of the members of the households. This includes information on whether a member of the household has experienced unemployment during the survey period.

The food security indicators that were used in the analysis were the annual per capita food expenditure (an indirect measure of food caloric intake) and the household dietary diversity index measured using Simpson-index (SI) (also known as Berry-index) that was calculated from FIES datasets using the formula:

$$SI=1-\sum_{i=1}^{n} p_i^2 \quad (1)$$

Where p_i is the proportion of consumed calories (in terms of value) of the ith food group in a sample of *n* food groups (Drescher et al. 2007; D'Errico et al. 2018; Nithya and Bhavani 2016).

Although household dietary diversity score (HDDS) is the more common measure of household dietary diversity used in developing countries like the Philippines, SI was used in the analysis since it does not only measure the quality of food intake but also reflects the distribution of the food types consumed by the household (Verger et al. 2021). However, SI does not increase if the distribution of food consumed moves in favor of healthier food types, which might be desired from a nutritional perspective (Drescher et al. 2007). The SI ranges from zero to one, with one indicating maximum diversity in the household's food basket.

The per capita food expenditure was deflated using the average core consumer price index (CPI) of June and December of the survey periods (obtained from the PSA database) to capture the real per capita food expenditure (the average core CPI in June and December 2003 was 67.9; the average core CPI in June and December 2006 was 79.2; the average core CPI in June and December 2009 was 89.8; and the base year is 2012). The average core CPI of June and December were used as deflators since FIES surveys are conducted twice per round. The first visit was July, covering the first six months (January to June), and the following visit was January of the succeeding year, covering the latter six months of the year (July to December). The prevailing market prices during the survey period were used by PSA in the computations of household expenditures, so the core CPIs in June and December were used for better accuracy of the estimates. However, since the expenditures were based on households' recall, measurement errors may still exist. Further, real per capita food expenditure may fall short as a proxy of caloric food intake since it captures both the quantity and quality of food intake.

As for the shock variables, the covariate shocks that were included in the study were climatological shocks, such as extreme rainfall and temperature and price shocks. The climatological shocks were represented by dummy variables equal to one if there were recorded extreme values on rainfall and temperature at the local weather satellite stations. Rainfall and temperature shocks were tested for correlation using pairwise correlation to check whether they are highly correlated. Based on the pairwise correlation, rainfall and temperature shocks that occurred in 2003 were not highly correlated (correlation = 0.031, significant at 5% alpha) and thus, were both included in the models. Price shocks were represented by dummy variables equal to one if their values deviate by two standard deviations from the historical average. Inflation was measured using the provincial CPIs. These variables were presumed to have direct impacts on household income, especially since some of the population being studied belongs to the agricultural sector, known to be vulnerable to weather, fuel, and food price shocks (Mina and Imai 2017). The data on climatological extremes were obtained from the Philippine Atmospheric, Geophysical and Astronomical Services Administration (PAGASA) and the price shocks were obtained from PSA website. These data were matched to each household using the Philippine Standard Geographic Code (PSGC), which is the standard classification and coding used in the Philippines for geographical-political subdivisions, that can be found in the merged FIES-LFS datasets. Note that while the geo-locations of the households were available in the datasets, climate shock dummies were limited to provincial-level variation since not all the cities/municipalities in the Philippines have their own weather satellite stations. The idiosyncratic shock that was considered in the analysis was the self-reported experience of unemployment of members of the household. Further, the household's distance to the nearest bank was estimated using Google Maps. Households' locations and addresses of all banks in the Philippines obtained from the *Bangko Sentral ng Pilipinas'* (BSP) website were pinned on Google Maps to calculate the shortest distance. A summary of the variables used in the analysis is shown in Table 1.

Table 1. Description of the variables used in the analysis

Variable	Definition/Notes
Log of real per capita food expenditure	log of real per capita annual food expenditure including those received as gifts and produced for own consumption; taken for the years 2003, 2006, and 2006
Change in per capita food expenditure between 2003 and 2006	difference of real per capita food expenditure in 2003 and 2006 (in PhP100)
Change in per capita food expenditure between 2006 and 2009	difference of real per capita food expenditure in 2006 and 2009 ((in PhP100); restricted sample (only those who experienced a loss in real per capita food expenditure in between 2003 and 2006 were included)
HH dietary diversity	measured in terms of Simpson Index (SI); values range from 0 to 1 where 1 indicates highest level of dietary diversity and 0 indicates no diversity in diet; taken for the years 2003, 2006, and 2009
Change in HH dietary diversity between 2003 and 2006	difference of SI between 2003 and 2006
Change in HH dietary diversity between 2006 and 2009	difference of SI between 2006 and 2009; restricted sample (only those who experienced a loss in household dietary diversity between 2003 and 2006 were included)
UBS components	
Infrastructural index	index used to indicate dwelling condition of the household; combines five dummies each of them equal to 1 for having a roof and walls made of strong material (galvanized, iron, al, tile, concrete, brick, stone, asbestos), toilet, water supply, and electricity. The index was created using factor analysis (FA) and indicates better dwelling conditions for higher value.
Transportation and communication	household expenditures for transportation and communication (in PhP)
Education	household expenditures for education services (in PhP)
Medical care	household medical care expenditure (in PhP)
Clothing	household clothing expenditures (in PhP)
AST components	
Wealth index	Index used to proxy the richness of the household; higher values are assumed for households with greater non-productive asset position; created using FA by combining dummy variables assuming value of 1 or 0 to indicate whether the household has specific non-productive assets such as radio, TV, VTR, stereo, refrigerator, washing machine, airconditioner, sala, dining, car, phone, microwave, oven, motorcycle, and own or owner-like possession of house and lot.
Interest earned	measured in PhP
Dividend	dividends from investment (measured in PhP)
Profit from stocks	profit from sales of stocks, etc. (measured in PhP)

Variable	Definition/Notes
Winning from gamblings	net winnings from gambling, etc. (measured in PhP)
Savings/business equity	measured in terms of withdrawal from Savings/Business equity (in PhP)
Backpay and proceeds from insurance	measured in PhP
Other receipts (excl. Loans and withdrawals)	measured in PhP
Inheritance	measured in PhP
Rental value of house	measured in PhP
SSN components	
Cash receipts/support from abroad	measured in PhP
Cash receipts/support from domestic source	measured in PhP
Total received as gifts	measured in PhP
Pension and retirement benefits	measured in PhP
Loans from other families	measured in PhP
AC components	
Income diversification index	index generated using FA with dummies for income from (1) wages/salary from agricultural activity, (2) wage/salary from non-agricultural activity, (3) crop farming and gardening, (4) livestock and poultry raising, (5) fishing, (6) forestry and hunting, (7) transfers, (8) other income sources, etc
Household head job/business indicator	dummy =1 if the head of the household has job/business
No children in the family	dummy =1 for household with no children family members (<15 years old)
Household head education	dummy = 1 if at least high school graduate
Number of family members employed for pay	count of family members employed
Income earners' share	count of family members employed for pay/profit divided by household size
Savings indicator	dummy variable =1 if with savings
Wife employment	dummy variable =1 if wife is employed
RCI	estimated using MIMIC; at time t = 2003
RCI2	estimated using SEM; at time t = 2003
Female household head	dummy =1 if the head of the household is female
Age of household head	in years
Agricultural HH indicator	dummy = 1 if the household is primarily engaged in agricultural sector
Urban/rural	dummy =1 if the household is residing in urban area
Household size	average family size for 1st and 2nd visit for 2003

Variable	Definition/Notes
Shocks (in 2003)	
Experienced unemployment	dummy =1 if any member of the family experienced unemployment
Weather shocks	provincial level variations
Temperature	dummy = 1 if the province where the household resides experienced extreme temperature as reported by PAG-ASA weather satellite stations
Rainfall	dummy = 1 if the province where the household resides experienced extreme rainfall (greatest amount of rainfall) as reported by PAG-ASA weather satellite stations
Price shock	Price shock was represented by dummy variable equal to 1 if annual consumer price index (CPI) (used to measure inflation) deviates by two standard deviations from historical average (1994-2002); provincial level variation
Distance to nearest bank	Measured in kilometers

Resilience estimation. In measuring resilience, the authors employed the Food and Agriculture Organization (FAO) Resilience Index Measurement and Analysis II (RIMA-II) approach which has the advantage of providing an adequate estimate of household resilience to food insecurity since it properly linked resilience capacity index (RCI) with household food security by jointly estimating RCI by its causes, pillars, and food security indicators (Bruck et al. 2018). Based on FAO's analytical framework, the fundamental pillars of resilience are: (1) access to basic services (ABS), (2) assets (AST), (3) social safety nets (SSN), (4) sensitivity (exposure to risk), and (5) adaptive capacity (AC); in the RIMA-II approach, the sensitivity pillar is considered exogenous and is included in the regression analysis to assess the real impact of the shocks on resilience capacity. However, some modifications were done in this study (Fig. 1). Use of basic services (UBS) instead of ABS was used as one of the pillars of resilience since the observed variables used to measure this dimension were in expenditure terms, which capture both the quality and quantity of service.

While there are other approaches in measuring resilience, the FAO RIMA-II approach dominates the literature and has been advocated (Ansah et al. 2019; Haile et al. 2022). The RIMA-II approach involves a two-stage procedure. The first step identifies the attributes that contribute to household resilience (those that constitute the pillars mentioned earlier) based on the observed variables using Factor Analysis (FA) (Fig. 1).

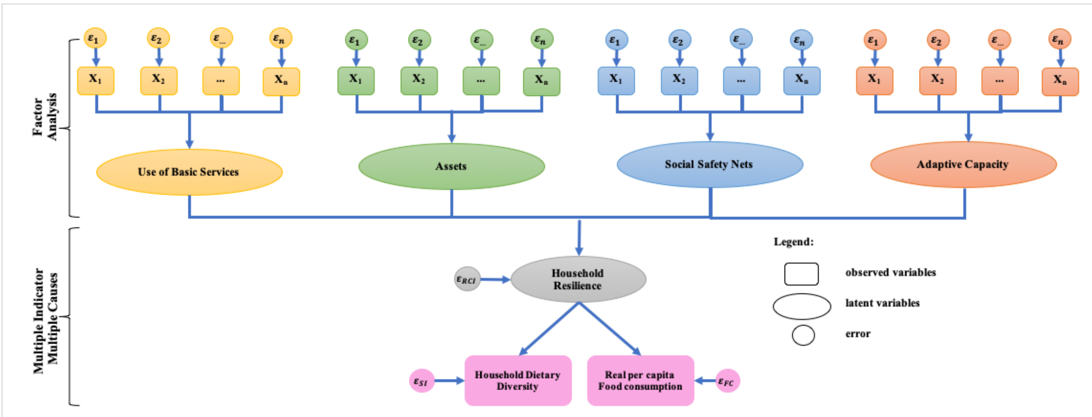


Figure 1. Analytical framework of RIMA-II approach
Note. Adapted from D'Errico et al. (2018)

By employing FA, a set of observed variables that are closely correlated is reduced into a single variable that may well proxy the pillar of resilience, which is a latent variable. The number of factors that was selected for each pillar has a minimum eigenvalue of one.

After which, a Multiple Indicators Multiple Causes (MIMIC) model was constructed to specify the relationships between resilience (unobserved latent variable), food security indicators (outcome indicators), and pillars (a set of attributes). The MIMIC model simultaneously estimates the measurement equation (2) and the structural equation (3). However, this was only used as a descriptive tool to establish the relationship between resilience and its components and subsequent regression analysis was used for the causal inference since there is a risk of endogeneity when the latent construct (RCI) and the outcome of interest are jointly determined or when the RCI is correlated with the error term (D'Errico et al. 2018; FAO 2016).

$$\begin{bmatrix}\text{Household dietary diversity}\\ \text{Real per capita food expenditure}\end{bmatrix} = [\Lambda_1, \Lambda_2] \text{ x } [\text{RCI}] + [\varepsilon_1, \varepsilon_2] \tag{2}$$

$$\text{RCI} = \beta_1\text{UBS} + \beta_2\text{AST} + \beta_3\text{SSN} + \beta_4\text{AC} + \varepsilon_3 \tag{3}$$

The RCI was standardized through a Min-Max scaling transformation as proposed by FAO (2016) and D'Errico et al. (2018) using the formula:

$$\text{RCI}_h^* = \frac{(\text{RCI}_h\text{-RCI}_{min})}{(\text{RCI}_{max}\text{-RCI}_{min})} \text{ x } 100 \tag{4}$$

Where h represents the h^{th} household.

Household resilience and food security. To assess how household resilience affects future food security outcomes, a multiple regression model was estimated where the dependent variable, the change in food security (FS) outcome (i.e., change in real per capita food expenditure or dietary diversity index) between 2003 and 2006 (change in $\text{FS}_{2003,\,2006}$), was regressed with the RCI and a vector of time-variant household characteristics **X** in 2003 and time-invariant household characteristics **Z**. The linear form and not the log of the outcome variable was used for the change in real per capita food expenditure since the log form excludes the negative changes in real per capita food expenditure in the sample. Shock variables were also included in the analysis to capture their marginal effects on the change in FS outcome. The interaction of RCI and shock variables was also included to capture the marginal effect of the RCI on the future food security status of households impacted by the shocks. Mathematically, the estimated equation is expressed as:

$$\text{change in FS}_{2003,2006} = \alpha + \beta_1\text{RCI}_{h,2003} + \beta_2\mathbf{S}_{h,2003} + \beta_3\text{RCI}_{h,2003} \text{ x } \mathbf{S}_{h,2003} + \beta_4\mathbf{X}_{h,2003} + \beta_5\mathbf{Z}_{2003} + \varepsilon \tag{5}$$

Where **S** is a vector of the shocks that affected the household between 2003 and 2006, $\boldsymbol{\beta}$s are the coefficients of the variables, α is the constant, and ε is the error term. The effect of the lagged resilience capacity estimate ($RCI_{h,2003}$) to the change in food security status of the households between 2006 and 2009 was also examined to check whether the current level of RCI influences long-term food security outcomes and speed of recovery as shown in equation (6). For this part, the sample was restricted to those who experienced a loss in food security outcomes between 2003 and 2006.

$$\text{change in FS}_{2006,2009} = \alpha + \beta_1\text{RCI}_{h,2003} + \beta_2\mathbf{S}_{h,2003} + \beta_3\text{RCI}_{h,2003} \text{ x } \mathbf{S}_{h,2003} + \beta_4\mathbf{X}_{h,2003} + \beta_5\mathbf{Z}_h + \varepsilon \tag{6}$$

Impact of shocks to food security outcomes through household resilience. To determine the separate impact of shocks on household resilience and food security outcomes and understand the dynamics of how shocks affect food security outcomes through household resilience, a two-stage least square (2SLS) regression was employed. An instrumental variable (IV) was used to address endogeneity issues between household resilience and food security since reverse causality may exist between the two wherein a more resilient household tends to be more food secure as it can adapt/adjust well to shocks and stressors. The household's distance to nearest bank was used as an IV for this purpose. Without directly affecting the household's food security, distance to the bank may improve the household's resilience by providing better access to credit and savings. Some caveat still remains, though, with regard to the exclusion restriction since banks are normally located strategically in commercial areas and areas with economic potential. Further, unobservable omitted variables (i.e., abilities of household) and measurement errors may also exist regarding the measure of household resilience capacity itself.

Using the pillars of resilience estimated through FA, Structural Equation Modelling (SEM) was employed to aggregate the resilience indicators and predict the latent variable, RCI. SEM is preferred than FA in this part because it allows correlation among residual errors, which is most likely the case when there is a high probability of intra-dimension correlation (D'Errico and Pietrelli 2017). Since measuring the latent variable, RCI, requires a formative measurement model (not the usual reflective measurement model) given that RCI is caused by the observed variables, one of the formative indicators, UBS, was fixed to have a loading of 1.0 and the error variance for the composite latent variable, RCI, was fixed at 0 (Acock 2013).

In the first stage of 2SLS, the RCI that was estimated using SEM was used as the dependent variable and was regressed with the shock variables ($\mathbf{S}_{h,2003}$), the instrument distance to nearest bank$_h$, and control variables ($\mathbf{X}_{h,2003}$, $\mathbf{Z}_h$):

$$RCI_{h,2003} = \alpha+\beta_1 \text{distance to nearest bank}_h+\beta_2\mathbf{S}_{h,2003}+\beta_3\mathbf{X}_{h,2003}+\beta_4\mathbf{Z}_h+\varepsilon \qquad (8)$$

In the second stage, the estimated $\widehat{RCI}_{h,2003}$ from equation (8) was used as an independent variable to estimate FS outcomes:

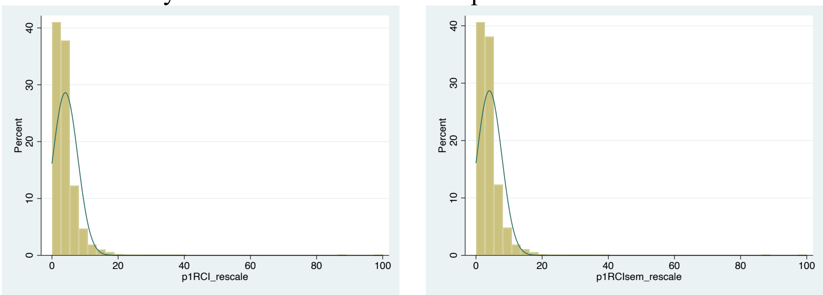
$$FS_{h,2003} = \alpha+\beta_1 \widehat{RCI}_{h,\,2003}+\beta_2\mathbf{S}_{h,2003}+\beta_3\mathbf{X}_{h,2003}+\beta_4\mathbf{Z}_h+\varepsilon \qquad (9)$$

The validity of the IV used in the model was tested using the Montiel Olea-Pflueger (MOP) Effective First-Stage F-statistics. However, only the relevance condition was tested since the model is exactly identified (a good IV must satisfy both the relevance and exogeneity conditions, but the latter cannot be tested in this study).

Robustness checks. To determine whether the results are robust, the same models were employed as above using different time periods. For instance, RCI in 2006 was estimated using MIMIC and multiple regression models were ran using the change in real per capita food expenditure and SI between 2006 and 2009 as outcome variables and same regressors measured in 2006 to check for the robustness of models (3) and (7) in Tables 4 and 5. Similarly, RCI in 2006 was estimated using SEM and a 2SLS model was ran using log of real per capita food expenditure and SI in 2006 as outcome variables and the same regressors measured in 2006 to check for the robustness of models (9) to (11) in Table 6. However, due to lack of available data, the robustness of models (4) and (8), which were used to measure the long-term influence of household resilience on food security outcomes, cannot be checked. Further, in estimating RCI in 2006, the total number of household members who are of working age (those aged 15 to 59 years old) was added as one of the observed variables in the AC pillar in order to generate a factor with a minimum eigenvalue of one.

RESULTS AND DISCUSSION

Household resilience. While Filipinos are anecdotally known for being resilient or being able to withstand or recover quickly from natural calamities, when measured, it was found that they generally have low level of household resilience (Fig. 2). From a maximum scale of 100, the mean RCI of households in 2003 was only around four. Less than one percent has a resilience index of more than 50.



(a) RCI (b) RCI2

Figure 2. Histogram of RCI across households, 2003

Among the four pillars, MIMIC estimates show that the UBS pillar contributed the most to their household resilience (Table 2). Transportation and communication, clothing, and education are among the most relevant variables in the UBS pillar (Table 3). This means that better access to these basic services largely contributes to improving the resilience of Filipino households. SSN and AC pillars also have a statistically significant contribution to the RCI estimates, although in relatively lower magnitudes. For SSN, cash receipts/support from abroad contribute substantially to enhancing the resilience of the Filipino households. Remittances from abroad allow them to recover easily from shocks. However, it is important to note that heavy reliance on remittances from abroad make them more vulnerable to global shocks since these global shocks affect real values of remittances.

Table 2. Coefficients of structural and measurement components of the Multiple Indicators Multiple Causes (MIMIC) model of Resilience Capacity Index (RCI)

Structural component		
Use of basic services (UBS)	0.267	***
	(0.073)	
Assets (AST)	0.181	
	(0.116)	
Social safety nets (SSN)	0.017	***
	(0.004)	
Adaptive capacity (AC)	0.124	***
	(0.016)	
Measurement component		
Per capita food expenditure[(a)]	1.000	
Dietary diversity (in terms of SI)	0.049	***
	(0.002)	

Goodness-of-fit statistics	
Standardized root mean squared residual (SRMR)	0.003
Coefficient of determination (CD)	0.437
Observations	6,042

Notes:

(a) Since the estimated RCI is not anchored to any scale of measurement as it is inherently observed, the coefficient of real per capita food expenditure loading (Λ_1) was set to one, implying that one standard deviation increase in RCI corresponds to one standard deviation increase in real per capita food expenditure (D'Errico et al. 2018; FAO 2016).

(b) In parenthesis are the standard errors; ***p<0.01

Table 3. Household resilience structure: absolute correlation of variables by pillar

UBS	
Infrastructural index	0.4277
Transportation and communication*	0.8698
Education*	0.7038
Medical care	0.3059
Clothing	0.8507
AST	
Wealth index*	0.6079
Interest earned*	0.6125
Dividend	0.2264
Profit from stocks*	0.6617
Winning from gambling	0.0333
Savings/business equity	0.2658
Backpay and proceeds from insurance	0.036
Other receipts (excl. loans and withdrawals)	0.1605
Inheritance	0.0171
Rental value of house*	0.8037
SSN	
Cash receipts/support from abroad*	0.8958
Cash receipts/support from domestic sources	0.1822
Total received as gifts	0.4071
Pension and retirement benefits	0.3352
Loans from other families	0.1473
AC	
Income diversification index	-0.2181
HH job/business indicator	0.0472
No children in the family (<15 years old)	0.0359

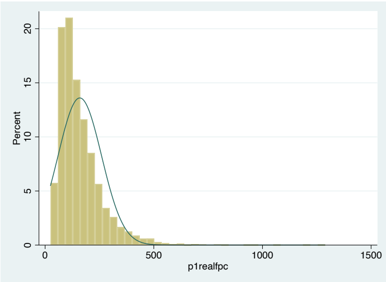
HH education (= 1 if at least HS grad)	0.1644
Number of family members employed for pay*	0.8391
Income earners' share*	0.7383
Savings indicator	0.2558
Wife employment*	0.6336

Note:
(a) The most relevant variables by pillar are denoted by asterisk (*).

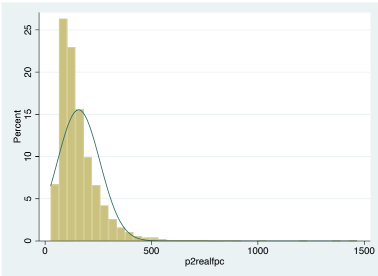
Ironically, income diversification index has a negative correlation with AC. It could be explained by the fact that some economic activities have negative correlations with each other (i.e., transportation and fishing, crop gardening and manufacturing, forestry and wholesale and retail, etc.).

Meanwhile for AC, the number of family members employed for pay, income earners' share, and wife's employment are the most important variables. A greater number of employed household members allows households to adapt well and better cope with shocks.

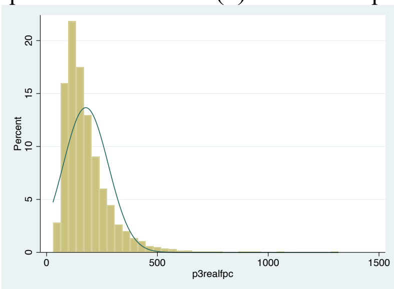
Food security status. In terms of food security status, there are generally lower levels of real per capita food expenditure across households across the three-year period but generally higher levels of dietary diversity (Figs. 3 and 4). With a maximum value of one, the mean SI of households in 2003 is 0.753. However, the mean values of SI declined to 0.718 from 2003 to 2009. This somewhat shows that while real per capita food expenditure is generally low, Filipino households maintain a generally diverse diet. To check whether SI similarly captures the dietary diversity condition of the household, the HDDS of the households in the sample was also computed using the formula: HDDS = sum of food groups consumed (INDDEX Project 2018). Using HDDS, with a maximum score of seven, the mean HDDS of households in 2003 is 6.89, 6.90 in 2006, and 6.91 in 2009, indicating high diversity in the diet.



(a) Annual real per capita food expenditure in 2003

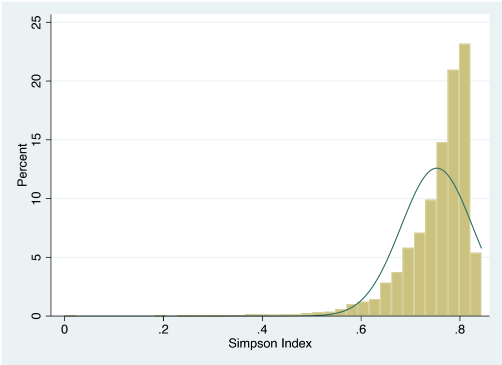


(b) Annual real per capita food expenditure in 2006

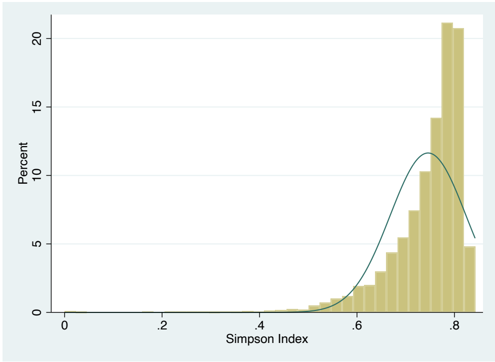


(c) Annual real per capita food expenditure in 2009

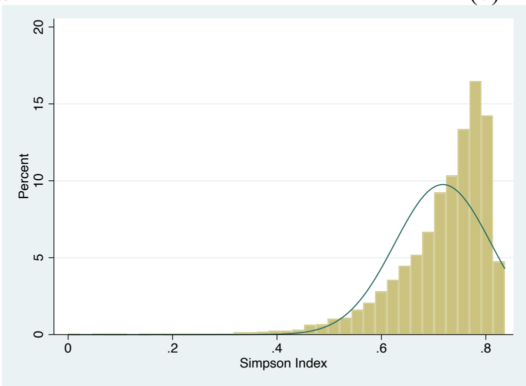
Figure 3. Distribution of annual real per capita food expenditure (in hundred PhP) in 2003, 2006, and 2009



(a) 2003 SI



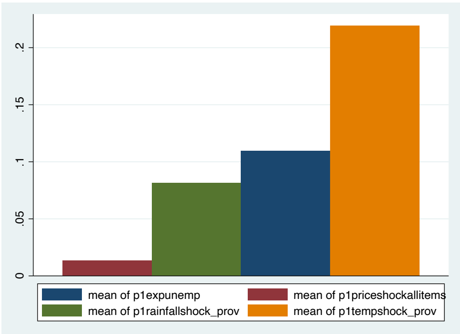
(b) 2006 SI



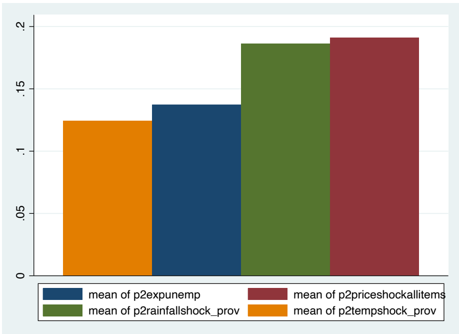
(c) 2009 SI

Figure 4. Household dietary diversity (measured in terms of SI) in 2003, 2006, and 2009

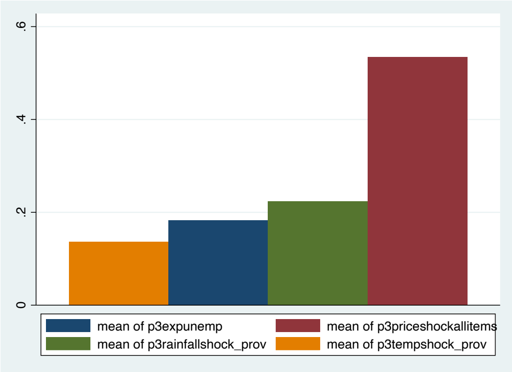
Exposure to shocks. Shocks ultimately affect household's food security status. The idea is that when households experience a shock at time *t*, they become more vulnerable at present and depending on how fast they recover, their future welfare may also be reduced. Based on the data, the most common shock experienced by households in 2003 was extreme temperature, followed by experienced unemployment of a family member (Fig. 5). Price shocks were the least experienced by the households during this period. However, this was reversed in 2006 and 2009. In 2006 and 2009, price shock became the most common shock experienced by the households and a higher number of households were exposed to this shock which may be due to the global financial crisis around this time.



(a) mean exposure to various shocks in 2003



(b) mean exposure to various shocks in 2006



(c) mean exposure to various shocks in 2009

Figure 5. Mean household exposure to various shocks in 2003, 2006, and 2009

Empirical results. Tables 4 and 5 show empirical evidence on the effect of household resilience to future food security outcomes. Models (1) and (5) show how current level of household resilience affects future short-term food security outcomes without controlling for the shock variables and their interaction with the resilience estimate; models (2) and (6) control for the shock variables; models (3) and (7) control for the shocks and include its interaction term with the resilience estimate to assess whether higher household resilience dampens the impact of the shock on future short-term food security outcomes; and models (4) and (8) determine whether current level of household resilience affects long-term food security outcomes and whether it is a significant factor for recovery. Further, models (4) and (8) assess whether shocks have lagged and long-term impacts on food security outcomes. Models (1) to (3) in Table 4 and models (5) to (7) in Table 5 include all the samples in the dataset while models (4) and (8) restrict the sample to those who experienced a loss in food security outcomes between 2003 and 2006.

Table 4. Relating changes in real per capita food expenditure and household resilience (FAO-RIMA II approach)

	Model (1)	**Model (2)**	**Model (3)**	**Model (4)**
VARIABLES	**Difference in real per capita food expenditure b/w 2003 and 2006**	**Difference in real per capita food expenditure b/w 2003 and 2006**	**Difference in real per capita food expenditure b/w 2003 and 2006**	**Difference in real per capita food expenditure b/w 2006 and 2009 (*Recovery indicator*)**
RCI	4.667***	4.639***	5.537***	4.059***
	(0.724)	(0.722)	(0.787)	(0.950)
Log of real per capita food expenditure in 2003	-87.01***	-87.00***	-87.71***	
	(3.555)	(3.545)	(3.387)	
Experienced unemployment		-0.527	3.844	-12.43
		(3.181)	(5.097)	(12.48)
Temperature shock		-0.834	6.644	0.888
		(2.608)	(4.583)	(6.436)
Rainfall shock		3.137	12.38	-16.23**
		(4.308)	(8.308)	(7.878)

VARIABLES	Model (1) Difference in real per capita food expenditure b/w 2003 and 2006	Model (2) Difference in real per capita food expenditure b/w 2003 and 2006	Model (3) Difference in real per capita food expenditure b/w 2003 and 2006	Model (4) Difference in real per capita food expenditure b/w 2006 and 2009 (*Recovery indicator*)
Price shock		-21.33**	-19.25	54.17***
		(8.504)	(11.84)	(12.63)
Experienced unemployment x RCI			-0.888	1.838
			(1.165)	(3.004)
Temperature shock x RCI			-1.731	-0.595
			(1.184)	(1.459)
Rainfall shock x RCI			-2.464	-0.485
			(2.271)	(1.705)
Price shock x RCI			-0.612	-11.04***
			(3.126)	(3.796)
Log of real per capita food expenditure in 2006				-37.94***
				(5.009)
Constant	827.2***	825.4***	829.5***	404.8***
	(34.36)	(34.47)	(33.09)	(47.59)
F-statistics				
(a) Shocks = 0		1.73	2.62	6.51
		(p< 0.14)	(p< 0.033)	(p<0.000)
(b) Shocks x RCI = 0			1.53	2.22
			(p<0.191)	(p<0.064)
Controlling for HH characteristics	Yes	Yes	Yes	Yes
Controlling for regional variations	Yes	Yes	Yes	Yes
Observations	6,104	6,104	6,104	3,042
R-squared	0.177	0.177	0.180	0.067

Notes:

(a) In parentheses are the robust standard errors; *** p<0.01, ** p<0.05, * p<0.1
(b) All models were tested for multicollinearity (mean variance inflation factor < 10).
(c) Except for the log of real per capita food expenditure in 2006, all the regressors are at time t=2003.

Table 5. Relating changes in household dietary diversity (SI) and household resilience (FAO-RIMA II approach)

Variables	Model (5) Difference in SI b/w 2003 and 2006	Model (6) Difference in SI b/w 2003 and 2006	Model (7) Difference in SI b/w 2003 and 2006	Model (8) Difference in SI b/w time 2006 and 2009 (*Recovery indicator*)
RCI	0.00317***	0.00318***	0.00366***	0.00341***
	(0.000361)	(0.000373)	(0.000326)	(0.000521)
SI in 2003	-0.689***	-0.689***	-0.692***	

Variables	Model (5) Difference in SI b/w 2003 and 2006	Model (6) Difference in SI b/w 2003 and 2006	Model (7) Difference in SI b/w 2003 and 2006	Model (8) Difference in SI b/w time 2006 and 2009 (*Recovery indicator*)
	(0.0234)	(0.0232)	(0.0230)	
Experienced unemployment		0.00488*	0.0104***	0.00883
		(0.00266)	(0.00396)	(0.00703)
Temperature shock		0.00858***	0.0128***	-0.00739
		(0.00243)	(0.00341)	(0.00606)
Rainfall shock		-0.000690	-0.00499	-0.00567
		(0.00407)	(0.00595)	(0.00787)
Price shock		-0.0170**	-0.0522***	-0.0251*
		(0.00796)	(0.0166)	(0.0137)
Experienced unemployment x RCI			-0.00116**	-0.000651
			(0.000519)	(0.000938)
Temperature shock x RCI			-0.000980**	0.00171*
			(0.000442)	(0.000891)
Rainfall shock x RCI			0.00107	0.00242**
			(0.000853)	(0.00118)
Price shock x RCI			0.0116***	-0.000105
			(0.00433)	(0.00464)
SI in 2006				-0.620***
				(0.0370)
Constant	0.538***	0.538***	0.538***	0.462***
	(0.0191)	(0.0192)	(0.0191)	(0.0314)
F-statistics				
(a) Shocks = 0		5.51 (p<0.000)	8.74 (p<0.000)	1.72 (p<0.144)
(b) Shocks x RCI = 0			5.25 (p<0.000)	2.21 (p< 0.065)
Controlling for HH characteristics	Yes	Yes	Yes	Yes
Controlling for regional variations	Yes	Yes	Yes	Yes
Observations	6,103	6,103	6,103	3,310
R-squared	0.313	0.316	0.318	0.315

Notes:

(a) In parentheses are the robust standard errors; *** p<0.01, ** p<0.05, * p<0.1
(b) All models were tested for multicollinearity (mean variance inflation factor < 10).
(c) Except for the SI in 2006, all the regressors are at time t=2003.

Empirically, regression results show that higher household resilience significantly improves future food security status. An improvement in household resilience significantly increases future real per capita food expenditure by around PhP554 (see Model 3 in Table 4; Model 3 is the preferred model since it controlled for the shock and interaction of shock and resilience bias), equivalent to about six percent of the annual per capita food threshold in the Philippines in 2006 (PSA 2016), and future household dietary diversity (Table 5). The results are consistent in all the models in terms of the signs of the coefficients and the significance level.

Restricting the sample to those who experienced a decline in real per capita food expenditure and household dietary diversity, models (4) and (8) in Tables 4 and 5 show that the lagged RCI (RCI in 2003) is a significant factor for recovery. This also implies that the current level of household resilience can influence even longer than two periods of food security status (long-term food security). Based on model (4), those who experienced a decline in their real per capita food expenditure between time 2003 and 2006 were able to recover about PhP406 in their real per capita food expenditure per unit increase in their level of household resilience, holding other factors constant.

Current level of dietary diversity and real per capita food expenditure also significantly affect future food security outcomes (Tables 4 and 5). However, the signs of their coefficients are negative. According to D'Errico et al. (2018), this may reflect the fact that a household with higher initial levels of food security may lessen its food intake without having to compromise its survival; whereas those with lower initial levels of food security cannot decrease much of its food intake since it may put their survival at risk. The results are also robust based on the robustness checks.

Impact of shocks on food security outcomes. Looking at the impact of shocks, it was found that in terms of real per capita food expenditure, the impact of covariate shocks on real per capita food expenditure was not immediate but lagged. The coefficients of the rainfall and price shocks that occurred in 2003 are not significant in models (2) and (3) but are significant in model (4) (Table 4). The lagged impact of rainfall shock in 2003 on the change in real per capita food expenditure between 2006 and 2009 was negative, indicating that those who experienced this shock in 2003 and experienced a reduction in their real per capita food expenditure between 2003 and 2006 have even worsened food security outcome in the succeeding period (Model 4). The negative impact of rainfall shock in 2003 translates to a reduction of about PhP1,623 in annual real per capita food expenditure between 2006 and 2009 (equivalent to 14% of the annual per capita food threshold in 2009; annual per capita food threshold in 2009 = PhP11,780 (PSA 2016)).

In addition, the price shock in 2003 also has a lagged impact on the change in real per capita food expenditure between 2006 and 2009. However, its coefficient is positive, that is, an increase of about PhP5,417 in annual real per capita food expenditure between time 2006 and 2009 for those who experienced this shock in 2003 and experienced a reduction in real per capita food expenditure between 2003 and 2006 (Model 4). Nevertheless, this might just reflect their attempt to recover the loss incurred in real per capita food expenditure from the price shock experienced in the previous period (this is equivalent to about 46% of the annual per capita food threshold in 2009). When interacting with the lagged RCI, the sign of its coefficient became negative, which could be because households with higher RCI tend to cope up better in the presence of shocks, so the cost of recovery is lower.

In terms of household dietary diversity, it was found that both idiosyncratic shock and covariate shocks have a significant impact to future household dietary diversity but only in the short term (see Model 7; Model 7 is the preferred model since it controlled for the shock and interaction of shock and resilience bias). Contrary to expectation, the direction of the impact of the unemployment of a family member is positive. There could be several possible explanations. First, it could be that those who have experienced the shock in 2003 may have recovered already in 2006—implying that the effect of this shock to household's dietary diversity is short-lived. Second, the unemployment of a family member may just be a temporary unemployment. And third, the unemployed family member may be the one who is in-charge with the food preparation (i.e., wife) which might explain why the sign of the interaction term of the shock and RCI estimate is negative (Model 7). That is, reduced adaptive capacity but better dietary diversity since the unemployed family member has more time to prepare for the food of the household.

As for the climatic shocks, its impact to household dietary diversity is significant in the short-term (Models 6 and 7) and in the long-term when interacted with the lagged RCI estimate (Model 8). However, the signs of the coefficients of the impact of the shock in the short term vary. Aggarwal (2021) noted that higher consumption should be interpreted as a 'cost of adaptation' rather than an improvement in living standards if it is a response to climatic shocks (i.e., an increase in food consumption due to heat stress). Also, when the climatic shocks interacted with the RCI estimate, the sign of the coefficient became negative (Model 7). The result is robust based on the robustness checks. If the increase in dietary diversity is interpreted as a 'cost of adaptation', the negative sign of the interaction term of the climatic shock and RCI estimate would mean that a higher level of household resilience reduces the cost of adaptation. In the long term, however, the lagged interaction term of the climatic shock and RCI estimate have positive signs which may indicate that those who experienced climatic shocks in 2003 and suffered a dietary diversity loss between 2003 and 2006 may have recovered between 2006 and 2009 due to their higher resilience capacity (Model 8).

With regard to price shock, it was found that its impact on household dietary diversity is only short. Its coefficient and the coefficient of its interaction term with RCI estimate are significant in model (7) but not in model (8) based on the joint hypothesis test. The price shock per se has a negative impact on household dietary diversity but when interacted with RCI estimate, the sign of its coefficient became positive. This might be indicative of the fact that higher level of household resilience allows the household to adapt better in the presence of a shock (if not speeds up their recovery). The impact of price shock on household dietary diversity is relatively high in magnitude (in absolute terms) compared to the impact of the other shocks.

Expounding resilience as a pathway to food security. The first-stage regression of the 2SLS model (Table 6) shows that price shock has a large impact (in absolute terms) on household resilience. The direction of its impact may be negative when the increase in prices of services decreases their use of basic services such as transportation and communication, clothing, education, and medical care but may also be positive (in the robustness check, the coefficient of the price shock is 0.743 and is significant at 1% alpha) when the increase in cost of goods and services stimulates them to expand their social networks (which is also another dimension of household resilience) to better cope up with the price shock (i.e., borrowing resources from neighbors who are not much affected of the shock/friends/distant relatives, resource-sharing/pooling, etc.). However, it is unclear whether idiosyncratic shock and climatic shocks have a significant impact on household resilience per se since the results are not robust based on the robustness checks. However, the lagged impact of rainfall shock in 2003 on the future real per capita food expenditure between 2006 and 2009 may indicate that rainfall shock impacts future real per capita food expenditure through household resilience (Model 4 in Table 4).

Table 6. Impact of shocks to food security outcome through household resilience (2SLS models)

	First-stage regression	**2SLS**	**2SLS**
VARIABLES	**Model (9) RCI2 in 2003**	**Model (10) Log of real per capita food expenditure in 2003**	**Model (11) SI in 2003**
Distance to nearest bank	-0.00340*** (0.000598)		
$\widehat{RCI}2$		0.173*** (0.0260)	-0.0216*** (0.00783)

	First-stage regression	2SLS	2SLS
Experienced unemployment	-0.103	-0.00148	-0.00360
	(0.216)	(0.0329)	(0.00587)
Temperature shock	-0.234*	0.0199	-0.0106**
	(0.133)	(0.0215)	(0.00445)
Rainfall shock	-0.526***	0.0166	-0.00781
	(0.195)	(0.0327)	(0.00736)
Price shock	-1.491***	0.131**	-0.0638***
	(0.314)	(0.0656)	(0.0168)
Constant	2.095***	9.615***	0.841***
	(0.290)	(0.0689)	(0.0186)
F-statistics			
Shocks = 0	8.42	4.26	15.68
	(p<0.000)	(p<0.372)	(p<0.004)
Controlling for HH characteristics	Yes	Yes	Yes
Controlling for regional variations	Yes	Yes	Yes
Observations	6,222	6,222	6,221
R-squared	0.216	0.201	

Notes:

(a) In parentheses are the robust standard errors; *** p<0.01, ** p<0.05, * p<0.1

(b) Testing for instrument validity, the first-stage F-statistic = 84.66 is greater than the rule of thumb (10). Further, using MOP Effective First-Stage F-statistics, the models are acceptable when there could be 10% bias in estimated coefficients in the worst-case scenario. MOP Effective F-statistics of models (10) and (11) is 32.262.

(c) All the regressors are at time t=2003.

Further, even after removing the impact of the shocks on RCI itself, it was found that RCI still has a significant impact on current food security outcomes, which is in line with the recent study of Egamberdiev et al. (2023). However, the direction of its impact varies depending on the outcome variable. For the log of current real per capita food expenditure, its impact is positive as expected. Current real per capita food expenditure is expected to increase by 17.3 percent with an improvement in the level of household resilience (Model 10). In contrast, the opposite is true for the current household dietary diversity, implying that improving household resilience tends to worsen household dietary diversity in the very short term (Model 11). The reason could be that in an attempt of the household to be more resilient amidst shocks, household dietary diversity may be sacrificed in the very short-term (although a higher current level of household resilience translates to better future household dietary diversity as discussed in the earlier section of this paper). This is also supported by D'Souza and Jolliffe (2016) wherein they noted that as a response to price shocks or negative shocks, households face some trade-offs to cope up in the short-term—rather than reducing calories, they adjust the type/composition of foods they ate (especially those whose caloric intake is already at the least). The result is robust based on the robustness checks.

Resilience as a pathway, it was found that price shock affects real per capita food expenditure only indirectly through household resilience as shown in models (9) and (11) (Table 6). In model (11), price shock negatively affects household resilience but do not have direct significant impact on current log of real per capita food expenditure based on the joint hypothesis test (Model 10). This might explain why its impact on the future real per capita food expenditure is lagged, as discussed in the earlier section of this paper. The results are robust based on the robustness checks.

With regard to dietary diversity, it is not clear on whether climatic shocks have indirect impact (through household resilience) on household dietary diversity since the result is not robust based on the robustness checks, but it does have a direct impact (i.e., temperature shock in Model 11). Further, it is not certain on whether price shock directly affects dietary diversity directly since the result is not robust based on the robustness checks although its indirect impact through household resilience is clear based on 2SLS models (Model 9). If climatic and price shocks are found to have both direct and indirect impacts on household dietary diversity through household resilience, the impacts of these shocks may have multiplier effects on the households' future dietary diversity.
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In terms of idiosyncratic shock, it is not clear on whether this type of shock affects household dietary diversity directly, indirectly, or both since the result is not robust based on the 2SLS models (i.e., in Table 6, the coefficients of experienced unemployment are not significant in models (9) to (11) but in the robustness checks, its coefficient is significant in the first-stage regression and in the 2SLS model using SI as the outcome variable). However, since it was found in the earlier section of this paper that the experienced unemployment shock has a significant impact on future short-term household dietary diversity, it may be that the difference in the results is due to the difference in the timing of the occurrence of the shock and the time of the survey.

CONCLUSION, POLICY IMPLICATIONS, AND RECOMMENDATIONS

The evidence suggests that improving the current level of household resilience improves future food security outcomes both in terms of real per capita food expenditure and household dietary diversity, and facilitates the recovery of the households who suffered losses in real per capita expenditure and dietary diversity.

However, while higher current level of household resilience improves current real per capita food expenditure, this does not necessarily translate to higher current household dietary diversity. Although the possibility of endogeneity issues may have also affected the results of the study, this could also reflect how households cope up in the short-term to negative shocks—they might sacrifice short-term diet diversity in response to the shocks. This kind of short-term coping mechanism may have long-term consequences on the household's health and human capital development, especially on households who are already suffering from mineral and vitamin deficiencies—further reductions in nutrition may be detrimental or may lead to malnutrition. Hence, it may be important for the government or other institutions involved to educate households on cheaper food alternatives that do not sacrifice diversity in the type of diet.

Understanding resilience as a pathway to food security, it was found that shocks may affect food security outcomes directly, indirectly, or both. When shocks affect both household resilience and food security outcomes, the impact of the shocks can have some sort of multiplier effects to future food security status. Without providing some system that could mitigate the negative impact of shocks to household resilience and/or interventions that could increase household resilience, the state of food security of the household in the future may be much worsened due to the negative multiplier effects, which could further trap vulnerable and poor households to poverty. Government institutions aiming to improve household resilience may prioritize the enhancement of the most relevant pillars (UBS, SSN, and AC) to make the greatest impact. For the UBS pillar, this would mean focusing on improving the quality and access to basic services on transportation and communication, education, and clothing. There might also be a need to improve other SSN factors, such as their access to/availment of pension and retirement benefits so that households will not be heavily reliant on remittances from abroad. Improving savings behavior of households may also improve the structure of their AC pillar and may cushion the households from temporary unemployment or job loss.

Aside from reducing the negative impact of shocks and enhancing household resilience, reducing household's vulnerability to climatic shocks (i.e., by promoting adaption of climate change adaptive technologies) may also be necessary as well as providing mechanism to stabilize prices/reduce price volatility especially food price as it has a relatively large magnitude of impact (in absolute terms). This is especially critical among the rural and agricultural households who are mostly affected by covariate shocks such as climatic shocks and price shocks.

In contrast, some shocks (i.e., experienced unemployment on household dietary diversity) are found to have short-term impacts that do not significantly affect long-term future food security outcomes. Shocks may also have lagged impacts to future food security outcomes because their impacts are indirectly through household resilience (i.e., price shocks on real per capita food expenditure). In addition, we found that some shocks (i.e., price shocks) may enable households to build capacities and expand social networks which improve their household resilience rather than worsening it. However, it is still noteworthy to further understand the coping mechanisms of households and formulate policies that take into consideration households' behavior amidst shocks since households may face trade-offs not only in short-term dietary diversity but also in other non-food activities (i.e., increasing school dropouts and rising child labor, increasing debt, etc.) which could perpetuate intergenerational transmission of poverty.

Nevertheless, the complexities of the direct and indirect effects and the short-term and lasting effects of shocks to food security outcomes make this study more relevant in formulating policies that aim to address short-term and long-term food insecurity.

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UNDERSTANDING INTENSIFICATION PRACTICES AND PRODUCTION RISK AMONG INDEPENDENT SMALLHOLDER OIL PALM FARMERS: INSIGHT FROM RIAU PROVINCE, INDONESIA

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ABSTRACT

Independent smallholder oil palm farmers play a crucial role in Indonesia’s palm oil sector, yet their productivity remains significantly below the national averages due to production risks and management constraints. This study examined the factors influencing the productivity of independent smallholders in Riau Province, Indonesia. A structured survey of 256 independent farmers was conducted between August to December 2024, and the data were analyzed using regression models to identify key determinants of yield variations. The results showed that smallholder productivity averages 11,289 kg of fresh fruit bunches (FFB) per hectare, which was notably lower than the national average. Variation in productivity was largely explained by differences in farm management practices, input use, and tree conditions. Most respondents were risk-averse, influencing their decision-making on farm investments, particularly input use. The estimation results revealed that plant age negatively affects productivity, emphasizing the urgency of replanting. Fertilizer applications (urea, TSP, KCl, and NPK) and labor input had strong positive effects on yield, highlighting the importance of proper input management. However, NPK fertilizer increased production risk, whereas the adoption of certified seedlings decreased production risk. Low adoption of certified seedlings and inconsistent input use hindered optimal productivity. These findings highlighted the need for policy interventions that address production risks and improve smallholders' capacity for sustainable oil palm cultivation, particularly by improving access to quality seedlings, credit, and extension services to accelerate the replanting process.

Key words: independent smallholders, risk preference, replanting

INTRODUCTION

Smallholder farmers are significant contributors to the global palm oil industry, producing a substantial portion of the world’s palm oil supply (de Vos et al. 2023a). In Indonesia, smallholders managed approximately 40% of the country’s 16.8 million ha of oil palm plantations (BPS 2024). Among these, independent smallholders constitute the majority, overseeing more than 3.5 million hectares (Raharja et al. 2020). This places independent smallholder oil palm farmers as key actors in ensuring both national and international food and energy security. They manage a significant share of the country's oil palm plantations and contribute substantially to regional and national economies (Ditjenbun 2023). Unlike smallholders integrated into corporate-supported plasma schemes, independent smallholders manage their oil palm plantations without direct assistance from plantation companies, making them more vulnerable to production risks and economic uncertainties (Petri et al. 2023). These risks pose significant challenges to their productivity, profitability, and long-term sustainability.

One of the key challenges faced by independent farmers is limited access to essential resources, such as capital, technology, and agricultural information. While plantation companies and plasma farmers benefit from corporate investment and technical guidance, independent farmers often operate with constrained financial resources and limited technological adoption (Jelsma et al. 2017; Raharja et al. 2020). For example, many smallholders use uncertified seeds due to cost constraints and lack of knowledge, leading to lower yields and suboptimal productivity (Ardana et al. 2024; Maskromo et al. 2025; Susanti and Ariyanto 2023). Research indicates that low yields among independent smallholders are not solely due to seed quality, but also result from inadequate implementation of Good Agricultural Practices (GAP), such as proper pruning and weeding practices, harvesting cycle, and adequate nutrient application (Jelsma et al. 2019; Lim et al. 2023; Monzon et al. 2023; Sugianto et al. 2023; Woittiez et al. 2018). Consequently, these farmers often rely on low-input, low-output farming systems, which hinder improvements in productivity and sustainability. In 2023, for example, the average crude palm oil (CPO) yield among smallholders' plantations was only 3.26 ton/ha, much lower compared to private estates (3.82 ton/ha) and government estates (4.44 ton/ha) (BPS 2024).

Riau province plays a pivotal role in Indonesia's palm oil sector, producing approximately 9.22 million tons of crude palm oil (CPO) in 2023 from a total planted area of 3.4 million ha, making it the largest oil palm-producing region in the country and contributing nearly 20% of national CPO output. It has the highest concentration of smallholder plantations, covering about 2.29 million ha or 34% of the national smallholder area, supported by a well-established palm oil industry (BPS 2024; Ditjenbun 2023). However, smallholder productivity in Riau averages only 3.18 t CPO/ha, below the national average of 3.62 t/ha, and the province contains around 100,616 ha of old, damaged, and unproductive trees in urgent need of replanting. The remaining plantation area consists of 730,082 ha of immature palms and 2,570,909 ha of mature palms. Limited access to superior seedlings and replanting resources further constrains productivity, making Riau both a critical contributor to and a focal point for interventions in Indonesia's palm oil sector. Therefore, addressing productivity issues requires more than just financial support or access to better planting materials. It necessitates a comprehensive approach that includes technical training, knowledge transfer and improved agricultural extension services (Hendrawan et al. 2024; Jelsma et al. 2024).

Production risk is a major concern for smallholders and significantly influences their livelihoods (Salman et al. 2010; Alam et al. 2024). Production risk encompasses uncertainties that adversely impact harvest, such as extreme weather events (e.g., droughts, floods, or erratic rainfall), pest and disease outbreaks, fluctuating market prices, and the availability of production inputs like fertilizers and pesticides. These risks directly affect smallholders' income and overall well-being (Haile et al. 2017; Sundström et al. 2014). Crop failure or yield reductions result in financial loses, making it difficult for farmers to recover their investment in production costs (Coulibaly et al. 2015; Mishra et al. 2018). Given these uncertainties, many farmers are hesitant to allocate significant resources for intensification practices, fearing that their investment may not yield sufficient returns (Kurkalova et al. 2006).

Farmers' risk preferences play a crucial role in their willingness to adopt (Lien et al. 2023; Patil and Veettil 2024), which affects their adoption of intensification practices such as fertilizer application, pesticide/herbicide use, and the selection of certified seedlings. For example, farmers who perceive high risks in fertilizer application, such as uncertainty in price fluctuations or unpredictable returns on investment, may underuse or entirely forgo fertilizers, leading to suboptimal yields (Adnan et al. 2020; Bozzola and Finger 2021; Hasibuan et al. 2022). Similarly, the adoption of certified seedlings is influenced by risk attitudes, where many farmers hesitate to purchase high-quality seedlings due to concerns over delayed financial returns, despite the long-term benefits for productivity and sustainability (Hasibuan et al. 2021; Ponce-Pacheco et al. 2025). Given that much of the existing research has focused on large-scale plantations and plasma smallholders, there remains a critical gap in understanding how independent smallholders assess and respond to production risks.

A comprehensive understanding of smallholders' risk behavior is essential for enhancing productivity and sustainability in the independent oil palm sector. By identifying the key factors influencing farmers' decisions and their risk-related constraints, policymakers and stakeholders can design targeted interventions to improve adoption rates of Good Agricultural Practices (GAP). Moreover, insights into risk behavior can guide government agencies, research institutions, and development organizations in formulating policies that provide effective risk management solutions, such as crop insurance schemes, input subsidies, and targeted agricultural extension services.

This study sought to bridge this knowledge gap by analyzing the relationship between production factors, risk behavior, and adoption of intensification practices among independent smallholder oil palm farmers. It employed the Just and Pope production function model, which allowed for the examination of two critical aspects: (1) the average productivity function, which explains how production inputs—such as superior seeds, fertilizers, pesticides, and labor—affect productivity; and (2) the productivity variance function, which assesses the impact of these inputs on output variability, serving as an indicator of production risk. This study will provide valuable insights into the nature of production risk and risk behavior in independent smallholder oil palm farming. The findings are expected to contribute to policy discussions on sustainable palm oil production by identifying key behavioral and risk-related constraints and proposing strategies to enhance the adoption of intensification practices. A deeper understanding of smallholders' risk behavior can help design more effective policies and interventions, ultimately improving productivity, sustainability, and the long-term welfare of independent smallholders.

METHODOLOGY

Study area and data collection. This study was conducted in Riau Province, Indonesia, from August to December 2024. A multi-stage sampling technique was employed to capture the diversity of independent smallholder oil palm farming systems. Four regencies, i.e. Rokan Hilir, Rokan Hulu, Kampar, and Siak, were selected based on the extensive presence of independent smallholder oil palm plantations. Data collection included structured surveys of smallholder oil palm households and in-depth interviews with key decision-makers to assess production risks and input utilization. In addition, independent smallholders refer to the oil palm farmers who operate independently without the support of large companies or government programs.

Sampling and survey design. A multi-stage sampling technique was employed for data collection, targeting four regencies: Rokan Hilir, Rokan Hulu, Kampar, and Siak. These regencies were chosen due to their extensive oil palm plantations and the prevalence of old and damaged oil palm trees. Multi-stage sampling was used for data collection across four regencies. Within each of these four regencies, three sub-districts were selected. A total sample of 64 individuals was obtained from each district. This resulted in a total sample size of 256 (64 samples/district x 4 districts). The study collected quantitative data through household surveys and interviews with 256 heads of households, identified as the key decision-makers. Households were selected as the primary focus for this study since risk management approaches are developed at the individual farm and household level (Kimura et al. 2010).

Analytical framework and model specification. A multiple linear regression analysis examined the impact of input utilization on agricultural output and production risk. Production risk was assessed based on the variance of output. The study employed the Just and Pope model (Robinson and Barry 1987), incorporating a Cobb-Douglas production function in natural logarithmic form. The production function is formulated as follows:

$$Ln(PROD) = a_0 + a_1 Ln(UT)_i + a_2 Ln(LHKS)_i + a_3 Ln(UREA)_i + a_4 Ln(TSP)_i + a_5 Ln(KCL)_i + a_6 Ln\,(NPK)_i + a_7 Ln(TTK)_i + a_8 Ln(PEST)_i + a_9 Ln(HERB)_i + a_{10} D1_i + \varepsilon \quad (1)$$

While the production variance is:

$$\sigma^2 Y_i = (Y_i - \hat{Y}_i)^2 \quad (2)$$

Hence, the formulation of production variance function (risk) is formulated as follows:

$$Ln(\sigma^2 Y_i) = \theta_0 + \theta_1 Ln(UT)_i + \theta_2 Ln(LHKS)_i + \theta_3 Ln(UREA)_i + \theta_4 Ln(TSP)_i + \theta_5 Ln(KCl)_i + \theta_6 Ln(NPK)_i + \theta_7 Ln(TTK)_i + \theta_8 Ln(PEST)_i + \theta_9 Ln(HERB)_i + \theta_{10} D1_i + \in \quad (3)$$

where PROD is fresh fruit bunch production (kg), UT is oil palm age (years), LHKS is land area (ha), UREA is the use of urea fertilizer (kg), TSP is the use of phosphate fertilizer (kg), KCl is the use of potassium fertilizer (kg), TTK is total labor usage (man-days), PEST is pesticide usage (liters), HERB is herbicide usage (liters), D1 is dummy variable for seedling usage (certified = 1, uncertified = 0), ε is error term, and I is farmer household (1 = 1... 256)

The analysis employed the Ordinary Least Squares (OLS) method. Before analysis, classical assumptions are tested to ensure model validity. These tests include normality, multicollinearity, and heteroscedasticity. Normality is assessed using the Kolmogorov-Smirnov test. Multicollinearity is checked through Variance Inflation Factors (VIF), with values below 10 indicating no issues. Heteroscedasticity is evaluated using the Glejser test. To ensure unbiased results, the model must pass all classical assumption tests. Subsequently, statistical tests are conducted, including R-squared, F-test, and t-tests. R-squared measures the model's overall fit, with higher values indicating better performance. The F-test assesses the joint significance of all independent variables, while the t-test evaluates the individual significance of each predictor.

Risk preference analysis. Risk preferences were analyzed using the Arrow -Pratt Risk Aversion Measure Approach (Arrow 1965). This method determines the degree of risk aversion based on the shape of a farmer's utility function (Keenan and Snow 2022). This approach allows for the characterization of several decision models through a set of intuitive consistency requirements (Baillon and L'Haridon 2021). The following steps were undertaken:

1. Determining the utility function (U(W)). The utility function represents how an individual evaluates wealth (W)—commonly used general forms of utility functions:

   U(W) = ln(W) (logarithmic utility function, for risk-averse individuals) or

   $U\,(W) = \frac{W^{1-r}}{1-r}$ (CRRA function - Constant Relative Risk Aversion).

2. Calculating the Absolute Risk Aversion Coefficient (ARA, RA). The ARA coefficient is calculated as

$$r_A\ (\mathrm{W}) = \frac{U''(W)}{U'(W)},$$

where: $U'(W)$ is the first derivative of the utility function (marginal utility) and $U''(W)$is the second derivative of the utility function. The value of r_A (W) > 0 indicates a risk-averse individual, r_A (W) = 0 indicates risk-neutral, and r_A (W) < 0 indicates risk-seeking.

3. Calculating the Relative Risk Aversion Coefficient (RRA, r) (if needed). It is defined as:

$$r_R\ (\mathrm{W}) = \mathrm{W}\ .\ r_A\ (\mathrm{W})$$

This coefficient indicates a level of relative risk aversion to changes in the scale of wealth.

4. Determining farmers' risk preferences. By calculating the value of r_A (W), farmers can be classified into three categories: Risk Averse: If r_A (W) > 0, farmers prefer making decisions that minimize risk. Risk Neutral: If r_A (W) = 0, farmers are indifferent to risk. Risk Seeking: If r_A (W) < 0, farmers tend to make riskier decisions.

5. Analysis of results and implications. A high ARA or RRA value indicates that farmers are highly risk-averse, so they prefer safer production techniques. A low ARA value indicates that farmers are more willing to take risks, for example, by adopting innovations or investing in more varied production inputs.

RESULTS AND DISCUSSION

Respondents profile. This study focused on independent oil palm farming households, defined as those operated autonomously by farmers who, through their own initiative and financial investment, established and managed their oil palm plantations without any affiliation with a specific company. Table 1 presents the demographic and socioeconomic characteristics of respondents. The average age of respondents was 49.03 years, with a standard deviation of 11.38 years, indicating a moderately diverse age distribution ranging from 25 to 76 years. The level of formal education varied significantly, with an average of 8 years and a standard deviation of 4.25 years. Some respondents had no formal education, while others had up to 18 years or hold a master's degree, reflecting varying access to education among independent smallholders.

Table 1. Respondent characteristics

Variable	Mean	Std. Dev.	Minimum	Maximum
Age (years)	49	11.38	25	76
Education (years)	8	4.25	0	18
Farming experience (years)	20	7.48	3	35
Number of family members	4	1.47	1	10

Source: primary data

Farming experience was a crucial factor in shaping farmers' decision-making and risk management practices. Respondents had an average of 20 years of farming experience, ranging from 3 to 35 years, demonstrating a mix of seasoned and relatively new farmers in the sector. Household size was also an important factor, with an average of 4 members per household and a standard deviation of 1.47, ranging from single-person households to families with up to 10 members. These characteristics provide a fundamental understanding of the respondent population, which was essential for contextualizing the findings on production risk and replanting decisions.

Input use, production and productivity of independent smallholders. Input use among smallholders reflected the level of intensification in their oil palm plantations, which directly influenced production and productivity. This study did not differentiate input application between wet and dry seasons; the data represented annual averages. Table 2 summarizes key variables related to farm production, productivity, input use, and management practices among independent oil palm smallholders in Riau Province.

Table 2. FFB Production, productivity, input use, and management practices among independent oil palm smallholders in Riau Province, 2024.

Variable	Mean	Std. Dev.	Minimum	Maximum
Production (kg FFB)	41736.73	30163.34	8820	212480
Productivity (kg FFB/ha)	11288.99	2625.53	3528	21248
Tree age (years)	17.56	4.68	3	28
Area (Ha)	3.74	2.57	1	21
NPK fertilizer (kg)	144.31	280.38	0	1608
Urea fertilizer (kg)	391.37	373.20	0	3000
TSP fertilizer (kg)	229.13	352.64	0	3000
KCl fertilizer (kg)	180.12	302.87	0	3000
Pesticides (liter)	9.28	31.97	0	500
Herbicides (liter)	9.51	10.86	0	75
Labor (man days)	58.36	142.93	7.19	2287.82
Certified seeds (1 if yes)	0.04	0.20	0	1

Source: primary data

The productivity of independent oil palm farmers, measured in fresh fruit bunch (FFB) yield per hectare, averaged 11,289 kg/ha, with a standard deviation of 2,625 kg/ha. This productivity was relatively lower than the national levels for smallholders, which reach 15.3 ton/ha (Monzon et al. 2021). The productivity varied widely, ranging from 3,528 to 21,248 kg/ha, reflecting differences in farm management practices, input use, and tree age and conditions. The productivity levels in smallholder oil palm plantations in Indonesia were influenced by the tree age, nutrient management, harvesting, weed control, and pruning (Monzon et al. 2023) . The average age of oil palm trees was 17.56 years, with a range from 3 to 28 years. This suggested that many plantations were approaching or exceeding their optimal production phase, highlighting the urgency of replanting efforts (Hendrawan and Musshoff 2024; Petri et al. 2023). Farm size also varied significantly, with an average landholding of 3.74 hectares, but with a large standard deviation (2.57 ha), indicating considerable heterogeneity in farm sizes. Some smallholders managed as little as 1 hectare, while others cultivate up to 21 hectares. This variation influences input use intensity and production efficiency.

Fertilizer application rates showed substantial variability among independent smallholders. The average NPK application was 144 kg per year, with some farmers not using it at all, while others applied as much as 1,608 kg. Urea fertilizer was used more extensively, with an average of 391 kg per year but high variability (0–3,000 kg). The same trend was observed for TSP and KCl fertilizers, with mean application rates of 229 kg and 180 kg, respectively. The wide variation suggested differences in affordability, access to inputs, and agronomic knowledge. Numerous studies indicated that fertilizer application in smallholder plantations was relatively low, leading to lower fresh fruit bunch yields compared to large plantations. For example, there was a need to increase potassium (K) fertilization to improve the oil palm yield (Thoumazeau et al. 2024) . Additionally, widespread nutrient deficiencies (potassium (K), nitrogen (N), boron (B), phosphorus (P), and magnesium (Mg)), have constrained productivity in smallholder plantations (Lim et al. 2023; Sugianto et al. 2023). This issue of nutrient deficiency was also raised in other studies (Agus et al. 2024; Monzon et al. 2021, 2023).

The use of pesticides and herbicides was relatively low on average but varied significantly. Pesticide use averaged 9.28 liters per year, with a standard deviation of 31.97 liters, indicating that some farmers relied heavily on chemical pest control while others used none. Herbicide application averaged 9.51 liters per year, with a maximum of 75 liters, demonstrating differing weed management strategies. Labor inputs, measured in man-days per year, average 58.36 but exhibit extreme variation, ranging from 7.19 to 2,287.82 man-days. This discrepancy likely reflects differences in farm size, reliance on hired labor, or variations in farm mechanization. Only 4% of respondents reported using certified seeds, highlighting a potential challenge in achieving high and stable yields. The low adoption of certified seeds suggested financial constraints or a lack of awareness about their benefits, which may contribute to increased production risks and lower farm productivity (Hutabarat et al. 2019; Jelsma et al. 2019; Maskromo et al. 2024; Schoneveld et al. 2019).

The findings highlighted the diverse conditions among independent smallholders, particularly in productivity, input use, and farm management practices. The significant variation in tree age suggested that many farmers were at a critical juncture for replanting. However, the relatively low use of certified seeds and uneven fertilizer application indicated potential barriers to effective replanting and yield optimization. The substantial variation in labor input suggested differences in farming intensity, potentially linked to household labor availability or financial constraints in hiring external workers. Additionally, the high standard deviations in input use emphasized the need for targeted interventions, such as improved access to fertilizers, pest management training, and financial support for replanting efforts. These results underscore the necessity of tailored policies that address production risks while enhancing smallholders' ability to engage in sustainable oil palm cultivation. Providing support mechanisms, such as subsidized certified seeds, training programs, and improved credit access, could mitigate risks and accelerate replanting efforts among independent smallholders in Riau Province.

Diagnostic testing for classical assumptions. To ensure the validity and reliability of the estimated model, a series of diagnostic tests were conducted to assess compliance with classical linear regression assumptions. The results indicated no evidence of multicollinearity, as all variance inflation factor (VIF) values were below the critical threshold of 10. The Jarque-Bera test confirmed that the residuals followed a normal distribution ($p > 0.05$ supporting the assumption of normality. Tests for heteroscedasticity yielded mixed outcomes, while the White test suggested potential heteroscedasticity. Both the Breusch-Pagan-Godfrey and Glejser tests were statistically non-significant. These results indicated that any heteroscedasticity present was likely minor and did not materially compromise the robustness of the model.

Factors affecting oil palm productivity. The factors influencing oil palm productivity were estimated using Eq. 1, with the results presented in Table 3. The model demonstrates robust explanatory power, evidenced by an adjusted R-squared value of 0.919, indicating that the independent variables accounted for a substantial proportion of the variance in palm oil production. The overall model significance was confirmed by the F-test ($p < 0.01$). Plant age (UT) exhibited a statistically significant negative relationship with production, whereas land area (LHKS), fertilizers (urea, TSP, KCl, NPK), and labor (TK) demonstrated statistically significant positive effects. In contrast, pesticides (PEST) and herbicides (HERB) did not have a significant impact on production.

Table 3. The estimation results of oil palm production function

Variable	Coefficient	
Constant	9.221	***
	(0.248)	
Plant age (years)	-0.172	***
	(0.051)	
Land area (Ha)	0.769	***
	(0.045)	
Urea fertilizer (Kg/ha)	0.038	***
	(0.004)	
TSP fertilizer (Kg/ha)	0.009	***
	(0.003)	
KCl fertilizer (Kg/ha)	0.014	***
	(0.003)	
NPK fertilizer (Kg/ha)	0.016	***
	(0.003)	
Labor (man-days/ha)	0.152	***
	(0.053)	
Pesticides (l/ha)	0.007	
	(0.010)	
Herbicides (l/ha)	0.005	
	(0.009)	
Dummy seedlings (1 if certified)	0.030	
	(0.026)	
Number of observations	256.000	
R-squared	0.919	
Adjusted R-squared	0.916	

Note: Standard errors are in parentheses. *, **, *** is significant at 0.5, 0.1 and 0.01 percent levels.

The negative and statistically significant relationship between plant age and production suggested that most oil palm plantations in the study area surpassed their peak productive phase and were entering a period of decline. This finding was consistent with prior research on the oil palm yield cycle. A typical yield curve shows productivity peaks between 7 and 15 years before gradually declining (Corley and Tinker 2021) . Older palm trees exhibited lower productivity due to physiological aging, reduced nutrient uptake efficiency, and an increase in trunk height, which made harvesting more difficult (Woittiez et al. 2017). This finding underscored the necessity for timely replanting strategies to sustain long-term productivity in oil palm plantations.

In addition to plant age, land area also exhibited a statistically significant and positive effect on oil palm production. This supported the principle of scale efficiency where larger plantations benefited from more efficient use of resources, greater opportunities for mechanization, and optimized input allocation (Barrett et al. 2010). Furthermore, larger farm sizes were often associated with wealthier farmers who were more capable of investing in good agricultural practices, leading to superior yields (Jelsma et al. 2019). However, scale alone was not sufficient, realizing the full productivity potential also depended on the effective and balanced use of key inputs.

Among these inputs, fertilizer application played a critical role. The significant positive relationships observed between production and the application of urea, TSP, KCl, and NPK fertilizers were consistent with prior studies emphasizing the importance of nutrient balance in achieving optimal yields (Goh et al. 2003; Lim et al. 2023; Sugianto et al. 2023; Woittiez et al. 2018). Proper fertilizer management not only enhances productivity but also minimize risks associated with over- or under-application, which could have led to soil degradation, nutrient leaching, and yield instability. Thus, access to training on nutrient management and soil health was essential for improving smallholder performance.

While inputs like fertilizer were crucial, labor remained a key determinant of productivity, especially among smallholder farmers who typically lacked access to mechanization (Bou Dib et al. 2018). The positive andsignificant impact of labor use was in line with the findings of Euler et al. (2016) and Kubitza et al. (2023), which emphasized the labor-intensive nature of smallholder oil palm farming. Effective oil palm maintenance required substantial human input for activities such as harvesting, fertilization, weeding, pruning, and pest management, all of which significantly influenced yields (Jelsma et al. 2017; Monzon et al. 2023). Efficient labor utilization directly influenced fresh fruit bunch (FFB) harvesting frequency, which in turn impacted overall productivity. Labor shortages, particularly in rural areas, could have been a limiting factor in achieving optimal yields (de Vos et al. 2023b; Habibi 2023), making mechanization and improved workforce management critical for sustainability.

Oil palm production risk. To complement the analysis of productivity, this study also investigated the factors contributing to production risk, using the estimated production variance function. This function modeled the variance in oil palm output as a function of various production inputs, providing insight into the factors that introduced volatility or uncertainty in yields. The dependent variable was the variance of oil palm production, and the explanatory variables include plant age, land area, usage of urea, TSP, and KCl fertilizers, type of seedlings used (certified = 1, uncertified = 0), total labor usage, as well as pesticides and herbicides. The results estimation offers a basis for understanding how different inputs influenced productivity (Table 4).

Table 4. The estimation results of oil palm risk function.

Variable	Coefficient
Constant	-0.002
	(0.055)
Plant age (year)	-0.006
	(0.011)
Land area (Ha)	-0.009
	(0.010)
Urea fertilizer (Kg)	-0.001
	(0.001)

Variable	Coefficient	
TSP fertilizer (Kg)	0.000	
	(0.001)	
KCl fertilizer (Kg)	0.000	
	(0.001)	
NPK fertilizer (Kg)	0.002	*
	(0.001)	
Labor (man-days)	0.018	
	(0.012)	
Pesticide (l)	0.001	
	(0.002)	
Herbicide (l)	-0.003	
	(0.002)	
Dummy seedling (1 if certified)	-0.017	***
	(0.006)	
Number of observations	256.000	
R-squared	0.096	
Adjusted R-squared	0.059	

Note: Standard errors are in parentheses. *, **, *** is significant at 0.5, 0.1 and 0.01 percent levels

A variance function test employing Ordinary Least Squares (OLS) regression was conducted to investigate factors influencing oil palm production risk. The model exhibited a low coefficient of determination ($R^2 = 0.0955$), indicating that the explanatory variables accounted for a limited proportion of the observed variance in production risk. Despite this low explanatory power, the model achieved statistical significance ($F(df1, df2) = 2.59$, $p = 0.0054$), suggesting that the included variables exert a discernible, albeit small, influence on production risk variability. Further investigation is warranted to identify additional factors contributing to production risk in this context.

A key finding of this study was the significant positive relationship between NPK fertilizer use and production risk ($p = 0.0194$). This indicates that using NPK fertilizer increased production instability. This result aligned with previous research. For example, Tchonkouang et al. (2024) highlighted how high-input agricultural technologies, like fertilizers, can lead to greater yield variability, particularly when weather conditions are unpredictable. Some inputs may increase expected output, but they can also elevate production risk due to their interaction with environmental factors, such as soil composition and rainfall patterns (Just and Pope 1979). However, single fertilizer components such as urea, TSP and KCl as well as labor use, were found to be statistically insignificant in relation to production risk. This suggests that while these inputs significantly enhance oil palm yield, they were not associated with variability in production outcomes.

Certified seed (D1) significantly reduced production risk ($p = 0.0024$), suggesting that specific periods or conditions could have mitigated risk. This findings aligned with Dercon and Christiaensen (2011), who highlighted the role of seasonality, climate stability, and adaptive practices in reducing output variability. Improved seed quality, coupled with optimal management, mitigated risk. Feder et al. (1985) linked certified seed adoption to farmers' risk preferences and yield stability expectations. Certified seeds, often bred for resilience, buffer against production shocks. Improved seed varieties in sub-Saharan Africa reduce yield variability, especially with integrated soil fertility management (Kassie et al. 2011).

Timing of input application was also critical. Well-timed interventions, like synchronized fertilizer application, maximize benefits and reduce yield uncertainty (Duflo et al. 2011). This was relevant for oil palm farmers, as strategic input application mitigates risks from aging plantations and declining soil fertility. Certified seed adoption is part of a holistic risk management strategy (Ardana et al. 2024). Smale et al. (2013) suggested that smallholders using improved seeds with diversification and adaptive land management are more resilient. This finding aligns with Just and Pope (1978) risk production function, differentiating inputs that increase expected yield from those reducing variability. These results highlighted the importance of certified seeds for stabilizing productivity, especially with favorable conditions and strategic input application. Future research should explore how seed certification standards interact with other practices to enhance long-term resilience in oil palm cultivation.

Farmers' risk preferences. Farmers' risk preferences play a pivotal role in shaping decision-making related to oil palm intensification. These preferences influence how farmers respond to uncertainty in input use, yield fluctuations, and market volatility. The study results revealed that a majority of farmers in the study area were risk-averse, accounting for 41.4% of the respondents (Table 5). This aligned with earlier research showing that Indonesian farmers generally exhibit risk-averse behavior (Hasibuan et al. 2021, 2023; Miyata 2003). Risk aversion tended to decline with increasing asset wealth, with non-agricultural households being the least risk-averse, followed by part-time and full-time farmers (Wu et al. 2024). Meanwhile, 38.6% were classified as risk-takers, and 19.9% as risk neutral.

Table 5. Oil palm farmers' risk preferences.

Risk Preferences	No. of respondents	Percentage
Risk averse	106	41.4
Risk neutral	51	19.9
Risk takers	99	38.6
Total	256	100

To further assess these preferences, the Arrow-Pratt (AR) Risk Aversion Measure was employed. This approach quantifies risk attitudes by evaluating the variance in production outcomes relative to input use. Inputs such as urea, TSP, KCl, NPK, and pesticides yielded positive AR values, suggesting that farmers were generally risk-averse when applying these inputs (Table 6). Conversely, negative AR values were observed for labor (TK) and herbicide use, indicating a more risk-taking attitude in these categories. On average, the overall AR value across all inputs was positive, confirming a prevailing tendency toward risk aversion among independent smallholders.

Table 6. Preference of oil palm smallholders towards production input.

Production input	Average AR value	Risk Preference
Urea	6883055.196	*risk-averse*
TSP	14701433.5	*risk-averse*
KCl	11905524.46	*risk-averse*
NPK	13685789.75	*risk-averse*

Production input	Average AR value	Risk Preference
Total labor usage	-41810578.37	*risk taker*
Pesticide	2454127.381	*risk averse*
Herbicide	-232600.4935	*risk taker*
Overall farmer preferences	1083821.632	*risk-averse*

Where:

AR > 0	risk-averse
AR < 0	risk taker
AR = 0	risk-neutral

However, risk preferences can moderate the effect of perceived risk. Higher profits and extensive social networks encouraged adaptive behavior, even among risk-averse farmers. Additionally, more educated, older male farmers with larger landholdings tend to perceive production risks more acutely (Mou and Li 2025). While risk-averse farmers do not entirely avoid risk, they require adequate compensation or incentives to accept it (Robinson and Barry 1987). This highlights the need for agricultural extension programs that emphasize the perceived benefits of technology adoption, farmers' preparedness, and technology-specific features (Owusu-Sekyere et al. 2024).

Production risk analysis indicated that certain inputs, such as NPK fertilizer, can amplify yield volatility, whereas certified seed may have a stabilizing effect. Given the strong risk-averse tendencies among independent smallholder farmers, there was a likelihood that they may reduce NPK fertilizer use to mitigate production risk. Conversely, promoting certified seed adoption presents a promising strategy, as its risk-reducing potential appealed to these farmers. However, the adoption rate of certified seed remained very low, which was likely attributed to a lack of awareness. Survey results indicated that most respondents use well-known oil palm varieties, but due to limited information, they may perceive uncertified varieties as equivalent to certified ones. In reality, numerous studies highlighted that the uncertified seeds used by farmers were often illegitimate, leading to significantly lower productivity (Jelsma et al. 2019; Maskromo et al. 2025).

CONCLUSION AND RECOMMENDATIONS

This study provides an in-depth analysis of the production risk faced by independent smallholder oil palm farmers in Riau Province, Indonesia, and its implications for accelerating the intensification program. The findings reveal substantial variations in demographic and socioeconomic characteristics, input use, and productivity levels among smallholders. The average productivity of 11,289 kg FFB/ha remains below the national benchmark, underscoring significant challenges in farm management and input application. Key factors affecting FFB production include plant age, land area, fertilizer application, and labor input. The study confirms that older plantations exhibit declining yields, emphasizing the urgency of replanting efforts to maintain long-term productivity.

The regression model demonstrates strong explanatory power, confirming the significant impact of land area and fertilizer application on output. The low adoption of certified seeds (4%) highlights a critical gap in achieving higher yields and reducing production risk. Furthermore, substantial variability in fertilizer application suggests disparities in input affordability, knowledge, and accessibility. These findings underscore the importance of targeted interventions to enhance smallholder productivity and mitigate the risks associated with aging plantations. Hence, we recommend several strategies. Firstly, the government and related industries should promote the use of certified seeds through subsidies, training, and awareness campaigns to improve yields and reduce production risks associated with uncertified seedlings. Secondly, given the significant impact of fertilizers on productivity, policies should focus on ensuring affordable access to fertilizers, providing training on optimal nutrient management, and encouraging site-specific fertilization practices to address widespread nutrient deficiencies. Thirdly, since aging plantations significantly reduce productivity, it needs to accelerate the replanting program for smallholders (PSR) that has been launched by the Indonesian government since 2017. Fourthly, labor availability and costs remain constraints for independent smallholders so that training programs on efficient farm management, labor-saving technologies, and small-scale mechanization should be introduced to optimize productivity. Fifthly, many smallholders struggle with the financial burden of replanting and farm investment. Expanding credit access through microfinance institutions, cooperatives, and government-backed loan schemes would enable smallholders to invest in improved farm inputs and replanting initiatives. Lastly, strengthening farmer cooperatives can improve smallholders' bargaining power, facilitate collective input procurement, and enhance knowledge sharing. Government and private sector collaboration should support cooperative development through capacity-building programs. The wide variability in farming practices highlights the need for more effective agricultural extension services. Expanding training programs on good agricultural practices (GAP), sustainable intensification, and yield optimization strategies will help farmers make informed decisions regarding replanting and farm management.

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Writing – Review and Editing: RSA, HAR, AIS, TN, AMH. All authors have read and agreed to the published version of the manuscript.

IDENTIFICATION AND CHARACTERIZATION OF BACTERIA ISOLATED FROM GARLIC THRIPS (*Thrips tabaci* LINDEMAN) (Thysanoptera: Thripidae) IN THE PHILIPPINES

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ABSTRACT

Thrips tabaci Lindeman (Thysanoptera: Thripidae) is a serious insect pest of garlic and onion in the Philippines. This study sought to isolate and identify species of bacteria associated with thrips infesting garlic plants in La Trinidad, Benguet, Philippines, from March 2020 to March 2021. A total of 135 live adult female thrips attached to the leaves were picked under a dissecting microscope and isolated in nutrient agar plates. Purification of bacteria was done by single colony isolation using 10^{-3} serial dilution, and morphology was determined using the standard bacterial colony characterization chart. Out of the 135 thrips, 104 yielded bacteria (77.03%). Analysis of *16S ribosomal RNA* gene sequence revealed the following: *Bacillus amyloliquefaciens, Peribacillus frigoritolerans, Brevundimonas diminuta, Comamonas koreensis, Enterobacter hormaechei, Enterobacter ludwigii, Rosenbergiella epipactidis*, and *Staphylococcus sciuri*, all with > 99% nucleotide identity. Most of the bacterial colonies were round, entire margin, creamy white color, and a smooth colony surface. These are new records in the Philippines. The findings of this study provided baseline information on the microbiota of garlic-associated thrips and offer promising leads for the development of bacterial-based biocontrol agents, with broader implications for sustainable pest management and microbial ecological research in agroecosystems.

Key words: *Bacillus, Enterobacter, Brevundimonas, Rosenbergiella, Staphylococcus*

INTRODUCTION

Garlic (*Allium sativum* L.) is one of the main condiment crops planted in the Philippines with an estimate of 6 to 7 thousand metric tons annual production from 2016-2020 (PSA 2021). Despite the high market potential and demand, garlic production in the Philippines is still very low (PSA 2014). One of the factors contributing to the low production is the continuous ravaging of insect pests and diseases (Declaro-Ruedas 2020; PSA 2014). Garlic thrips (*Thrips tabaci* Lindeman*)* is a destructive insect pest that was recorded in Batanes, Davao, Ilocos Norte and Misamis Occidental, Philippines

(Reyes 2021) on various crops including garlic, onion, tobacco, banana, mango, tomato, melon, eggplant, potato, and pepper (Reyes 1994a; 2017b). These tiny phytophagous insects damage their hosts either by direct feeding in the plant tissues through their piercing-sucking mouthparts or indirect transmission of plant pathogens (Reyes et al. 2022). The nymphs and adults damage crops by sucking the leaf sap resulting in leaf scarring and streaking. At high levels of infestation, plants may wilt and eventually die or bulbs become severely damaged. Chemical control remains the primary strategy in managing insect pests in garlic (PSA 2014).

Microbial communities associated with insects have long been recognized to have a significant role not only in the growth and survival of their host insects but also in its effect on the host plants and the spread of plant pathogens. Like other insects, thrips can also harbor numerous microorganisms such as bacteria, fungi and viruses (De Vries et al. 2008; Garcia-Rodriguez et al. 2014). Depending on their relationship, these microorganisms can be pathogenic to, symbiotic with, or vectored by insects (Sanchez-Contreras and Vlisidou 2008). Microorganisms that live in the insect without harming its host are called symbionts. Symbiotic microorganisms that live within their host are called endosymbionts while those that are located on the surface are called ectosymbionts (Douglas 2009). Meanwhile, insect pathogens or sometimes referred as entomopathogens, are microorganisms that destroy and kill their insect host. Some insects, however, play the role of vectors by carrying and spreading pathogens. The most intensively studied thrips-associated microorganism is probably the Tomato spotted wilt virus (TWSV), a pathogen spread by several thrips species including *Thrips tabaci*, *T. palmi*, *Frankliniella occidentalis*, and *F. fusca*, (de Assis et al. 2004; Wijkamp et al. 1993). Thrips are common vectors of plant viruses (Jones 2005) therefore, work on thrips-associated viruses are abundant. On the other hand, most research on thrips-associated fungi were mainly on screening and evaluation of potential entomopathogenic fungi such as *Metarhizium anisopliae, Peacilomyces* spp. and *Beauveria bassiana* against different species of thrips (Niassy et al. 2012; Sengonca et al. 2006). Records of fungi isolated from thrips are limited but a notable work was reported by Kirisik and Erler (2024) on the potential of *Beauveria bassiana, Isaria fumosorosea,* and *Lecanicillium psalliotae* isolated from western flower thrips (*Frankliniella occidentalis*) as entomopathogens that can cause significant mortality against pupae and adult females of *F. occidentalis*. In the Philippines, two endophytic fungi were reported from garlic thrips (*T. tabaci*), which are *Fusarium proliferatum* and *Aspergillus candidatus* based on its gene sequences and fungal morphology (Reyes et al. 2021). *F. proliferatum* is considered an entomopathogenic fungus of various insect pests and could have significance in biological control management utilizing fungal entomopathogens.

For thrips-associated bacteria, several studies had been conducted for onion thrips (*T. tabaci*), chili thrips (*Scirtothrips dorsalis*), Western flower thrips (*F. occidentalis*)*,* avocado thrips (*S. hansoni, F. panamensis, F.* sp.), and tobacco thrips (*F. fusca*) (Cano-Calle et al. 2022; Dickey et al. 2014; Wells et al. 2002). Molecular identification using 16S gene sequencing showed *Pantoea agglomerans* and *Pantoea ananatis* as the most commonly associated bacteria in the majority of these thrips. Both of these *Pantoea* species are multifaceted bacteria that can cause rot disease in various crops including onion (Dutta et al. 2014) but can also be beneficial as biological control agents (Lorenzi et al. 2022). The association of a symbiont *Erwinia* under the family *Enterobacteriaceae* with western flower thrips, *F. occidentalis* (Pergande), was also reported, although its role as gut bacteria is still unclear (De Vries et al. 2012). Species of *Wolbachia* is another bacterial symbiont associated with several thrips species including *Aptinothrips rufus* Haliday*, Sciothrips cardamom* (Ramakrishna), *Suocerathrips linguis* Mound & Marullo*, Heliothrips haemorrhoidalis* (Bouche), *Echinothrips americanus* Morgan, *Caliothrips fasciatus* (Pergande), *Pezothrips kellyanus* (Bagnall), and *Thrips palmi* Karny (Saurav et al. 2016; Schausberger 2018). In garlic thrips and its associated bacteria, limited studies have been conducted in other countries, and no previous effort has been made yet in the Philippines.

Understanding the microbiota of thrips is crucial as it offers ecological insights into the insect with huge potential in pest management and biotechnological applications. In the present study, bacteria from garlic thrips, *Thrips tabaci* Lindeman was isolated and the identities were confirmed based on cultural and molecular characteristics. This study sought to provide information on the bacterial microbiota of garlic thrips in the Philippines that holds potential for multiple applications, especially in bacteria-based microbial pest management.

MATERIALS AND METHODS

Thrips collection and identification. Adult thrips were collected from infested 'Ilocos White" garlic plants grown in the experimental area of Benguet State University (BSU) in La Trinidad, Benguet, in March 2020 and March 2021. The thrips were brought to the laboratory, examined under dissecting microscope, and adult female thrips were identified using the comprehensive diagnostic keys of thrips in the Philippines (Reyes 1994), and online resources, Lucid Key Server – Lucid Central (Hoddle et al. 2019).

Isolation of bacteria from the thrips. Thrips-infested fresh garlic leaves collected from La Trinidad, Benguet, Philippines were brought to the laboratories of National Crop Protection Center, University of the Philippines Los Bańos and Benguet State University, then examined under a dissecting microscope. Live, adult female thrips attached to fresh garlic leaves were picked individually inside the laminar flow hood using a very fine insect hairbrush with the aid of a dissecting microscope. Prior to isolation, adult thrips were surface sterilized with 10% bleach (sodium hypochlorite) and washed three times with sterile distilled water for at least two minutes for each wash and then blotted dry with sterile tissue paper inside a laminar flow hood to reduce possible external contamination. A total of 135 live and adult female thrips were plated in two batches: the macerated thrips and the individual thrips using nutrient agar (NA) with five thrips for each plate to ensure sufficient representation across replicates, maximize the likelihood of bacterial recovery, and allow for comparison between pooled and individual isolation methods. The plates were then sealed using parafilm and placed under room conditions to allow bacterial growth and then observed after 24 hours. Bacteria that directly grew from the isolated insects were individually isolated in separate plates of NA. After plating the bacterial colonies, serial dilution was done to purify the bacteria and to allow single colony formation. A loopful of individual bacterial isolates was placed in separate 1.5mL tubes containing 1mL sterile distilled water and incubated overnight for at least 12 hours at room temperature. After incubation, 100ul of bacterial solution was transferred into another tube containing 900ul of sterile distilled water which served as the 10^{-1} dilution, until higher dilutions were achieved. Samples were plated at 10^{-1} – 10^{-3} dilutions following the bacterial streak method on NA plates and then isolates were allowed to grow for at least 12 hours. As soon as single colonies grew, these were transferred individually to test tube slants for further processing. While single colonies are still growing, these were characterized under a microscope following the cultural and morphological characterization methods for bacteria (Ahern 2018; Breakwell et al. 2007). Colony morphology analysis was done 24 hours after isolation from serial dilution using a dissecting microscope. Colony characteristics such as shape, margin, elevation, appearance, color, opacity, and pigmentation were observed by visual assessment under a dissecting microscope.

Molecular identification of the bacterial isolates. Fresh isolates of the bacteria were prepared for molecular identification using nutrient broth and nutrient agar plates. Samples were sent to Macrogen, Inc., South Korea through Kinovett Scientific Solutions Company, Philippines for molecular analysis using *16S ribosomal RNA* gene. Genomic DNA was extracted by Macrogen, and sequencing was performed through capillary sequencing using standardized commercial protocols appropriate for bacterial samples. The 16S rRNA gene was amplified using universal primers 27F (5'-AGAGTTTGATCMTGGCTCAG-3') and 1492R (5'-TACGGYTACCTTGTTACGACTT-3') (Miller et al., 2013). The integrity of the extracted DNA was confirmed through agarose gel electrophoresis. The raw nucleotide sequence of each sample was checked, edited, and aligned to produce the consensus sequence using the software package Geneious Prime® 2023.0.2 (Biomatters Ltd., Auckland, New

Zealand). The consensus sequences were then compared with those deposited in GenBank to confirm bacterial species identity, obtaining the highest percentage genetic identity using NCBI BLASTN from https://blast.ncbi.nlm.nih.gov/Blast.cgi. A phylogenetic tree derived from 16S of the consensus sequences and twenty bacterial sequences obtained from GenBank was generated. The molecular phylogenetic analysis of the bacterial species isolated from *T. tabaci* was inferred using the Maximum Likelihood method based on the Tamura-Nei model with 1000 bootstraps. For evolutionary analyses, the software Geneious was used with 644 positions and an additional twenty GenBank sequences in the final dataset to make the phylogenetic tree more informative.

RESULTS AND DISCUSSION

Thrips identity and taxonomic classification. The thrips collected from the garlic were identified as *Thrips tabaci* Lindeman (Reyes 1994). Photomicrographs of the female garlic thrips are presented in Figure 1. *T. tabaci* belongs to Order Thysanoptera, Suborder Terebrantia, and family Thripidae. Adult female thrips had a yellowish brown body with dark setae, rounded and elongate mouth cone, pale grey forewings with four distal setae and an anterior vein, and yellow legs. The striae of pleurotergites had ciliate microtrichia (Hoddle et al. 2019; Reyes et al. 2021).

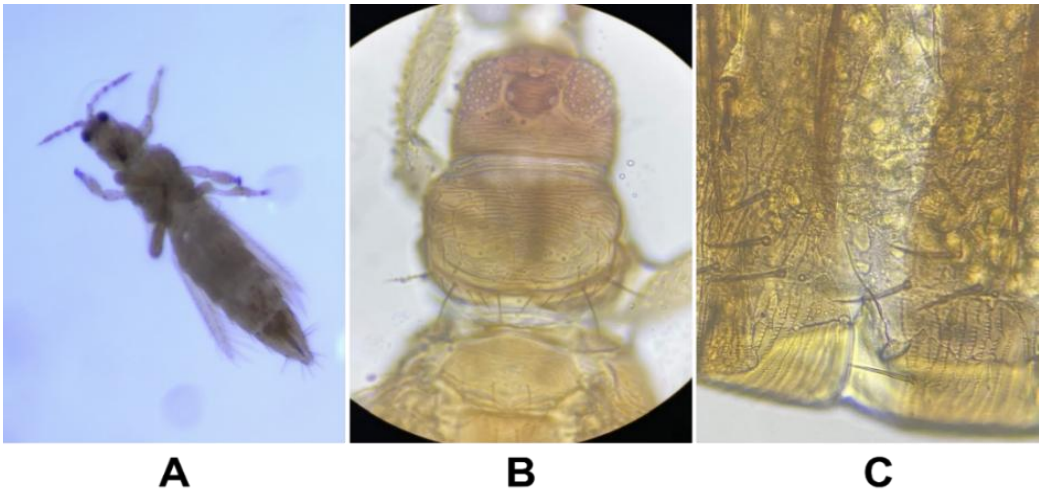

Figure 1. Photomicrograph of adult female *Thrips tabaci* Lindeman infesting garlic: (a) whole body (45x); (b) head and thorax (400x); (c) pleurotergites (400x)

Identity and phylogenetic tree of bacterial isolates. Molecular identification of bacteria is essential since morphological characterization often poses challenges to species resolution. Out of the 135 thrips plated in nutrient agar, 104 yielded bacteria (77.03%). Using the 16s rRNA gene marker, 8 species of bacteria isolated from *T. tabaci* were identified. Two of these belong to the genus *Enterobacter*, and one each from the *Bacillus, Peribacillus, Brevundimonas, Comamonas, Rosenbergiella* and *Staphylococcus* genera. Nucleotide sequence alignment using the NCBI BLASTN database showed that all the bacteria had at least 99% nucleotide identity (Table 1).

The phylogenetic tree (Fig. 2) reveals close genetic relationships between the following isolate-reference pairs: SBA6 and *E. ludwigii*, SBC3 and *E. hormaechei*, SBS5 and *R. epipactidis*, SBB01 and *B. amyloliquefaciens*, SBA7 and *P. frigoritolerans,* SBC1 and *S. sciuri*, SBS2 and *B. diminuta*, and SBA5 and *C. koreensis*. This analysis provides insights into genetic relatedness and divergence patterns among the bacterial species associated with garlic thrips. Six of these bacterial species were isolated from live thrips collected from fresh garlic leaves: *Enterobacter hormaechei,* *Comamonas koreensis, Enterobacter ludwigii, Peribacillus frigoritolerans, Bacillus amyloliquefaciens,* and *Staphylococcus sciuri*. Additionally, *Brevundimonas diminuta* and *Rosenbergiella epipactidis* were recovered from surface-sterilized, macerated thrips.

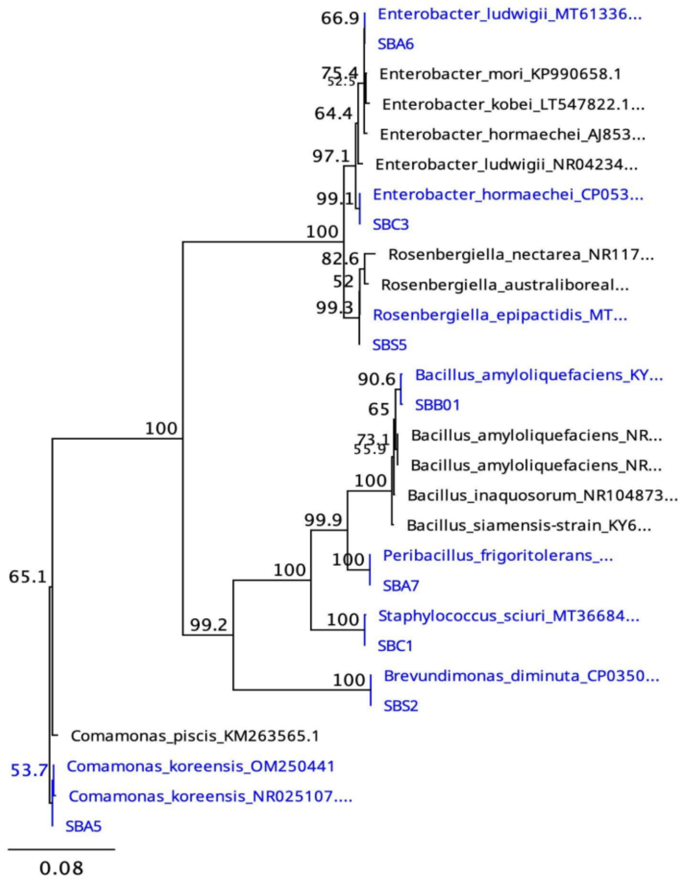

Figure 2. Maximum Likelihood phylogenetic tree based on 16S rRNA gene sequences showing the relationship of selected bacterial isolates (SBA5–SBA7, SBC1–SBC3, SBB01, SBSS2, SBSS5) with closely related reference strains. Bootstrap values (>50%) based on 1000 replicates are shown at the nodes. The scale bar signifies the number of substitutions per site.

Table 1. Molecular identity of the bacteria from garlic thrips (*T. tabaci*) based on 16s rRNA full sequence.

No.	Isolate code	Query Sequences	Scientific name	Percent identity	GenBank Accession number
1	SBB01	OR437230	*Bacillus amyloliquefaciens*	100	JX316756
2	SBA7	OR437229	*Peribacillus frigoritolerans*	99	CP128118
3	SBS2	OR437233	*Brevundimonas diminuta*	100	LC420060
4	SBA5	OR437227	*Comamonas koreensis*	99	NR_025107

No.	Isolate code	Query Sequences	Scientific name	Percent identity	GenBank Accession number
5	SBC3	OR437232	*Enterobacter hormaechei*	100	CP059422
6	SBA6-1	OR437228	*Enterobacter ludwigii*	99	MG602668
7	SBS5	OR437234	*Rosenbergiella epipactidis*	99	MT341879
8	SBC1	OR437231	*Staphylococcus sciuri*	100	MT366845

Colony characteristics of the bacteria. Colonies of the bacterial isolates in the nutrient agar plate at 24 hours after isolation are presented in Figure 3. Most of the isolates were punctiform (less than 1mm in diameter) except for *P. frigoritolerans* with colony size of at least 1 mm in diameter. The shapes and margins of the colonies were difficult to assess using the naked eye due to their tiny sizes, but under a dissecting microscope, the distinction of each bacterial colony became more apparent. *C. koreensis* was distinguishable among the isolates due to its undulate margin. *P. frigoritolerans* appears to be slightly filiform with convex elevation. The rest had an entire margin with a smooth colony surface. In terms of color and pigmentation, all the isolates were consistently creamy white and without pigmentation. All the bacteria grew fast and well in NA at room temperature, except for *Rosenbergiella epipactidis,* which had much slower growth. The colony of *R. epipactidis* was also difficult to isolate due to its strong adherence to the agar medium. The rest can be easily isolated due to their non-sticky characteristics when transferred using a bacterial loop. A summary of the colony characteristics is presented in Table 2.

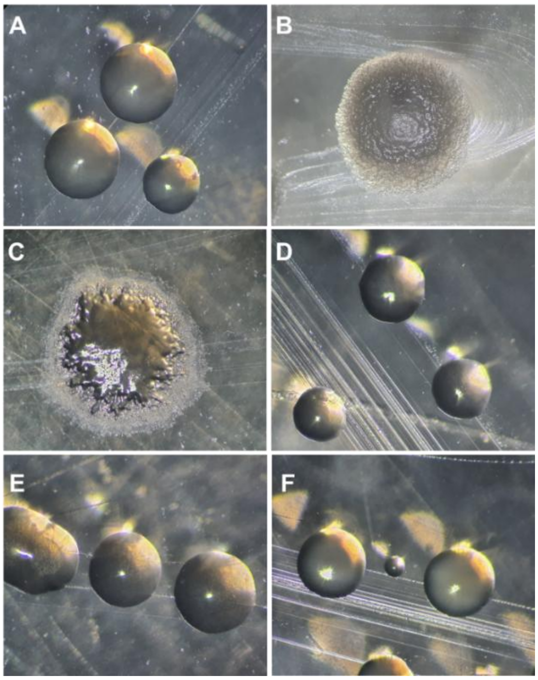

Figure 3. Colonies of bacteria on nutrient agar plate 24 hours after isolation. Photos taken under dissecting microscope at 3x-4x magnification. A-*Bacillus amyloliquefaciens*, B- *B. frigoritolerans*, C- *Comamonas koreensis* , D- *Enterobacter kobei*, E- *E. roggenkampii*, F- *Staphylococcus sciuri*.

Table 2. Colony characteristics of the bacteria isolated from *T. tabaci* in nutrient agar 24 hours after isolation under room temperature.

Scientific name	Shape	Size	Margin	Elevation	Appearance	Color	Opacity	Surface Texture	Pigmentation
Bacillus amyloliquefaciens	punctiform	0.6-0.7 mm	entire	convex	glistening	creamy white	translucent	smooth	Non-pigmented
Peribacillus frigoritolerans	round	1-1.2 mm	slightly filiform	convex	dull	creamy white	opaque	rough with concentric ring	Non-pigmented
Comamonas koreensis	punctiform	0.6-0.8 mm	undulate	convex	glistening	creamy white	translucent	wrinkled	Non-pigmented
Enterobacter hormaechei	punctiform	0.3-0.6 mm	entire	convex	glistening	creamy white	translucent	smooth	Non-pigmented
Enterobacter ludwigii	punctiform	0.5-0.8 mm	entire	convex	glistening	creamy white	translucent	smooth	Non-pigmented
Staphylococcus sciuri	punctiform	0.5-0.7 mm	entire	convex	glistening	creamy white	translucent	smooth	Non-pigmented

The information that was obtained in this study provides insights into the bacterial microbiota associated with garlic thrips (*Thrips tabaci* Lindeman) and can be useful for the development of appropriate management strategies. In the Philippines, this is the first report of bacteria isolated from *T. tabaci* of garlic identified using *16S ribosomal RNA* gene sequencing. The association of these bacteria with *T. tabaci* is still unclear; however, just like other insect-microbe relationships, these bacteria can be antagonistic or symbiotic with their host insect, pathogenic to the thrips and its host plant, or vectored by the insect. The most interesting bacterial isolate obtained from this study was the genus *Bacillus,* which was also reported in onion thrips (Gawande et al. 2019) and avocado thrips. *Bacillus amyloliquefaciens* was specifically reported in avocado thrips (Cano-Calle et al. 2022). *Bacillus* are gram-positive bacteria that are known to produce toxins and other secondary metabolites that can kill their hosts (Vairagkar et al. 2021). Numerous *Bacillus* species, including the broadly adopted *B. thuringiensis,* are used as biological control agents (BCA) against various agricultural insect pests. *B. amyloliquefaciens* is a common bacterial endophyte of many plants (Sun et al. 2006; White et al. 2014). Intensive studies were already conducted using various strains of *B. amyloliquefaciens* due to their numerous benefits not only in bioremediation (Xie et al. 2013) and biofertilization (Luo et al. 2022) but also in controlling agricultural pests. Some studies have demonstrated the insecticidal activity of *B. amyloliquefaciens* against *Myzus persicae* (López-Isasmendi et al. 2019) and *Tuta absoluta* (Ben Khedher et al. 2015). Interestingly, *B. amyloliquefaciens* is also used as a biopesticide against *Fusarium oxysporum, Ralstonia solanacearum, Colletotrichum truncatum* (Huang et. al. 2014; López-Isasmendi et al. 2019; Singh et al. 2021). In contrast, a rare case of *B. amyloliquefaciens* was reported in Korea causing bacterial rot in onion bulbs (Hwang et al. 2012). This means that *B. amyloliquefaciens* can have potential as a biological control agent, or it can be a disease-causing pathogen carried by garlic thrips. The pathogenicity test of this *B. amyloliquefaciens* from *T. tabaci* against insect pests and pathogens, including tests for garlic and onion, could therefore provide new knowledge and information for pest management of onion and garlic in the Philippines. Other thrips-associated *Bacillus* species that were reported include *B. cereus, B. thuringiensis, B. safensis,* and *B. velezensis* from a pooled population of avocado thrips (*Frankliniella* sp., *Frankliniella panamensis* and *Scirtothrips hansoni*) in Colombia (Cano-Calle et al. 2022).

Furthermore, *Peribacillus frigoritolerans* (formerly *Bacillus frigoritolerans*) has been reported to have numerous benefits, just like other species of *Bacillus*. Several strains of this species have potential as plant growth promoter (Batool et al. 2019), as post-harvest biocontrol agents against plant pathogens (Chacón-López et al. 2021), and as entomopathogens of coleopterans (Selvakumar et al. 2011). The association of *P. frigoritolerans* in thrips and other pathogens of garlic, and the assessment of its insecticidal and antimicrobial potential, are also interesting areas for future research to address pest management issues.

Additionally, two of the bacteria obtained in this study were identified as *Enterobacter hormaechei* and *E. ludwigii*. Currently, no local studies on the association of these bacteria with thrips or garlic plants have been conducted yet. However, the genus *Enterobacter* was included in the report of Cano-Calle et al. (2022) as one of the genera of bacteria associated with avocado thrips, *S. hansoni* and *F. panamensis,* but more abundant in *Frankliniella* sp. This genus was also found in onion thrips *T. tabaci* in India (Gawande et al. 2019) and in chili thrips *Scirtothrips dorsalis* (Dickey et al. 2014). Currently, these two *Enterobacter* species belong to *Enterobacter cloacae* complex (ECC) causing animal and human infections (Kosako et al. 1996; Zhou et al. 2017). Although considered as human and animal pathogens, some studies suggested that both *E. hormaechei* and *E. ludwigii* are excellent plant growth promoter that can help boost plant vigor, induce disease resistance, and increase yield by enhancing plant nutrient uptake of tomato, cotton, and other crops (Ranawat et al. 2021; Wang et al. 2025).

Other bacteria from garlic thrips are *Staphylococcus sciuri, Brevundimonas diminuta, Rosenbergiella epipactidis,* and *Comamonas koreensis.* The genus *Staphylococcus* was reported in onion thrips (*T. tabaci*) in India (Gawande et al. 2019) and in gall-inducing thrips (*Gynaikothrips uzeli*) including *Brevundimonas* and *Enterobacter* (Tyagi et al. 2022). Currently, reports on *B. diminuta* and *S. sciuri* as human pathogens (Hu et al. 2015; Lupande-Mwenebitu et al. 2021) and animal pathogens (Beims et al. 2016) are the only available data. *Rosenbergiella epipactidis*, on the other hand, belongs to the family *Erwinianeae* formerly *Enterobacteriaceae* and was isolated from the nectar of flowers (Lenaerts et al. 2014) and also a common insect microbiota (Álvarez-Pérez et al. 2023). The genus *Rosenbergiella* is one of the bacteria associated with onion thrips (*T. tabaci*), avocado thrips (*S. hansoni*), and it was reported to be easily dispersed by western flower thrips (*F. occidentalis*) (Cano-Calle et al. 2022; Gawande et al. 2019; Vannette et al. 2021). Although the previous reports did not specify the species of *Rosenbergiella* obtained, the results of this study complement the previous studies and confirm the association of *Rosenbergiella* sp. with thrips. For *Comamonas koreensis,* limited studies were available on their properties, characteristics, habitat, hosts and significance.

Compared to the previous works of De Vries et al. (2008) and Jin et al. (2023) on the bacterial microbiota of *T. tabaci* in onion, the bacteria reported in this study are not the same and not even closely related to the ones they found. Based on the biochemical and 16S rDNA analysis they conducted, the three bacterial species isolated from the larvae of *T. tabaci* were identified as *Serratia marscens, Pseudomonas sp.* and *Erwinia herbicola,* which is synonymous with *Pantoea agglomerants* (De Vries et al. 2008). *P. agglomerans* in adult onion thrips (*T. tabaci*) has been reported in Korea (Jin et al. 2023). However, a study on microbiome profiling of adult *T. tabaci* in onion using 16S rRNA gene sequencing provided a more comprehensive list of bacterial genera associated (Gawande et al. 2019). From their report, five genera were found similar to the ones obtained from *T. tabaci* of garlic and these are *Bacillus, Enterobacter, Rosenbergiella, Brevundimonas*, and *Staphylococcus.* Therefore, the results of this study complement the previous works on the associated bacteria of *T. tabaci* in onion and other thrips species in other crops.

CONCLUSION

Eight bacterial species were obtained from 104 out of 135 live (77.03%) adult female thrips (*T. tabaci*) collected from "Ilocos White" garlic in La Trinidad, Benguet. The bacteria were identified as the following: *Bacillus amyloliquefaciens, Peribacillus frigoritolerans, Brevundimonas diminuta, Comamonas koreensis, Enterobacter hormaechei, Enterobacter ludwigii, Rosenbergiella epipactidis*, and *Staphylococcus sciuri.* All of the isolates were consistently nonpigmented and most were punctiform with entire margin and smooth surface except for *P. frigoritolerans* and *C. koreensis.* From the seven bacterial genera obtained from garlic thrips, five were also found in *T. tabaci* of onion and other species of thrips infesting other crops. Findings of this study provided insights into the bacterial microbiota of adult *T. tabaci* in garlic. A study on the association of these bacterial species with garlic thrips is an interesting area for future studies. A thorough investigation on the specific roles of these bacteria in disease spread, pathogenicity, and biological control could provide opportunities for better pest management. Scientific evidence showing the vectoring relationship between the thrips and the identified bacteria may provide new insights on the spread of bacterial pathogens. Moreover, knowledge on host specificity, whether the identified bacteria can infect limited species of host plants (specialist) or variety of hosts (generalist), can have numerous applications in disease diagnosis, management practices, breeding of resistant varieties, and biosecurity. Furthermore, exploring the biological control potential of the identified bacteria against insect pests such as thrips and other plant pathogens can also provide opportunities for the development of better pest management solutions.

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UNDERSTANDING PRO-ENVIRONMENTAL BEHAVIOR OF WOMEN SHOPPERS IN NORTHERN MINDANAO, PHILIPPINES: AN EXPANDED TPB-NAM FRAMEWORK USING MIXED METHODS

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ABSTRACT

The irreversible consequences of plastic pollution to health and the environment opened a wide array of research. Expanding on the Theory of Planned Behavior (TPB) and Norm Activation Model (NAM), this paper identified the predictors of intention to use (IU) eco-friendly shopping bags. KII and FGDs were conducted with women shoppers in Iligan City, Philippines. Results from the PLS-SEM modeling showed that product image, policy support, and education level have direct and positive effects on the intention to use. Socio-economic variables such as marital status, household size, and income have significant moderating effects, while education level has a significant mediating effect. Subsequently, thematic analysis revealed that shoppers prioritized durability, aesthetics, affordability, perceived pro-environmental policies as effective, and affirmed targeted campaigns to foster sustainable shopping practices. Hence, collective efforts between government and private entities may explore implementation of incentive schemes (i.e., discounts and rewards) and regular city-wide "green days" for "bringing-selling-using" of eco-friendly shopping bags as these can increase awareness and continuous adoption of sustainable practices, eventually shaping pro-environmental behavior across age, gender, and income groups over time.

Key words: sustainable consumption, SmartPLS, theory of planned behavior, norm activation model, intention to use

INTRODUCTION

In the 21st century, plastic pollution has become one of the pressing environmental challenges with widespread ecological, economic, and public health implications. The accumulation of plastic waste in oceans, inland waters, and even in remote ecosystems is documented (Essel et al. 2015; Farvazova 2020), resulting in biodiversity loss, disruptions of food systems, and risks to human health (Naeem et al. 2016). The global reliance on single-use plastic bags amplifies these challenges, with an estimated 500 million plastic bags used annually (Spokas 2008). The improper disposal and persistence of plastic materials in the environment have resulted in the formation of microplastics – small plastic fragments from the breakdown of larger items, e.g. plastic food packaging, have been found in soil, marine organisms, and human food chains (Seltenrich 2015; Yuan et al. 2002).

The escalating environmental concern has catalyzed a global shift toward sustainable consumption practices and the development of alternative materials. Eco-friendly shopping bags are reusable, biodegradable, or made from recycled materials, and emerged as a substitute for single-use plastic bags. The promotion of eco-friendly shopping bags by businesses demonstrates responsible environmental practices while meeting the growing consumer expectation for products that are pro-environment, that benefit both the environment and future generations (Karalar and Kiraci 2011; Steg et al. 2009). These bags not only lessen single-use plastics but also reflect a growing consumer awareness and demand for environmentally responsible products (Ekasari and Zaini 2020; UNCTAD 2023). Yet, the adoption of such sustainable practices remains minimal across populations with significant variation in behavioral responses to environmental campaigns and product innovations (Osarodion et al. 2023).

Recent studies provide insights into these consumer behaviors, such as Cam et al. (2025) who suggest that product attributes, environmental concern, and supply-side factors directly influence eco-bag use in Vietnam although product features were observed to have indirect effects on consumer behavior. Ethical self-identity and attitudes are important in predicting intention to use biodegradable bags, moderated by religiosity (Zaman et al. 2023). In Indonesia, authority endorsement and institutional signals increase in shop owner's willingness to distribute reusable bags (Spranz et al. 2018). Ekasari and Zaini (2020) identified that environmental knowledge, and perceived behavioral control predict the use of eco-bags, but this study did not account for demographic characteristics as moderators. More recently, perceived price and green product features influence green buying behavior while perceived responsibility is weak, suggesting that external cues outweigh intrinsic norms under certain circumstances (Nugraha and Soelasih 2023). The studies emphasize the complex interplay of psychological constructs, product-related factors, and institutional support in shaping pro-environmental behavior.

In trying to understand sustainable shopping practices, particularly identifying drivers of this pro-environmental behavior within a specific local policy context, an expanded Theory of Planned Behavior (TPB) and Norm Activation model (NAM) were adopted, with environmental awareness (EA), support for policy (SFP), willingness to pay (WTP), and product image (PI) included in the framework as additional constructs to account for institutional and consumer-market factors relevant to the research locale. This study is enthused by previous studies adopting NAM (De Groot et al. 2009; Schwartz 1977; Setiawan et al. 2021; Yang et al. 2018) and TPB (Ajzen 1991).

The construct adopted from NAM is personal norm (PN) while attitude (ATT), subjective norm (SN), and perceived behavioral control (PBC) were adopted from TPB. PN refers to a person's subjective feeling of obligation to act in a pro-environmental way. It is activated when individuals become aware of the consequences of their actions and feel a sense of responsibility to address those impacts. Complementary to NAM, TPB is a robust framework that predicts pro-environmental consumer behavior with three core determinants influencing behavioral intention, namely, ATT which refers to the individual's perceptions of the desirability or undesirability of using eco-friendly reusable bags (Hale 2003), SN which is the person's perceptions of the influencers (e.g., family, peer, or society) who would think that individuals should or should not act (Ajzen 1991), and PBC which refers to the belief in one's ability to easily access and utilize eco-friendly shopping bags, reflects consumers' judgment of how easy it is to perform certain behavior and their ability to control (Ye 2022). As this study integrates constructs from NAM and TPB, variables such as EA, SFP, WTP, and PI are also added in the model to account for institutions, particularly depicting the locale's context. EA refers to people's perceptions of environmental issues, including aggregate aspects of environmental knowledge. It is an important aspect in preparing individuals to find solutions to environmental issues and is seen as a key factor that affects people's consumption behavior (Fu et al. 2020). SFP refers to people's positive support for government regulations on environmental safeguards. Positive support is essential in the transition from non-environmental to sustainability-driven consumption practices. EA and SFP are essential factors to fostering personal responsibility, aligned with NAM's emphasis on how knowledge of environmental impacts and endorsement of policy initiatives can activate norms and influence pro-environment actions. WTP describes the grocery shoppers' level of acceptability and its relationship to the additional cost of eco-friendly shopping bags. PI is also added to TPB to describe consumers' preferences in terms of durability, convenience, design, function and purpose that influences intention to use. These constructs have been widely used to assess consumer-level environmental decision-making, such as the adoption of sustainable products like eco-friendly reusable shopping bags.

However, consumer choices are not in isolation. The role of institutional support and policy interventions is recognized in shaping sustainable practices among consumers. Local ordinances that restrict plastic bag use, promote eco-bag alternatives, or incentivize sustainable behavior can strengthen consumers' motivation and create a more enabling environment for behavior change (Karalar and Kiraci 2011). Similarly, perceived product image (i.e., quality, functionality, design) influences consumer preference and adoption, and recent evidence from emerging markets shows that institutional support and market-related signals are significant, with external factors outweighing internal psychological constructs (Chatrakamollathas and Nuengchamnong 2024). Thus, the interplay of psychological, social, and structural factors warrants further empirical investigation.

Demographic characteristics such as marital status, household size, income, and education are also included in the expanded framework as studies have shown that consumer heterogeneity influences pro-environmental behavior, an aspect that remains understudied in literature (Ekasari and Zaini 2020; Nugraha and Soelashi 2023). This study surveyed women because of their main role as decision makers in household budgeting and practices (i.e., grocery shopping, recycling) (Fry et al. 2023; Guiot et al. 2019), and their stronger engagement in sustainable lifestyles compared to men (Sahin et al. 2012). The expanded TPB and NAM frameworks cover both rational decision-making and moral responsibility of consumers. In particular, the constructs EA, WTP, SFP, and PI, capture psychological, marketing, socio-economic, and institutional aspects of consumer behavior. Socio-demographic moderators like civil status, education level, income, and household size provide different paradigms on sustainable shopping practices.

In the Philippines, plastic pollution has remained a long-standing challenge despite national and local-level policy efforts, such as the implementation of the Ecological Solid Waste Management Act of 2000. In the case of Iligan City, the chosen locale of this study, its local government unit (LGU) enacted a local ordinance, through an executive order, for a single-use plastic ban. In response, business establishments provide a range of eco-friendly shopping bag alternatives such as brown paper bags, carton boxes for free or reusable bags for sale. While these alternatives are available and accessible, the actual adoption and support for the local ordinance are not consistent and significant. For this reason, it is imperative to understand the constructs that shape consumers' pro-environmental behavior as inputs for evidence-based policy impact evaluation to redesign initiatives and programs depending on time relevance and policy goals.

MATERIALS AND METHODS

Research locale. Iligan City was deemed a suitable research locale for this study because of the present implementation of single-use plastic ban and promotion of eco-friendly reusable bags in shopping markets. Figure 1 shows the commonly available eco-friendly reusable bags substitute to single-plastic shopping bags in Iligan City. As of 2019, approximately 30% of all LGUs in the Philippines had enacted some form of plastic regulation, predominantly total bans of plastic bags. The widespread adoption is often influenced by national mandates, such as RA 9003 or the Ecological Solid Waste Management Act of 2000, and the pressing need to mitigate flooding exacerbated by clogged drainage systems. While Iligan City shares these common policy initiatives with other regions, Iligan City's approach stems from its specific historical, industrial, and environmental context, which has necessitated an evolving policy framework. The city's proactive approach in adopting diverse management technologies is a compelling case to study. The present policy and changes in business operations that promote eco-friendly shopping bags should be sustained, especially for a booming area aspiring to become a smart city by 2030. In Iligan, there are existing institutions, private firms (i.e., Republic Cement Inc.), and facilities (i.e., material recovery processing and landfill) installed and operational to support the local resolution promoting sustainable consumption, and yet the increasing amount of waste generated and disposed at the landfills is becoming a pressing dilemma for Iligan City officials and residents alike. Local waste generation outpaces recovery efforts, resulting in the City Materials Recovery and Composting Facility (CMRCF) exceeding its full capacity (Dela Cerna, 2019).

Figure 1. Commonly available "eco-friendly reusable shopping bags" in Iligan City, Northern Mindanao, Philippines

Research participants. Studies by Sanchez et al. (2016); Kennedy et al. (2015); Vicente-Molina et al. (2013) showed that women were observed to exhibit stronger pro-environmental values, particularly in the study of Tien and Huang (2023) where 1,839 women adults showing higher environmental values than men. In most households, women stereotypically manage household budgeting and grocery shopping more frequently than men (Pewresearch.org 2019), and as such they are a significant representation of the consumers' demographic in understanding sustainable shopping practices. This study focuses on women shoppers to strengthen the findings that isolate and analyze the constructs influencing intention to use within a highly relevant and influential demographic group. This allows for a deeper and focused assessment rather than generalization of findings that obscure important demographic-related shopping preferences and behavior. The study's focus on women provides in-depth insights into a key consumer group but its findings may have limited generalizability to other genders and populations.

A total of 257 women grocery shoppers in Iligan City, Philippines were surveyed for this study. This sample size of 240 was determined using the minimum required number of participants for adequate statistical power from G*Power software. To ensure robustness and account for potential incomplete questionnaires or unfinished interviews due to unforeseen and uncontrolled circumstances (i.e., weather, health-related issues), or other data contaminations and qualifications, an additional 36 respondents or 15% of the sample size was added. The total number of questionnaires that were subject to analysis was 257. Convenience sampling was used by inviting 257 women grocery shoppers pre-selected shopping areas and establishments where eco-friendly reusable bags were accessible to participate in the survey. The convenience sampling method ensured completion of the study within the budget and time availability. These 257 women grocery shoppers surveyed in Iligan City, Philippines, were pre-qualified based on select demographic characteristics such as currently working, adult or above 18 years old, and a resident of Iligan City before the enactment of Executive Order. A series of KII and FGDs was then conducted in wet markets, shopping areas, and commercial centers around Poblacion, Iligan City, from June to August 2024.

Construct identification and modeling. The first part of the research instrument is composed of 33 indicators for nine constructs, describing the respondent's intention to use, degree of awareness, and stance on eco-friendly reusable shopping bags with corresponding Likert scale (i.e., very low awareness to very high awareness, strongly disagree to strongly agree). The constructs and indicators were adopted from the literature and tested to ensure relevance and appropriateness to meet the objective of the study. Each construct from NAM and TPB is hypothetically influencing consumers' IU eco-friendly shopping bags. While Educ level, Marital status, HH size, and Income were included in the model as moderating variables. Moderating variables do not directly influence IU but will shape the constructs' effect on IU. The model and the insights are intended to provide evidence-based inputs for need-based action strategies in promoting sustainable shopping practices. The model is expected to identify the drivers that translate consumers' preferences into consistent choice and action to support local resolutions and eco-friendly shopping bag features that aim to reduce waste and harm the environment.

Construct analysis. Responses from both KII and FGD were tabulated and sorted in Microsoft Excel. Using Stata, the values for Cronbach's Alpha and average variance extracted (AVE) were obtained for the reliability and validity of constructs. The results were further analyzed through partial least squares - structural equation modeling using the SmartPLS software to establish the complex interrelationships of several constructs, with a small sample size and non-normally distributed data (Hair et al. 2011). The model was subject to correlation analysis and internal discriminant validity using the Fornell-Larcker criterion and Heterotrait-Monotrait (HTMT) Ratio (Hair et al. 2024). The outer and inner variance inflation factor (VIF) values were also derived from the collinearity diagnostics. VIF values are critical in assessing the presence of multicollinearity between predictor variables, which can distort the reliability of regression coefficients of the study.

The goodness-of-fit of the model was assessed using the Standardized Root Mean Square Residual (SRMR) and the Normal Fit Index (NFI). The SRMR is an absolute measure of model fit by representing the square root average squared discrepancy between the observed and model-implied correlation matrices. The threshold value is 0.08. Lower SRMR (< 0.08) indicates a better fit and is considered acceptable for PLS path models (Hu and Bentler 1999; Henseler et al. 2015). The NFI is a relative measurement that compares the fit of the proposed model to a null model, with values ranging from 0 to 1. The threshold value is 0.90. Higher NFI (>0.90) indicates a good model fit (Bentler and Bonett 1980; Hair et al. 2017).

Selected socioeconomic variables were also obtained to provide context for interpreting subsequent findings and ensure a better perspective in understanding diverse backgrounds that shape respondents' pro-environmental behavior (Nowell et al. 2017). The qualitative data obtained from the two focus group discussions (FGD) were subject to thematic analysis (Braun and Clarke, 2006) to identify recurring patterns related to the factors of intention to use reusable bags. The FGD was conducted after the completion of data collection and the initial quantitative phase. The questions in the FGD were formulated based on the initial results from the KII, specifically on the constructs that were significantly driving intention to use. The whole duration of the discussion was recorded in a secure device as agreed and with consent from the participants. The recording was then transcribed and analyzed.

RESULTS AND DISCUSSIONS

Intention to use constructs and the model. Table 1 presents the summary of values of Cronbach's Alpha that range between 0.711 to 0.903 and are above the acceptable threshold of 0.70. This indicates the strong reliability of each item to measure intention to use. All the AVE values are above 0.50 and range between 0.691 to 0.908, indicating convergent validity and verifying that the items within each construct effectively represent the integration of NAM and TPB in the study. The model achieved a good fit with all constructs, demonstrating high factor loading and satisfactory reliability and validity metrics, thus supporting the proposed framework and its application in understanding the interplay of each construct that drives the intention to use eco-friendly reusable bags.

Table 1. Values for Cronbach's Alpha (α) and average variance extracted per construct.

Construct	Indicator	α	Ave
NAM			
EA	EA1. To what extent are you aware that plastic bags negatively affect human health?	0.844	0.691
	EA2. To what extent are you aware that plastic bags negatively affect animal health?		
	EA3. How aware are you that plastic bags pose a threat not only to marine life but also to agricultural land?		
	EA4. How aware are you of the City's ban on single-use plastics and the encouragement to use eco-friendly reusable bags?		
PN	PN1. I believe that using eco-friendly reusable bags protects the environment for future generations.	0.899	0.908
	PN2. I believe that if I use eco-friendly reusable bags, I can be a good example of an environmentally concerned citizen.		
SFP	SFP1. I will support coding days by using and buying eco-friendly shopping bags.	0.893	0.701
	SFP2. I will support imposing fines and penalties on coding days.		
	SFP3. I will support increasing fines and strict penalties for using plastic bags to shift shoppers toward using eco-friendly reusable bags.		
	SFP4. I support bringing eco-friendly reusable bags to dry sections of the public market to minimize the use of single-use plastic.		
	SFP5. I support that collaboration among businesses, governments, and communities is necessary for a sustainable future.		
TPB			
ATT	ATT1. Bringing eco-friendly reusable bags is meaningful.	0.903	0.774
	ATT2. Bringing eco-friendly reusable bags for grocery shopping is necessary.		
	ATT3. I prefer to use eco-friendly reusable bags over other kinds of eco-friendly shopping bags displayed at the counter.		
	ATT4. I use eco-friendly reusable bags to comply with the local mandate.		
SN	SN1. I am influenced by my family to use eco-friendly reusable bags.	0.837	0.754

Construct	Indicator	α	Ave
	SN2. The family members in our household wish me to use eco-friendly reusable bags for grocery shopping.		
	SN3. Social expectations encourage me to use eco-friendly reusable bags.		
PBC	PBC1. It is easy for me to use eco-friendly reusable bags.	0.711	0.638
	PBC2. I can easily remember and prepare to use eco-friendly reusable bags before going to the grocery supermarket.		
	PBC3. It is up to me whether to use eco-friendly reusable bags.		
WTP	WTP1. I am willing to buy the eco-friendly shopping bags displayed at grocery supermarkets rather than using my eco-friendly reusable bags.	0.868	0.787
	WTP2. I am willing and prefer buying the eco-friendly shopping bags displayed at the supermarket instead of using eco-friendly reusable bags to avoid the hassle when I go grocery shopping.		
	WTP3. I am willing to pay for eco-friendly shopping bags even if it is costly.		
PI	PI1. I intend to use eco-friendly reusable bags because they are still durable.	0.872	0.663
	PI2. I intend to use eco-friendly reusable bags because they are more convenient than paper bags and carton boxes displayed at the counter.		
	PI3. I intend to use eco-friendly reusable bags because of their design that promotes environmental sustainability.		
	PI4. I am satisfied with the purpose and function of eco-friendly reusable bags.		
	PI5. I am satisfied with the eco-friendly reusable bags because of their color.		
IU	IU1. I intend to use eco-friendly reusable bags to reduce environmental impact.	0.872	0.663
	IU2. I intend to use eco-friendly reusable bags to decrease waste in the landfills of the city.		
	IU3. I intend to support the policy on using eco-friendly reusable bags.		
	IU4. I intend to use eco-friendly reusable bags for sustainable consumption.		

Figure 2 presents the algorithm model. The model drew several relationships among the constructs. The arrows in the model are the pathways and standardized path coefficients, indicating the strength and direction of the relationships between constructs from the two theories of the study.

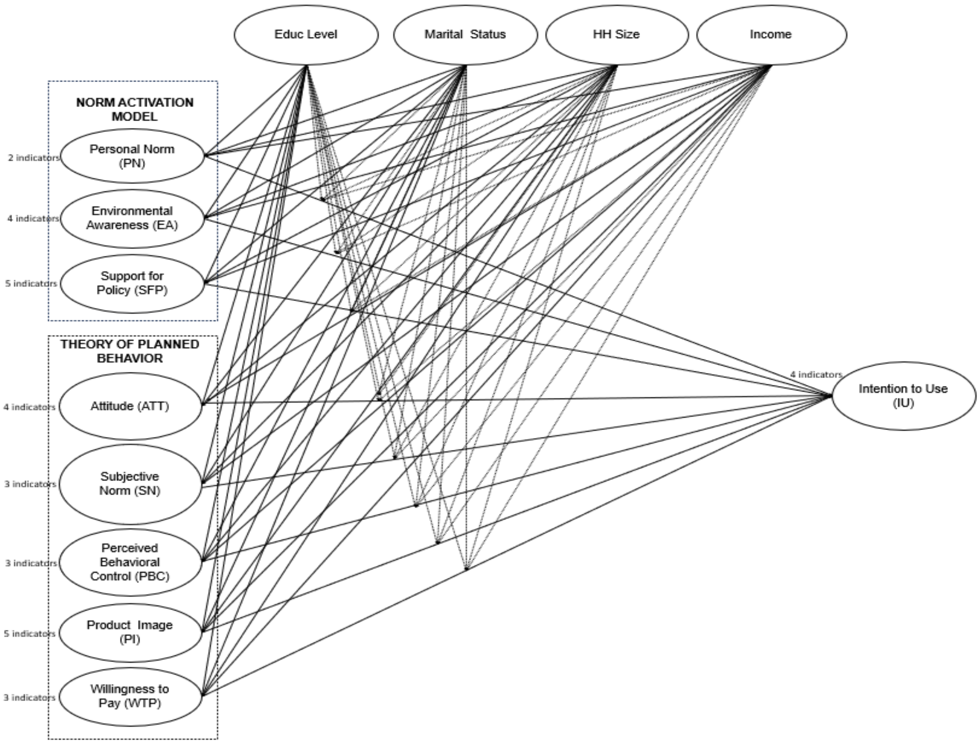

Figure 2. The algorithm of the expanded TPB and NAM as adopted in the study.

A cross-loadings analysis showed a correlation between indicators and multiple constructs. The indicators IU1 to IU4, PBC1 to PBC2, PI1 to PI4, PN1 to PN2, SFP1 to SFP5, SN1 to SN3, and WTP1 to WTP3, along with education level, household size, income group, and marital status, demonstrated strong loadings with a value above 0.70.

Table 2 presents the measurement of discriminant validity using the Fornell-Larcker criterion. Attitude (ATT), household size (HH), income, and marital status have perfect discriminant validity, with a threshold value of 1.00. For other constructs, values range between 0.799 to 0.953, showing an acceptable discriminant validity. Overall, all values are beyond the threshold of 0.70, implying a significant path in the model (Hair et al. 2024). Thus, each construct is distinct and exhibits stronger internal correlations, reinforcing construct differentiation and theoretical consistency. On the other hand, Table 4 presents another measurement of discriminant validity using the HTMT ratio. The recommended value of the HTMT ratio is equal to or below 0.90 (Henseler et al. 2015). Ratios range from 0.017 to 0.729, which are all less than 0.9, thus implying that the two constructs, e.g., Educ Level and ATT, are distinct and that discriminant validity has been achieved.

Socio-economic constructs like household size, income group, marital status, and education level also showed consistent positive loadings to ATT, PN, PBC, SFP, and PI. These cross-loading results indicate strong contributions of each indicator to its respective construct, affirming the constructs' distinctiveness within the model.

Table 2. Measurement of discriminant validity using the Fornell-Larcker Criteria.

	ATT	Educ Level	EA	HH size	Income	IU	Marital Status	PBC	PN	PI	SN	SFP	WTP
ATT	0.880												
Educ Level	0.173	**1.000**											
EA	0.385	0.080	0.831										
HH size	0.052	-0.141	0.028	**1.000**									
Income	0.106	0.254	0.048	0.022	**1.000**								
IU	0.616	0.132	0.341	0.006	0.059	0.908							
Marital Status	0.034	-0.013	0.034	0.079	-0.019	0.027	**1.000**						
PBC	0.604	0.126	0.224	0.008	0.158	0.466	-0.025	0.799					
PN	0.595	0.151	0.402	0.075	0.123	0.600	-0.047	0.428	0.953				
PI	0.624	0.074	0.359	0.016	0.089	0.661	0.063	0.565	0.529	0.815			
SN	0.601	0.082	0.177	0.035	0.183	0.452	0.043	0.660	0.372	0.591	0.868		
SFP	0.659	0.168	0.384	0.035	0.042	0.665	0.063	0.400	0.710	0.617	0.435	0.837	
WTP	0.224	0.027	0.090	0.002	0.038	0.270	0.027	0.323	0.136	0.442	0.338	0.360	0.887

Table 3. Measurement of discriminant validity using the Heterotrait-monotrait (HTMT) Ratio per construct.

	ATT	Educ Level	EA	HH size	Income	IU	Marital Status	PBC	PN	PI	SN	SFP	WTP
ATT													
Educ Level	**0.184**												
EA	0.443	**0.087**											
HH size	0.059	0.141	**0.029**										
Income	0.113	0.254	0.057	**0.022**									
IU	0.667	0.137	0.383	0.017	**0.061**								
Marital Status	0.034	0.013	0.038	0.079	0.019	**0.050**							
PBC	0.729	0.142	0.312	0.016	0.177	0.555	**0.079**						
PN	0.655	0.159	0.463	0.079	0.130	0.656	0.050	**0.519**					
PI	0.692	0.079	0.431	0.028	0.092	0.715	0.069	0.713	**0.576**				
SN	0.696	0.089	0.229	0.046	0.201	0.512	0.049	0.842	0.428	**0.692**			
SFP	0.729	0.177	0.452	0.047	0.054	0.725	0.067	0.500	0.790	0.685	**0.505**		
WTP	0.240	0.060	0.125	0.075	0.039	0.285	0.035	0.452	0.133	0.521	0.383	**0.399**	

Table 4 presents the PLS-SEM algorithm and bootstrapping report showing the direct and indirect effects of each construct on IU and the p-values. PI and SFP show a direct and significant effect on intention to use, with p-values of 0.000 and 0.009, respectively, indicating that product-related and institutional factors are reliable predictors of IU. While the moderating effect for marital status x WTP, household size x ATT, and income x SN indicates that socio-economic variables moderate the relationships. Lastly, educational level shows a significant indirect effect on IU with a p-value of 0.036, suggesting a limited effect on IU.

Table 4. PLS-SEM algorithm model and bootstrapping report.

Relationship	X	x̄	STDEV	Path Coefficients	T statistics	P values
Direct effects						
PI → IU	0.269	0.262	0.073	0.260	3.664	0.000
SFP → IU	0.313	0.336	0.119	0.359	2.624	0.009
Educ Level → SFP	0.179	0.180	0.061	0.179	2.927	0.003
Marital Status x WTP → IU	-0.229	-0.206	0.104	0.248	2.210	0.027
HH size x ATT → IU	0.273	0.228	0.105	0.261	2.613	0.009
Income x SN → IU	0.196	0.207	0.072	0.193	2.704	0.007
Indirect effects						
Educ Level → IU	0.114	0.119	0.054	-0.007	2.100	0.036

X = observation

x̄ = sample mean

Figure 3 presents the graphical presentation of the algorithm from Table 2, which shows the interaction between constructs from the expanded TPB and NAM on IU. Both SFP from NAM and PI from TPB are in orange markings, showing the direct effect on IU. While ATT, SN, and WTP from TPB are in green markings have significant moderating effects on IU through WTP, ATT, and SN constructs. Interestingly, education level has a direct effect on both SFP and IU. Education provides consumers with information on the consequences of plastic pollution, which may shape the consumer's preferences and behavior, suggesting the inevitable role of education as a catalyst for change. For this study, this means that well-informed consumers can lead to active participation in adherence to new policy and the adoption of sustainable shopping practices over time.

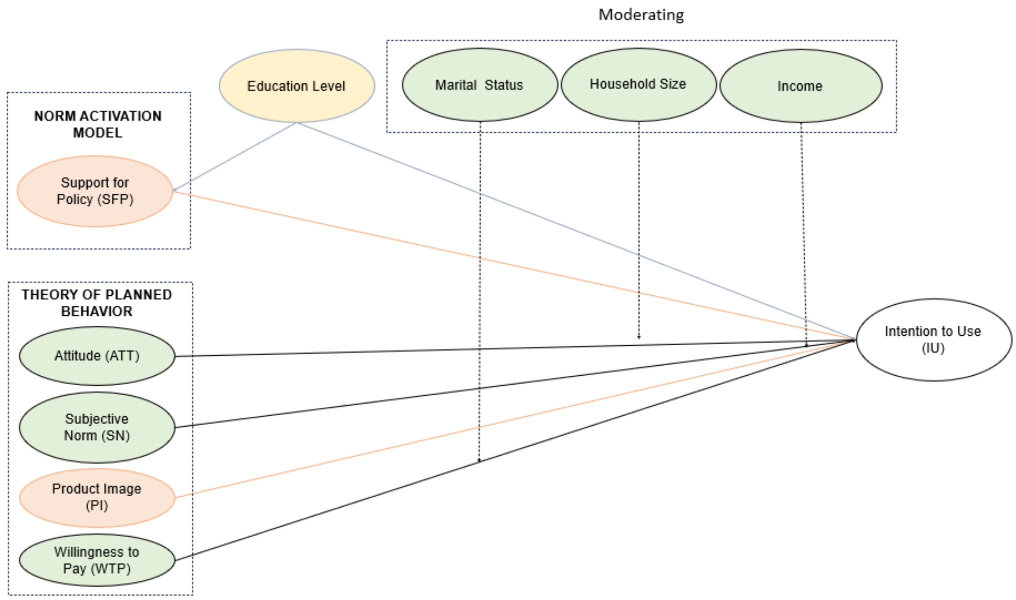

Figure 3. The algorithm of constructs from the expanded TPB and NAM affecting IU.

Table 5 presents the variance inflation factor (VIF) obtained from the collinearity diagnostics. VIF in the study ranges between 1.154 to 4.718, and within the threshold, indicating no significant collinearity issues. However, EA3, SFP2, SFP3, ATT2, ATT3, WTP2, IU2, IU3, and IU4 exhibit moderate multicollinearity but within the acceptable range. The indicators from each construct are sufficiently independent of each other, dependable, and do not redundantly measure the same underlying dimension of the theoretical underpinnings of NAM and TPB.

Table 5. Outer and Inner VIF values from the collinearity diagnostics.

Theory	Construct	Indicator	VIF	
NAM	EA	EA1	2.675	No serious multicollinearity
		EA2	2.692	No serious multicollinearity
		EA3	**3.010**	**Moderate multicollinearity**
		EA4	1.265	No serious multicollinearity
	PN	PN1	2.996	No serious multicollinearity
		PN2	2.996	No serious multicollinearity
	SFP	SFP1	2.069	No serious multicollinearity
		SFP2	**4.062**	**Moderate multicollinearity**
		SFP3	**3.032**	**Moderate multicollinearity**

Theory	Construct	Indicator	VIF	
		SFP4	2.039	No serious multicollinearity
TPB	ATT	ATT1	2.755	No serious multicollinearity
		ATT2	**3.268**	**Moderate multicollinearity**
		ATT3	**3.137**	**Moderate multicollinearity**
		ATT4	2.421	No serious multicollinearity
	SN	SN1	2.120	No serious multicollinearity
		SN2	2.241	No serious multicollinearity
		SN3	1.720	No serious multicollinearity
	PBC	PBC1	1.907	No serious multicollinearity
		PBC2	1.921	No serious multicollinearity
		PBC3	1.154	No serious multicollinearity
	WTP	WTP1	2.247	No serious multicollinearity
		WTP2	**3.149**	**Moderate multicollinearity**
		WTP3	2.163	No serious multicollinearity
	PI	PI1	2.355	No serious multicollinearity
		PI2	2.301	No serious multicollinearity
		PI3	2.339	No serious multicollinearity
		PI4	2.239	No serious multicollinearity
		PI5	1.498	No serious multicollinearity
	IU	IU1	2.792	No serious multicollinearity
		IU2	**4.039**	**Moderate multicollinearity**
		IU3	**4.718**	**Moderate multicollinearity**
		IU4	**3.796**	**Moderate multicollinearity**

The model fit from the PLS SEM was assessed using the two indices, SRMR and NFI. The model yielded an SRMR value of 0.274 (Table 6), which is above the threshold of 0.08 (Hu and Bentler 1999), and an NFI value of 0.611, below the accepted benchmark (Bentler and Bonnet 1980). These values suggest that the model could be further improved and that the proposed expanded framework may not adequately capture the underlying relationships. The model fit indicates some divergence between the proposed expanded framework and the observed data. Specifically, the high SRMR and low NFI values suggest that while the framework incorporates theoretically grounded constructs, the relationship hypothesized may not fully capture the complexity of intention to use eco-friendly reusable shopping bags in the Iligan context. However, this does not undermine the relevance of constructs such as PN, ATT, SN, PBC, EA, SFP, WTP, and PI, instead highlights that their unique interactions may be context dependent. Thus, the findings deem for refining causal pathways and exploring additional contextual variables that may influence behavioral intention, particularly regarding the heterogeneity of consumer groups.

Several factors may help explain the weaker performance of the expanded TPB-NAM model, suggesting that its predictive capacity is partly structured by contextual misalignment. While studies of Yang et al. (2018) and Setiawan et al. (2021) may have applied NAM and TPB to predict pro-environmental behavior in other Asian regions, Iligan City represents a different landscape where strong policy interventions and readily available shopping bag alternatives is contributory. In this study, the role of institutional authority and regulatory signals direct individual attitudes and norms, consistent with Sprantz et al. (2018) who highlights the decisive role of policy and shaping pro-environmental behavior. The extent and selection of constructs included in the model may also have contributed to its mixed performance of the expanded model. With nine constructs and multiple hypothesized paths, the potential for overlapping effects or weak causal linkages is high (Nugraha and Soelasih 2023; Zaman et al. 2023). This suggests that some theoretically sound constructs have limited predictive power across contexts. Moreover, focusing exclusively on women may have caused sample specificity. While evidence suggests that women are more likely to engage in sustainable consumption lifestyles (Sahin et al. 2012), their adoption of eco-friendly bags may depend on product attributes and market conditions, which aligns with Nguyen et al. (2022) showing that product attributes and accessibility prevail over psychological factors. Thus, these findings suggest that while TPB and NAM remain strong theoretical foundations, their explanatory power can vary across context. It is then deemed to integrate institutional, demographic, and market-level subtleties into future model refinements.

Table 6. Summary of indices for model fit.

	Saturated model	Estimated model	
SRMR	0.062	0.274	Does not meet threshold (Above threshold)
NFI	0.761	0.611	Does not meet threshold (Below threshold)

Accepted threshold for SRMR < 0.08-0.10
Accepted benchmark for NFI > 0.90

Model and construct analysis. Table 7 presents the path coefficients from the bootstrapping report with remarks on direct and indirect effects of constructs on consumers' IU. The hypotheses presented in the table demonstrate statistically significant paths at 5% level. PI has a strong and positive influence on IU with a path coefficient of 0.260, indicating that consumers are more likely to use eco-friendly reusable shopping bags when these are perceived as stylish and durable, aligning with Chuang and Ma (2001), but contradicting Yeow et al. (2014), who suggest that inconvenience shapes consumer behavior. SFP is the strongest predictor of IU with a path coefficient of 0.359, indicating that the enforcement of a single-use plastic ban reinforces consumer preference for reusable bags, aligning with Patterson et al. (2017). Education level's direct effect on IU is weakly negative (path coefficient = 0.007). suggesting that while education promotes awareness, it does not necessarily result in behavioral shifts, which other factors like lifestyle and social status may influence (Afroz et al.2009). The analysis also found significant moderating effects of marital status on WTP, and household size on ATT indicate IU of eco-friendly shopping bags, aligning with (Roberts 1996; Barr et al., 2011).

Path coefficients and IU model fit. The path coefficients highlight several key constructs, with SFP (path coefficient = 0.359) and PI (path coefficient = 0.260) having the strongest direct effects on IU. This suggests that external factors like institutions and perceived quality have a stronger influence than internal psychological factors. Chatrakamollathas and Nuengchamnong (2024) similarly found that institutional support and product attributes are significant determinants of the adoption of eco-friendly bags in emerging markets. However, with the expanded framework adopted in this study, the findings showed that external drivers interact with socio-demographic moderators such as household size, marital status, and income, highlighting the need for context-specific intervention. The significant negative path from education level to IU (path coefficient = 0.179) is particularly revealing. It challenges the linear assumption of TPB where knowledge is a direct precursor to intention. The significant moderating effects provide deeper insights into the complex expanded TPB-NAM framework. The interaction of marital status and WTP (path coefficient = 0.248) supports the TPB's emphasis on perceived behavioral control, showing that married individuals with limited household budgets are motivated by the long-term cost-saving aspect of reusable bags, aligning with other studies on household consumption patterns. Similarly, significant interactions between HH size and ATT (path coefficient = 0.261) indicate that larger households, driven by a higher volume of waste, led to a stronger positive attitude towards reusable bags. This aligns with NAM's underpinning that sense of personal obligation is activated by awareness of consequences, which is particularly relevant in Iligan's plastic waste problem. The moderating effects were significant reinforces the direct paths in the model were likely oversimplified. The poor model fit does not negate the construct's relevance but indicates that the relationships are not universal and have limited generalizability. Rather, they are highly dependent on socio-economic contexts, which are consistent with existing local statistical reports and studies.

Table 7. Bootstrapping report with remarks.

Relationship	Path Coefficients	T statistics	P values	Remarks
Direct Effects				
PI → IU	0.260	3.664	0.000	Significant
SFP → IU	0.359	2.624	0.009	
Educ Level → SFP	0.179	2.927	0.003	
Marital Status x WTP → IU	0.248	2.210	0.027	
HH size x Att → IU	0.261	2.613	0.009	
Income x Sub Nor → IU	0.193	2.704	0.007	
Indirect Effects				
Educ Level → IU	-0.007	2.100	0.036	Significant

Socio-economic profile of the respondents. Table 8 presents the counts and percentage of respondents in terms of education level, marital status, income group, and household size. The profile of respondents shows a group of shoppers predominantly composed of well-educated single women from low-middle income households with 3 to 5 members, which may provide an insight to the poor model fit. The high education level suggests a baseline of environmental awareness, which may not be the primary driver of behavior as the model hypothesizes. Similarly, the significant portion of single women and those with low-middle income may have different motivations and constraints (i.e., financial capability) of which the constructs from the expanded NAM and TPB may inadequately capture. Also, the findings that most respondents have 3 to 5 members in their households may suggest minimal influence on shopping practices and directly undermine the potential for larger households to be a significant motivator of a sustainable shopping lifestyle. For the socio-economic profile, the model's poor model fit may be due to its inability to attribute for the specific, and possibly conflicting, motivation and constraints unique among women shoppers.

Table 8. Socio-economic profile of the study participants.

	Category	Count	
Education Level	No schooling completed	2	1%
	Some grade school completed	14	5%
	Some high school, no diploma	36	14%
	High school graduate, diploma or the equivalent	45	18%
	Some college credit, no degree	50	19%
	Bachelor's degree	74	29%
	Master's degree	33	13%
	Doctorate Degree	3	1%
			100%
Marital Status	Single	146	57%
	Married	111	43%
			100%
Income Group	High income	5	2%
	Upper-middle income	68	26%
	Low-middle income	136	53%

	Category	Count	
	Low income	48	19%
			100%
Household Size	2 members	21	8%
	3 to 5 members	148	58%
	6 more members	88	34%
			100%
Age	15 to 20 years old	47	18%
	21 to 30 years old	75	29%
	31 to 40 years old	46	18%
	41 to 50 years old	41	16%
	51 to 60 years old	45	18%
	61 years old and above	3	1%
			100%
Employment Status	Employed	124	48%
	Unemployed	31	12%
	Student	70	27%
	Self-employed	32	12%
			100%

Table 9 presents a summary of themes from the qualitative analysis showing interrelated dimensions of sustainable shopping practices particularly on the intention to use eco-friendly shopping bags. This provides crucial insights regarding the model obtained from SEM by highlighting the key terms associated with the constructs from each theory that were enriched by the participant's actual experiences. The participants consistently emphasized their preference for "recyclable bags" due to durability, aesthetics, and affordability, suggesting that PI is not just functional utility but also social value and long-term effectiveness. This supports the model that highlights the direct effect of PI on IU as shoppers perceived eco-friendly bags as practical and socially desirable alternatives than single-use plastic bag. Also, participants highlighted the role of SFP, particularly local ordinances and firm-level initiatives were effective in shaping pro-environmental behavior. Participants affirmed the importance of targeted awareness campaigns and education to enhance environmental knowledge resulting to increase acceptance of sustainable practices. Notably, there were also significant behavioral barriers like "forgetfulness" and "impromptu shopping" that were not represented in the constructs of the expanded TPB and NAM but are common challenges.

Table 9. List of themes from the qualitative analysis mapped within the expanded framework.

List of Themes and Number of Codes	Framework	Interpretation from Participant's Narratives
Preference and Perception (3), Practicality and Usability (1), Cost Sensitivity (1), Economic Considerations (1), Social Influence and Pressure (2), Practicality and Convenience (2), Financial Influence (2), Marital Status and Family Influence (2), Income-Driven Behavior (2)	TPB (16)	ATT: Codes from "Preference and Perception" and "Economic Considerations" suggest shoppers prefer eco-friendly bags not only for durability and aesthetics but also for long-term value. This supports the SEM finding that PI has significant direct effect to IU. SN: Codes from "Social Influence and Pressure" and "Marital Status and Family Influence" highlights the role of family members, peers, and household members in shaping pro-environmental behavior. This supports the moderating effects of marital status and household size in the model, and where social context alters the strength of predictors. PBC: Codes from "Practicality and Usability", "Practicality and Convenience", "Financial Influence", and "Income-driven Behavior" suggest the practical and financial constraints that influence or affect IU eco-friendly shopping bags. This reinforces the model that income moderates IU, while suggesting that affordability and convenience influence perceived control.
Environmental Policy Support (2), Behavioral and Policy Change (3), Policy Influence (16), Educational Influence (17)	NAM (38)	PN: Codes from "Behavioral and Policy Change" indicates that shoppers develop this sense of obligation to develop pro-environmental behavior when institutional policies are in place, suggesting that external cues reinforce moral responsibility.

List of Themes and Number of Codes	Framework	Interpretation from Participant's Narratives
		EA: The strong representation of "Education and Influence" indicates that awareness of environmental issues is influence by formal education and campaigns. This supports the pathway where education level predicted SFP, highlighting awareness as a precursor to norm activation and policy adherence. SFP: Codes from "Environmental Policy Support" and "Policy Influence" indicates that participants strongly perceived ordinances and enforcement as effective approach for influencing behavior. This supports the model that SFP has significant direct effect in IU, confirming that institutional support is the strongest driver of pro-environmental behavior in this context.

While the model showed limitations in overall fit, the notable and compelling findings from this mixed method provides valuable insights into the complexity of pro-environmental behavior. Zaman et al. (2023) and Cam et al. (2025) emphasized the consumer-level determinants such as attitudes, norms, or ethical identity, but this study identified that institutional factors (i.e., support to policy), product attributes (i.e., image, durability, prestige), and demographic characteristics (i.e., income, marital status, household size) interact in ways that conventional models tend to oversimplify. The quantitative-qualitative approach strengthens the findings by contextualizing the model with the narratives that highlight the importance of habitual behavior (Muposhi et al. 2021), policy enforcement and institutional trust (Spranz et al. 2018; Wang et al. 2023), and market accessibility (Nguyen at al. 2022). The expanded TPB-NAM framework contributes to the science-based evidence that the intention-behavior gap in pro-environmental behavior is understood through a multi-level lens to account for psychological, structural, and socio-economic factors that should be simultaneously analyzed. Future research direction may include the refinement of the models that incorporate habits, enforcement mechanisms, and social group interactions using longitudinal or system-based approaches to account for the interaction between consumers' motivation, institutions, and market dynamics.

CONCLUSION

The intention to use eco-friendly reusable bags is shaped by a complex interaction of psychological, social, and economic factors drawn from the expanded TPB and NAM frameworks. The model provides two important insights: 1) the path coefficients showing SFP from NAM and PI from TPB have direct effects on IU, suggesting that external factors, e.g., institutional and perceived quality, significantly affect more than internal psychological factors; and 2) the moderating effects of marital status and household size suggest deeper insights into the complex expanded TPB-NAM framework. The qualitative findings and socio-economic characteristics provide a critical context with how PI, SFP, and education level have a significant direct effect on IU, while income, household size, and marital status have significant moderating effects. With this, one-size-fits-all approach is ineffective for shaping pro-environmental behavior among consumers in Iligan setting. An innovative and future-thinking approach is required to translate these findings into effective policy action, such as tiered incentive schemes and "green days". However, such policy should be continuously refined based on income groups along with targeted campaigns in various media platforms to address the persisten gaps in environmental awareness highlighted by Ogiemwonyi (2024) and Sánchez et al. (2016). Lastly, future research opportunities should include and aim to strengthen the theoretical foundation with appropriate constructs and measurements. Multidisciplinary frameworks, e.g., system analysis, theory of change, should be adopted and continuously explored to understand and appreciate the interplay of psychological and social aspects without neglecting rigor and external validity. Consequently, this will develop a robust and replicable model that can estimate, predict, and understand consumer behavior patterns. This study is partly relevant, but with other complementing transdisciplinary approaches, the findings may contribute to the existing evidence of policy gaps and innovatively address the plastic waste problem before reaching the tipping point of irreversible ecological consequences.

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SALINE HOT SPRING WATER TREATMENT TO CONTROL POST-HARVEST FUNGAL DISEASE ON MANGO CV. 'IRWIN'

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ABSTRACT

Japanese Mango cv. 'Irwin' is affected by two post-harvest diseases, anthracnose and stem-end rot, which are currently managed by chemical applications. Although effective, misuse of pesticides may lead to damage to the environment, human health, and potential resistant development by pathogens. Due to these, new strategies need to be developed for the effective management of these diseases. In this study, saline hot spring water (SHSW) was evaluated as a medium for hot water treatment to control post-harvest diseases in inoculated and non-inoculated mangoes while maintaining fruit quality in terms of weight loss, fruit hardness, peel color, and soluble sugar content. Non-inoculated mangoes harvested in Miyako Island, Japan, were dipped in SHSW at 60 °C for 1 min and sterilized distilled water (SDW) at the same conditions, cooled under running tap water for 10 min, and then stored at 25-27°C for 12 days in June 2019. Treated mangoes did not show symptoms of anthracnose at 6 days post-treatment but showed mild symptoms of anthracnose at 12 days post-treatment, while mild symptoms of stem-end rot appeared from 6 days post-treatment. The hot treatment with SHSW did not negatively affect the mango fruit quality compared to the control and SDW after 6 days. Furthermore, fungi causing anthracnose and stem-end rot were inhibited in inoculated mangoes followed by treatment at 60 °C for 1 min and stored at 25-27 °C. Hot water treatments with SHSW at 60 °C for 1 min effectively inhibited the quiescent (non-inoculated) and superficial (inoculated) infections of anthracnose without affecting fruit quality but these did not inhibit the quiescent infection of stem-end rot.

Key words: Anthracnose, natural resource, physical control, Okinawa, stem-end rot.

INTRODUCTION

Mango (*Mangifera indica* L.) is a tropical and subtropical tree whose climacteric fruit is appreciated worldwide. In 2019, Japan produced approximately 3,519 tons of mango fruit (Portal Site of Official Statistics of Japan 2022), mainly cv. 'Irwin' in greenhouse conditions in the southern prefectures of Kagoshima, Miyazaki, and Okinawa.

In Japan, as in other areas, mango fruit is affected by post-harvest diseases, principally anthracnose, caused by *Colletotrichum gloeosporioides* (Penz.) Penz. & Sacc. and *Colletotrichum* *acutatum* J.H. Simmonds (Taba et al. 2004; Takushi et al. 2013a; Takushi et al. 2013d), and stem-end rot (SER), caused *by Lasiodiplodia theobromae sensu stricto* (Pat.) Griffon & Maubl. (Takushi et al. 2013c), *Neofusicoccum parvum* (Pennycook & Samuels) Crous, Slippers & A.J.L. Phillips (Takushi et al. 2017), and *Diaporthe* sp. (Ajitomi et al. 2019).

The use of fungicides during the preharvest stage of cultivation is the primary method for controlling both diseases in Japan (Takushi et al. 2013b; Takushi et al. 2018), with six active ingredients (captan, iminoctadine, fludioxonil, azoxystrobin, kresoxim-methyl, and mancozeb) approved for the control of anthracnose, and three active ingredients (procymidone, copper sulfate, and *Bacillus subtilis* strain Y1336) approved for the control of SER (MAFF 2022). However, some of these fungicides may have side effects on the environment and consumers' safety (Brandhorst and Klein 2020; Brock et al. 2020; Ostby et al. 1999), including the potential development of resistance to these active ingredients by fungal causal agents (Al-Jabri et al. 2017; Chen et al. 2020; Dowling et al. 2020; Rehman et al. 2015; Schnabel et al. 2021).

As an alternative, physical control techniques such as hot water treatments have been developed as a postharvest treatment for fungal control and insect disinfestation (Asio and Cuaresma 2016), which varies in temperature and time of dipping depending on the mango variety and fruit size (Arauz 2000), showing an efficacy of 60-80% for control of anthracnose (McGuire 1991), while improving general appearance of fruits (Prusky et al. 1999). Immersion time can be 1h or more when the temperature is below 50 °C, while treatments can be less than 4 min at temperatures above 50°C (Lurie 1998). Along with the previous, protocols were developed for each case, for example, mango cv. ´Sindri´ had been treated at 45 °C for 75 min (Anwar and Malik 2007), cv. ´Keitt´ at 50 °C for 30 min (Djioua et al. 2008) and 52 °C for 5 min (Kumah et al. 2011), cv. ´Carabao´ at 47-48 °C for 15 min (Kitma and Esguerra 2009), 53 °C for 20 min (Alvindia and Acda 2015), 55°C for 10 min (Montecalvo et al. 2019), and 60 °C for 35 sec (Esguerra et al. 2004, Pasilan et al. 2020), cv. ´Kensington´ at 53 °C for 5 min followed by vapor heat at 47 °C for 15 min (Jacobi and Giles 1997), cv. ´Diab´ at 50 °C for 10 min (Yousef et al. 2019), cv. ´Tommy Atkins´ at 50 °C for 3 min (Gutiérrez-Alonso et al. 2004), and cv. ´Ataulfo´ at 46 °C for 70 min (Ochoa-Rosas et al. 2020).

In the case of Japanese mango, cv. ´Irwin´ was treated at 52°C for 60-90 min for inhibition of anthracnose on inoculated mangoes, without affecting the fruit quality (weight loss, moisture content and soluble solid content) for 14d when stored at 13°C and 90% relative humidity, showing tolerance to heat injury (Hasbullah et al. 2001); and at 60°C for 40 sec for inhibition of anthracnose on inoculated mangoes, being as effective as treatment at 52°C for 20 min followed by cooling for 10 min, showing mild symptoms after 4d (Teruya et al. 2012). While both studies clearly demonstrated the effectiveness of hot water treatments on mango anthracnose in Japan, neither have reported the effects of hot water treatments on quiescent infections of anthracnose, which occurs in Japanese mango during May and June (De la Cruz Padilla et al. 2020), nor on direct contact and quiescent infections of SER in Japanese mango cv. "Irwin".

Although the hot water treatment's effectiveness, the treatment requires heating of the water, which could become prohibitive with the rising cost of oil and liquefied petroleum gas in international markets, as the local electricity generation in the Okinawa Prefecture relies in fossil fuels (Ministry of Economy, Trade and Industry-Agency for Natural Resources and Energy 2022). Due to this, the use of saline hot spring water (SHSW), a local natural resource, is proposed for the implementation of hot water treatments in Japanese mango, for which there is no previous study on either its effects on the fruit quality and the disease inhibition of postharvest diseases of mango.

In this study, the effect of hot water treatment (by dipping) using SHSW, a natural resource in Miyako Island, Okinawa Prefecture, was evaluated on the inhibition of non-inoculated and inoculated post-harvest fungal pathogens (anthracnose and SER) and mango fruit quality.

MATERIALS AND METHODS

Saline hot spring water. SHSW was collected from a pilot well in Bora, Gusukube in Miyako Island, Okinawa Prefecture, Japan in 2019, and stored in the lab for later use. According to the "Document of Mineral Spring Analysis No.2014-00145-C01", conducted following the "Standard Methods for Analysis for Mineral Springs" by the Ministry of Environment (2014) of Japan, the *in-situ* temperature of the HSW was 68.7 °C, with an *in-situ* pH of 7.3 and a laboratory pH of 7.2 at 21.6 °C. Based on the chemical composition of the collected HSW and following the criteria of the Ministry of Environment of Japan, the spring water was categorized as "Sodium chloride high salt hot spring", in which the quantity of dissolved substances (excluding gases) exceeds 1,000 mg in 1kg of spring water, and the main anion is chloride ion (Cl^-). The total cation content was 9,920 mg/kg, predominantly sodium ion (Na^+) with 9,270 mg/kg, and the total anion content was 15,855.7 mg/kg, primarily Cl^- with 15,300 mg/kg.

Mango fruit. For the experiments, mature and healthy-looking mangoes cv. 'Irwin' harvested in June 2019 on Miyako Island, Okinawa Prefecture, were used, 60 for hot water treatments in non-inoculated mangoes, and 27 for inoculation followed by treatments.

Pathogens. Four fungal isolates were selected for inoculation (Fig. 1): three *Colletotrichum* spp. isolates (CG1, CG2, and CG3) and one *Lasiodiplodia* spp. isolate (LT). *Colletotrichum* isolates were obtained from anthracnose lesions from 3 different mango fruits collected in Miyako Island, while *Lasiodiplodia* isolates were obtained from a mango fruit showing advanced symptoms of SER. Slices of lesions were put on 1.5% water agar plates and incubated for 1-2 days. Single hyphae growing from the slices were transferred to 2% malt extract agar medium and incubated for 7 days at 27 °C. For the inoculation assay, the fungal isolates were incubated at 27 °C in potato dextrose agar (PDA) for a week.

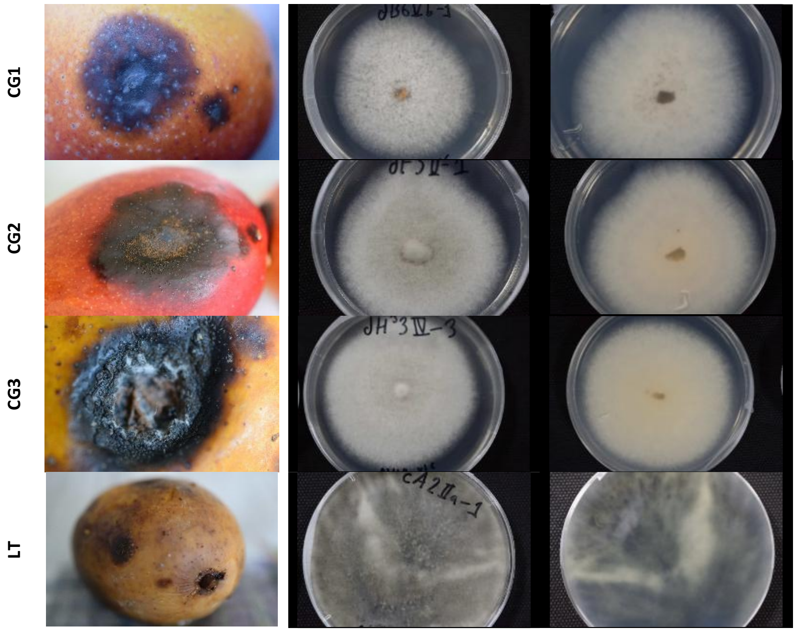

Figure 1. Fungal isolates from mangoes harvested in Miyako Island, Japan. At left, the sample materials from which the fungi were isolated. At center and right, the front and behind of each fungal isolate in PDA plates after 7d at 27°C. CG1, CG2, and CG3 correspond to three different isolates of *Colletotrichum* spp., while LT corresponds to an isolate of *Lasiodiplodia* spp.

Hot water treatment of non-inoculated mangoes for disease inhibition and fruit quality. The mangoes were divided into five groups (12 fruits/replicates per group): non-treated (control), SHSW at 60 °C for 60 sec followed by cooling under running tap water (wc = with cooling) for 10 min (SHSW 60 °C wc), sterile distilled water (SDW) at 60 °C for 60 sec followed by cooling for 10 min (SDW 60 °C wc), SHSW at room temperature (RT, 26~28 °C) for 10 min (SHSW RT) and SDW at room temperature for 10 min (SDW RT).

For the hot water treatments, SHSW and SDW were heated in a water bath (IWAKI Thermo Bath THB-6D, 20cm diameter x 12cm depth) at 60±0.2 °C. The surface temperature of 5 hot-treated mangoes with HSW and SDW was measured at three sections (two lateral and the stem area) with a handheld infrared thermometer at four timepoints: before treatments, just after treatment, 10 min, and 60 min following the treatment. The mango fruits were dipped into hot water for 60 sec without water circulation. After treatments, the mangoes were stored at 26-28 °C in different boxes sorted by the treatment. Mangoes were evaluated for disease severity according to "Evaluation of disease severity", and for fruit quality according to "Evaluation of mango fruit quality".

Disease severity. Disease severity was evaluated using a 5-point scale, where: 0 = no symptoms, 1 = less than or equal to 10% of the diseased area, 2= 11 ~ 25% of the diseased area, 3 = 26 ~ 50% of the diseased area, and 4 = more than 50% of the diseased area. The mango fruit surface was divided into three sections for assessment: two longitudinal faces (X, Y), corresponding to the mango fruit cheeks, and one lateral face (Z), corresponding to the stalk or stem of the fruit. Six mangoes per treatment were selected for the evaluation, and the value was assessed at 6 days and 12 days after treatments.

Mango fruit quality.

Weight loss. The weight of six randomly selected mangoes of each group was measured at day 0 using a digital balance, with weight values expressed in grams (g). Later, 3 of those selected mangoes were measured 6 days after treatments, and the remaining 3 were measured at 12 days.

From the measurements, the percentage of weight loss (WL [%]) was computed using the following formula:

$$WL(\%) = \frac{(W_0(g) - W_d(g)) * 100}{W_0(g)},$$

where W_0 is the initial weight at day 0, and W_d is the weight at day 6 or 12.

Fruit hardness. Fruit hardness was measured using a hand-held fruit hardness tester (Fujiwara Scientific Fruit Hardness Tester KM-1, Tokyo, Japan) at 0, 6 and 12 days after treatments. Three fruits per treatment were selected and 4 measures (in kg/cm^2) were taken from the area near the equator of each fruit.

Peel color differences. Peel color was determined using a colorimeter (Konica Minolta Chroma Meter CR410, Tokyo, Japan) under the CIELAB color space configuration (where L represents the luminance, a* denotes the red/green hue, and b* is the yellow/blue hue). The values were measured just after the treatment and 6 days after treatment. Later, peel color differences were calculated using the following formulas: $\Delta L = L - L_0$, $\Delta a^* = a^* - a_0^*$ and $\Delta b^* = b^* - b_0^*$. In which L_0, a_0^*, and b_0^* are the values after treatments, and L, a^* , and b^* are the values at 6 days. The total color difference (ΔE*) was calculated using the following formula:

$$\Delta E^* = \sqrt{(\Delta L)^2 + (\Delta a^*)^2 + (\Delta b^*)^2}.$$

The CIELAB values were then converted into LCh color space values for chroma (C^*) and hue (h) using the following formulas:

$$C^* = \sqrt{(a^*)^2 + (b^*)^2} \text{ and}$$

$$h = \left(\text{arctan}\left(\frac{b^*}{a^*}\right) \Rightarrow \text{arctan}\left(\frac{b^*}{a^*}\right) \geq 0\right) \vee \left(arctan\left(\frac{b^*}{a^*}\right) + 360° \Rightarrow arctan\left(\frac{b^*}{a^*}\right) < 0\right).$$

The difference between each measure of C^* and h and the initial values were calculated as: $\Delta C^* = C^* - C_0^*$ and $\Delta h = h - h_0$.

Soluble sugar content. The soluble sugar content (°Bx) was measured from the mango fruit pulp juice with an analog handheld refractometer. Three fruits per treatment were assessed at 6 days after treatment, and the remaining were assessed at 12 days after treatment.

SHSW treatment of mango fruits inoculated with *Colletotrichum* spp. and *Lasiodiplodia* spp.. Twenty-seven mangoes were divided into 9 groups (3 fruits/replicates per group): one control consisting on mangoes treated by dip in hot water treatment (HWT) at 60 °C for 1 min with SHSW, 4 groups of mango fruits inoculated with post-harvest disease causal agent followed by HWT with SDSW (T1: CG1+HWT, T3: CG2+HWT, T5: CG3+HWT and T7: LT+HWT), and 4 groups of mango fruits with inoculation only (T2: CG1, T4: CG2, T6: CG3 and T8: LT).

The mangoes were inoculated by attaching two PDA fungal plugs of approximately 1 cm diameter for 24h on the mango fruit surface. In the case of the control group, non-inoculated PDA plugs were attached. Depending on the treatment group, the mangoes were soaked in SHSW at 60 °C for 1 min, without subsequent cooling. After the treatments, the mangoes were stored in boxes separated by treatment groups at 25~27 °C. The weight of the fruits of each mango fruit was assessed at 0 days, 8 days, and 16 days after treatments, from which weight loss (%) at 8 days and 16 days was calculated. Each disease spot in the inoculated areas was measured at 8 and 16 days after treatment. The fungi were reisolated from the diseased spots to fulfill Koch's postulates.

Statistical analysis. The data were analyzed using the Real Statistics Resource Pack (release 7.3) (Zaiont, 2020). The Shapiro-Wilk and D'Agostino-Pearson tests were used to determine whether the data were normally distributed. For the normally distributed datasets, parametric tests were applied: one-way ANOVA for single-factor comparisons and two-way ANOVA for two-factor comparisons, both followed by Tukey's HSD test. For the non-normally distributed datasets, non-parametric tests were applied: the Kruskal-Wallis' test and Dunn's test for single-factor comparison, and the Scheirer-Ray-Hare test and Tukey's HSD test for two-factor comparisons.

RESULTS AND DISCUSSION

Fungal pathogens in inoculated mango fruits. The inoculated and treated mangoes (T1, T3, T5, T7) were less affected by the pathogens than the inoculation-only mangoes (Table 1, Fig. 2 and Fig. 3), where T4 (CG2) and T8 (LT) had the largest disease spots after 8 days. T8 exhibited the highest weight loss and was significantly different from the other samples after 16 days. Measurements of the disease spots were not taken on T8 fruits at 16 days due to decay. In the CG-inoculated groups, the disease spot size (Table 1 and Fig. 3) was larger in the T4 (CG2) and T6 (CG3) fruits than in the T2 (CG1) fruits 16 days after treatments. The disease spot left by the pathogens in the hot water treated mangoes did not grow any further, suggesting that the inoculated pathogens were inhibited by the hot water treatment (Fig. 3).

Figure 2. Inoculated mangoes followed by hot water treatments (HWT) with SHSW. Control (HWT), inoculation followed by HWT (T1: CG1+HWT, T3: CG2+HWT, T5: CG3+HWT, and T7: LT+HWT), and inoculation-only (T2: CG1, T4: CG2, T6: CG3, and T8: LT) mangoes after 7 and 14 days.

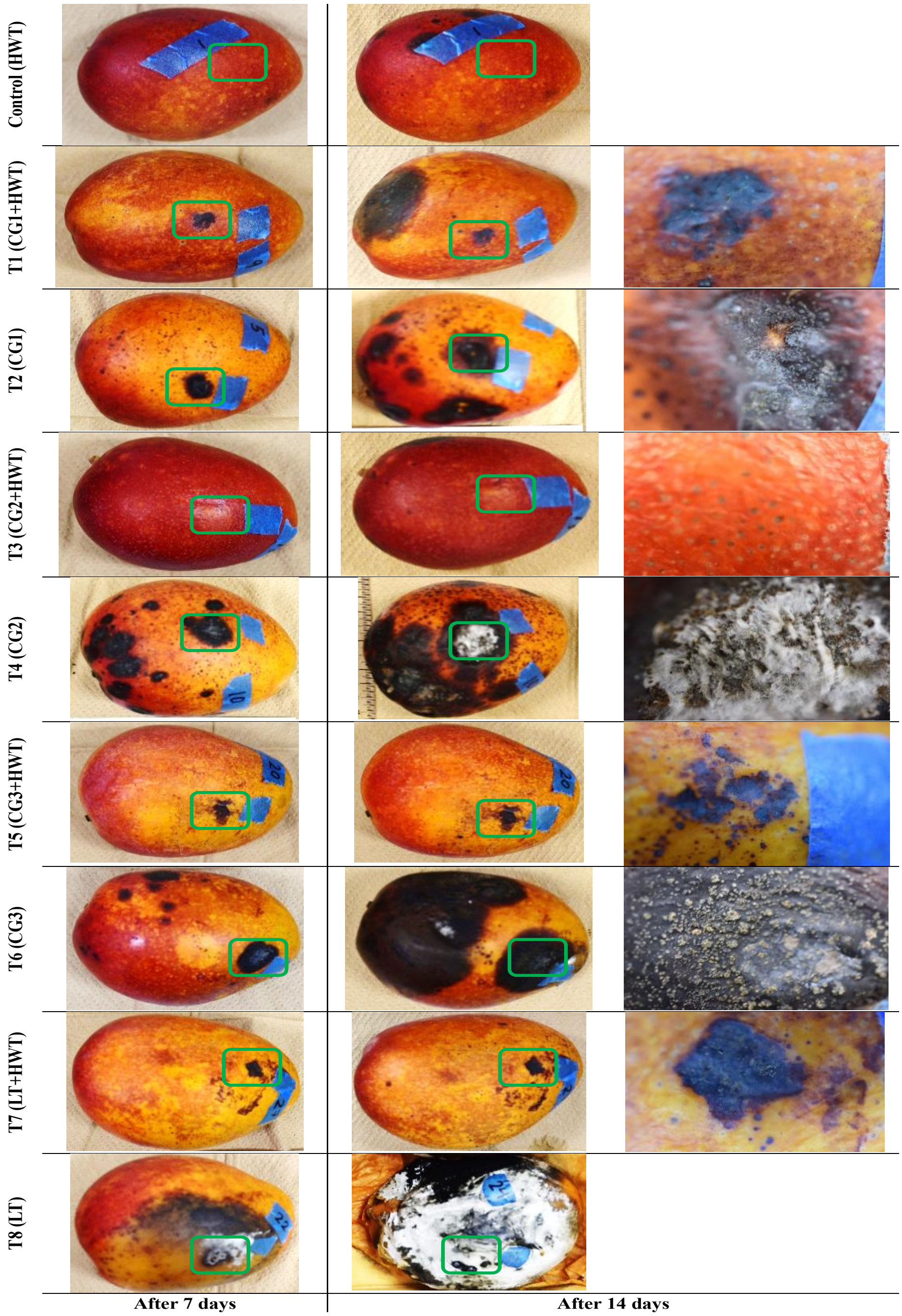

Figure 3. Disease spot on control, inoculation-only mangoes with *Colletotrichum* spp. (CG1, CG2 and CG3) and *Lasiodiplodia* spp. (LT), and inoculation followed by hot water treatment (HWT) with SHSW. At left, mangoes from 7d after treatments; at center, mangoes from 14d after treatments; and at right, closeup of the inoculated areas after 14 days (photos of control and T8 were not taken). Green boxes indicate the inoculated area.

Table 1. Mango fruit weight loss and disease spot size (mean ± SEM) treated with hot water treatment (HWT) with SHSW on inoculated mangoes.

(unit: %, cm)

Treatments	**Weight loss (n=3)** [1,2]			**Disease spot size (n=6)** [2]	
	Day 8	**Day 16**		**Day 8**	**Day 16**
Control	7.22±0.19 ^{a}	14.2±0.31 ^{b}	^{B}	-	-
T1 (CG1+HWT)	4.2±2.4 ^{a}	11.39±1.52 ^{b}	^{B}	0.35±0.17 x 0.31±0.14 ^{D}	0.35±0.17 x 0.31±0.14 ^{D}
T2 (CG1)	5.78±0.41 ^{a}	14.68±1.22 ^{b}	^{B}	1.78±0.17 x 1.31±0.1 ^{B}	2.3±0.08 x 2.06±0.07 ^{B}
T3 (CG2+HWT)	6.68±0.96 ^{a}	13.75±1.81 ^{b}	^{B}	0.48±0.22 x 0.48±0.22 ^{D}	0.48±0.22 x 0.48±0.22 ^{D}
T4 (CG2)	6.59±0.65 ^{a}	18.88±4.76 ^{ab}	^{B}	2.65±0.23 x 2.11±0.12 ^{A}	3.5±0.24 x 3.06±0.23 ^{A}
T5 (CG3+HWT)	8.05±0.59 ^{a}	15.83±0.7 ^{b}	^{B}	0.8±0.33 x 0.6±0.24 ^{CD}	0.8±0.33 x 0.6±0.24 ^{CD}
T6 (CG3)	6.74±0.18 ^{a}	15.34±1.41 ^{b}	^{B}	1.71±0.26 x 1.43±0.26 ^{B}	3.4±0.15 x 2.88±0.27 ^{A}
T7 (LT+HWT)	7.49±1.5 ^{a}	15.44±2.37 ^{b}	^{B}	1.03±0.18 x 1.26±0.22 ^{BC}	1.03±0.18 x 1.26±0.22 ^{C}
T8 (LT)	7.57±0.63 ^{a}	32.98±6.01 ^{a}	^{A}	8.08±1.61 x 7.08±1.33 ^{A}	- [3]

[1] In the same column, different letter by row means significant difference ($p < 0.05$) under an one-way ANOVA test followed by Tukey's HSD test.
[2] Different capital letters by row means significant difference ($p<0.05$) under a two-way ANOVA test followed by Tukey's HSD test.
[3] Samples completely covered by the pathogen and with advanced decay.

Disease incidence of non-inoculated mangoes. The symptoms of SER and some mild symptoms of anthracnose were observed in the control mango fruits at 6 days after treatment. Symptoms of SER were distinguished from anthracnose by their size and watery appearance as streaking in the conductive tissues is a characteristic sign of SER (Fig. 4).

Hot water treated mangoes (SHSW 60°C wc and SDW 60 °C wc) showed significant suppression when compared with control (Table 2 and Fig. 4), with mild symptoms of SER, after 6 days. Furthermore, the hot water treated mangoes (HSSW 60°C wc and SDW 60 °C wc) showed significant suppression compared with control and non-heated treatments (Table 2 and Fig. 4), with symptoms of SER and mild symptoms of anthracnose after 12 days.

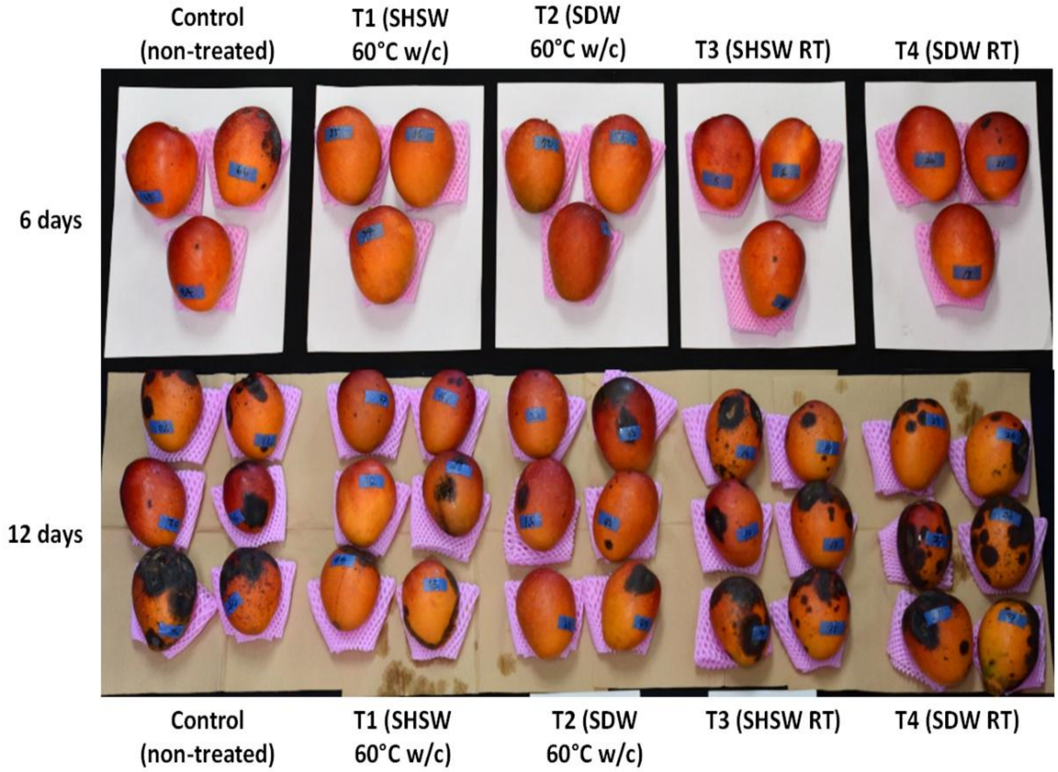

Figure 4. Non-inoculated mangoes after hot water treatments. Control, hot water treated mangoes with SHSW and SDW followed by cooling for 10 min (T1=SHSW 60°C w/c and T2=SDW 60°C w/c), and SHSW and SDW at room temperature (T3=SHSW RT and T4= SDW RT) soaked mangoes after 6d (at up) and 12d (at down). Symptoms of stem-end rot from quiescent infections were detected in all the treatments after 12d.

These results are different from those of mango cv. 'Carabao' at 59- 60 °C for 25 sec, showing symptoms of anthracnose and SER at 5 and 4-6 days after treatments respectively, although the incidence of both diseases were lower than the control (Pasilan et al. 2020). At 12 days, all the sides of the fruits in treatments and control showed disease incidence, being the stem area (side 'Z') of the fruit the most affected, as confirmed by Scheirer-Ray-Hare test and Tukey's HSD test ($p<0.05$), with symptoms of quiescent infection of SER detected in this area (Table 2), consistent with the characteristics of quiescent infections of SER, in which the pathogens colonize the conductive tissues of stem of the fruit (Galsuker et al. 2018).

Table 2. Effect of SHSW and SDW treatments on disease severity of non-inoculated mango fruits (mean ± SEM)

Treatment	**Disease severity (n=6)** [3]							
	Day 6				**Day 12**			
	$\mathbf{X}^{A\,1}$	$\mathbf{Y}^{A\,1}$	$\mathbf{Z}^{A\,1}$		$\mathbf{X}^{A\,2}$	$\mathbf{Y}^{A\,2}$	$\mathbf{Z}^{B\,1}$	
Control	1 ± 0.57^{a}	1.3 ± 0.88^{a}	2 ± 1^{a}	A	2.4 ± 0.42^{a}	2.3 ± 0.39^{ab}	3.6 ± 0.22^{a}	A
SHSW 60°C wc	0^{a}	0^{a}	0^{b}	B	1.44 ± 0.29^{b}	1.66 ± 0.37^{bc}	2.22 ± 0.54^{b}	B
SDW 60°C wc	0^{a}	0.66 ± 0.66^{a}	0^{b}	B	1.33 ± 0.37^{b}	0.77 ± 0.36^{c}	1.33 ± 0.47^{b}	B
SHSW RT	0.33 ± 0.33^{a}	0^{a}	0.66 ± 0.33^{ab}	AB	2.88 ± 0.26^{a}	3 ± 0.33^{ab}	3.77 ± 0.22^{a}	A
SDW RT	0.33 ± 0.33^{a}	0^{a}	1^{a}	AB	3 ± 0.28^{a}	3.2 ± 0.27^{a}	4^{a}	A

[1] In the same column, different letter by rows means significant difference ($p<0.05$) under a Kruskal-Wallis's test followed by Dunn's test.

[2] In the same column, different letter by rows means significant difference ($p<0.05$) under an one-way ANOVA test followed by Tukey's HSD test.

[3] Different capital letters by rows/columns mean significant difference ($p<0.05$) under a Scheirer-Ray-Hare test followed by Tukey's HSD test.

Mango fruit surface temperature during treatments. The surface temperature of the fruits before treatment (23.5~25.5°C) was close to room temperature (24~25°C) and rose to 43~49°C after being dipped at 60°C (Table 3). After 60 min, none of the mango fruits from the SHSW and SDW comparison groups (27~28°C) reached room temperature, which was later confirmed by Scheirer-Ray-Hare test. The temperature values were not significantly different between treatments but were significantly different when considering the time. The temperature values between the mango sides were not significantly different.

As such, the surface temperature of hot-treated mangoes in both SHSW and SDW was not different between these two treatments, changing along with the time of application.

SHSW, SDW and temperature. As was observed in non-inoculated mangoes, both SHSW and SDW at room temperature had little to no effect on disease severity as it did not differ from the disease severity values of the control and showed signs of advanced decay like control 12 days after treatment (Table 2 and Fig. 4).Therefore, SHSW and SDW were effective at reducing the disease incidence when heated to 60°C and not effective at room temperature, the effectiveness of the treatment on the inhibition of the fungal pathogens relies on the temperature rather than the water sample used for the treatment. Plus, SHSW and SDW had similar effects on fruit when used for hot water treatments, as was observed in temperature surface, fruit quality and disease severity.

However, because the *in-situ* temperature of the SHSW used in this study was 68.7°C, heating is not necessary for the application of this treatment if performed near the spring source. The application of hot water treatments by Philippine exporters requires water tanks powered by electricity, liquefied petroleum gas, or kerosene for heating, and the water should be changed every three days (Aveno and Orden 2004). The use of SHSW might reduce the cost of heating, thereby making the application of hot water treatments for mango fruits even more cost-effective.

Inhibition of Anthracnose The results of both experiments suggest that hot water treatment at 60°C for 1 min is effective in inhibiting quiescent and direct contact infections of anthracnose.

In the case of inoculated mangoes, the disease spot sizes of the three *Colletotrichum* spp. (Fig. 4) followed by treatment did not show any growth after treatment. By contrast, inoculated mangoes cv. \`Irwin\` treated at 60°C for 40 sec showed mild symptoms of anthracnose after 4-5 days when stored at RT (Teruya et al. 2012), while inoculated mangoes cv. 'Carabao' treated at 53 °C for 20 min reduced symptoms of anthracnose in 48.71-52.53% after 14 days due to possible quiescent infections (Alvindia and Acda 2015). Although in this study, inoculation was done using fungal plugs instead of conidia spraying, those showed that the conidia of *C. gloeosporioides* can be completely inhibited when treated at 51 °C in a chamber (Teruya et al. 2012), while both conidia and mycelium can be inhibited *in-vitro* over 70% at 53 for 20 min (Alvindia and Acda 2015), or over 90% at 55°C for 15 sec (Nascimiento et al. 2014).

Nevertheless, even when the surface temperature of the mangoes, just after treatments, was lower (45.6±0.36 ~ 46.04±0.68°C in SHSW 60 °C wc, and 44.04±4.03 ~ 49.08±0.4 °C in SDW 60 °C wc) than the previously suggested temperatures, symptoms of anthracnose appeared at 12 days after hot water treatment in this study. This suggests that direct contact between the fruit surface and the heated medium is critical in inhibiting anthracnose. The heat transfer to the mango surface was uniform from both SHSW and SDW, as the statistical analysis on the temperature of the mango surface after treatments in our study suggests (Table 3).

Table 3. Temperature of the mango fruit surface before and after hot water treatments (mean ± SEM, n=5).

(unit: °C)

Treatment	Before [d]			After [a]			10min [b]			60min [c]		
	X	**Y**	**Z**	**X**	**Y**	**Z**	**X**	**Y**	**Z**	**X**	**Y**	**Z**
SHSW 60°C wc	23.66 ±0.09	24.14 ±0.42	24.28 ±0.39	46.04 ±0.68	45.6 ±0.36	42.9 ±0.63	29.22 ±0.15	29.38 ±0.07	29.56 ±0.19	27.74 ±0.16	27.78 ±0.15	28.04 ± 0.34
SDW 60°C wc	24.86 ±0.08	25.02 ±0.11	25.34 ±0.2	49.08 ±0.4	44.04 ±4.03	46.14 ±0.73	29.54 ±0.15	29.82 ±0.2	30.1 ±0.2	27.5 ±0.17	28.3 ± 0.21	28.32 ± 0.08

Different letter by columns indicates significant difference (<0.05) under a Scheirer-Ray-Hare test followed by Tukey's HSD test.

Inhibition of SER Hot water treatment at 60 °C for 1 min with SHSW was effective in inhibiting direct contact SER infections, as shown in the results of the inoculation with *Lasiodiplodia* spp. followed by hot water treatment (T8: LT+HWT) (Table 1 and Fig. 3). However, it is ineffective against quiescent infections of stem-end rot as observed in the treatments in non-inoculated mangoes (Fig. 4).

Treated mangoes with SDW showed symptoms of SER at 6d after treatment and in SHSW and SDW at 12 days, with special presence in the stem area (side Z), while in inoculated mangoes followed by treatments, symptoms of stem-end rot appeared in non-inoculated areas, even in the mangoes inoculated with *Lasiodiplodia* spp. followed by hot water treatment.

Quiescent infections of SER occur during the inflorescence and flowering stages in mango trees, in which *Lasiodiplodia theobromae*, as an endophytic fungus, colonize the mango stem area, turning pathogenic when fruit ripening due to biochemical and physiological changes in the mango fruit. (Galsuker et al. 2018). In previous studies, *in-vivo* assays inhibited conidia and mycelium of *L. theobromae* over 90% after treatment at 55 °C for 15 sec (Nascimento et al. 2014) and at 53 °C for 50 min (Alvindia and Acda 2015), although treatments at 50 °C for 15 sec inhibited *L. theobromae* conidia by around 60% and mycelium by 5.5% (Nascimiento et al. 2014).

In *in-vivo* treatments, 53 °C for 20 min reduced SER incidence by 48-60.68% after 14 days (Alvindia and Acda 2015), 55 °C for 10 min reduced SER incidence by 70% after 21 days at 13 °C (Montecalvo et al. 2019), and 59-60 °C for 35 sec reduced SER incidence by 20-25% in cv. 'Carabao' (Esguerra et al. 2004; Pasilan et al. 2020). The previous, combined with our findings, might suggest that the heat of the water during the treatments is effective in inhibiting surface infections of stem-end rot, due to the direct contact between the mango skin and the medium (SHSW and SDW), even when mango skin reached a temperature of 43~49 °C just after treatments. However, this heat is ineffective on quiescent infections of stem-end rot, as the surface temperatures of the treated mangoes just after treatments in our study were lower (max. 46.04 °C in SHSW 60 °C wc and 49.08 °C in SDW 60 °C wc) than the necessary for inhibiting the mycelium of the stem-end rot fungus and even lower than the fruit surface temperature of 55 °C reached by Teruya et al. (2012). The difference in the surface temperature obtained by Teruya et al. (2012) and this study might be due to the absence of water circulation in this study, reducing the heat transfer to the fruits.

In future studies, it is suggested that the application of temperatures higher than 60 °C for 1 min or shorter with water circulation, which is expected to increase the chances of the fruit surface reaching an adequate temperature for the control of quiescent infections of stem-end rot. Moreover, as the mango fruits in this study were stored post-treatment at room temperature, the use of refrigeration after treatments should be evaluated to extend the shelf life of mango and the inhibition of SER, as was previously reported in Montecarlo et al. (2019) in cv. 'Carabao', while trying to prevent chilling injury (Rodeo and Esguerra 2013).

Mango fruit quality. Values of weight loss showed that treated mangoes with SDW 60 ºC w/c had the highest weight loss at 6 days (16.74±10.24) and 12 days (27.05±13.97). However, there was no significant difference between the treatments, including SDW 60 ºC w/c, and the control in weight loss at 6 days and 12 days (Table 4). Mangoes treated with SHSW and SDW at 60 °C for 1 min showed no significant difference in fruit quality (weight, peel color, firmness, and soluble sugar content) compared to the control after 6 days at room temperature. In the case of firmness, the values of all the treatments were similar and there was no significant difference between them. Soluble sugar content at 6 d and color differences in all the treatments and the control were also similar (Table 4 and 5).

This is consistent with an earlier study wherein peel color was not affected by hot water treatments at 60 °C (Teruya et al. 2012). Likewise, mango cv. 'Carabao' treated at 59-60 °C for 35 sec showed no difference in peel color and visual quality at 6 days after treatment (Pasilan et al. 2020).

Table 4. Effect of SHSW and SDW treatments on fruit quality of non-inoculated mango fruits (mean ± SEM).

Treatment	Weight Loss (n=3), %		Hardness (n=3) kg/cm^2			Soluble sugar content, ^{O}Brix	
	Day 6 [1]	Day 12 [1]	Day 0 [2]	Day 6 [1]	Day 12 [2]	Day 6 (n=3) [2]	Day 12 (n=9) [2]
Control	4.87± 22^{a}	12.8± 1.22^{a}	0.92^{a}	0.78± 0.01^{a}	- [3]	11.43± 0.69^{a}	- [3]
SHSW 60°C wc	6.17± 0.31^{a}	11.18± 0.88^{a}	0.93^{a}	0.79^{a}	0.73± 0.01	12.33± 0.33^{a}	10.79 ±0.41^{a}
SDW 60°C wc	16.74± 10.24^{a}	27.05± 13.97^{a}	0.92^{a}	0.8^{a}	0.77± 0.01	12.83± 0.92^{a}	11.12±0.3^{a}
SHSW RT	4.87± 0.22^{a}	12.8± 1.22^{a}	0.92^{a}	0.8± 0.01^{a}	- [3]	10.66± 1.2^{a}	- [3]
SDW RT	14.64± 8.81^{a}	13.21± 1.45^{a}	0.9^{a}	0.8± 0.01^{a}	- [3]	11.33± 0.88^{a}	- [3]

[1] In the same column, different letter by rows indicates a significant difference ($p<0.05$) under a Kruskal-Wallis's test, followed by Dunn's test.

[2] In the same column, different letter by rows indicates significant difference ($p<0.05$) under a one-way ANOVA test followed by Tukey's HSD test.

[3] Samples discarded due to fruit decay

The effect of both SHSW 60 ºC wc and SDW 60 ºC wc on mango fruit quality (weight loss, firmness, soluble sugar content, color difference) was not different at 12 days. The values of hardness and soluble sugar content were not taken at 12 days for Control, SHSW RT, and SDW RT mangoes, as the fruits had to be discarded due to decay. In a previous study, treated mangoes cv. 'Carabao' had better peel color and suffered less deterioration of visual quality than the control at 12 days (Pasilan et al. 2020).

In general, hot water treatments on mango tend to increase the fruit quality in terms of peel color on cv. 'Kensington' and cv. 'Sindh' (Anwar and Malik 2007; Djioua et al. 2009; Jacobi and Giles 1997), while color, fruit hardness, pH, total soluble solids and titratable acids are either increased or not compared to the control in cv. 'Carabao' and 'Keitt' (Alvindia and Acda 2015; Kitma and Esguerra 2009; Kumah et al. 2011; Montecalvo et al. 2019), although some protocols might provoke lenticel spotting in cv. 'Carabao' (Esguerra et al. 2004). Due to this, the design of treatment protocols should be carried out taking into consideration the mango fruit variety and the desired result: improving storage time, fruit quality, and/or reducing the incidence of pests or diseases.

Some of the samples were destroyed during the measurement of quality values; thus, it is suggested that non-destructive measurements be used for the assessment of fruit quality when the main objective is the evaluation of disease inhibition on the fruit, as maintaining the number of samples during the entire experiment is critical for the evaluation.

Table 5. Effect of SHSW and SDW treatments on peel color of non-inoculated mango fruits (mean ± SEM).

Treatment	Peel color differences (n = 3) [1]					
	ΔL	**Δa**	**Δb**	**ΔC***	**Δh**	**ΔE***
Control	-0.5 ± 1.83[a]	-1.92 ± 0.74[a]	12.65 ± 2.84[a]	6.22 ± 1.87[a]	13.63 ± 2.85[a]	13.2 ± 2.6[a]
SHSW 60°C wc	-2.8 ± 1.09[a]	-2.97 ± 1.71[a]	2.95 ± 1.71[a]	-0.29 ± 2.34[a]	5.29 ± 1.56[a]	6.38 ± 0.78[a]
SDW 60°C wc	0.37 ± 2.26[a]	-4.54 ± 0.87[a]	8.79 ± 2.52[a]	2.14 ± 1.48[a]	12.45 ± 2.4[a]	10.68 ± 2.08[a]
SHSW RT	-4.01 ± 0.75[a]	-1.24 ± 2.19[a]	7.63 ± 3.23[a]	3.37 ± 0.4[a]	8.25 ± 4.4[a]	9.38 ± 3.11[a]
SDW RT	-4.46 ± 0.84[a]	-2.21 ± 0.16[a]	6.83 ± 5.39[a]	1.99 ± 3.01[a]	7.87 ± 5.2[a]	10.32 ± 3.51[a]

[1] In the same column, different letter by rows indicates significant difference ($p<0.05$) under a one-way ANOVA test followed by Tukey's HSD test.

CONCLUSION

This is a pioneering study that used saline hot spring water for hot water treatments of mango fruits and reported the effect of hot water treatments at 60 °C for 1 min on stem-end rot. Hot water treatment with saline hot spring water at 60 °C for 1 min, followed by cooling for 10 min, is effective in reducing the appearance of anthracnose from recent direct contact and quiescent infections, while maintaining mango fruit quality. The treatment is only effective against recent direct contact infections, but not against quiescent infections of stem-end rot.

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VULNERABILITY ASSESSMENT TO CLIMATE-RELATED HAZARDS OF RICE FARMER HOUSEHOLDS IN THE PHILIPPINES USING LOSS RATIO

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ABSTRACT

The Philippines faces increasing climate-induced risks to rice production, emphasizing the need for vulnerability assessment as a basis for evidence-based adaptation and policy development. This study introduces an alternative approach where the vulnerability index is defined as the probability that the loss ratio exceeds a specified threshold. A fractional logit regression model was used to identify factors influencing farmers' loss ratios. Using multi-stage stratified random sampling, 100 respondents were selected from major rice-producing municipalities across 11 provinces in key rice-growing regions in the Philippines. Data were collected from July 2022 to February 2023 using a structured questionnaire. Results indicate that a higher share of rice income in total household income, exposure to climate hazards such as typhoons and droughts, and participation in crop insurance are all associated with an increased loss ratio. Conversely, higher loan amounts, access to agricultural training, and government assistance significantly reduce the loss ratio. The findings underscore the critical role of institutional support, financial access, and adaptive capacity-building in minimizing climate-related losses and enhancing the resilience of rice-farming communities in the Philippines.

Key words: rice production, agriculture, climate change, rice farming, vulnerability index

INTRODUCTION

The Philippines is vulnerable to climate change (USAID 2023) and is directly exposed to several climate-related hazards (World Bank 2013 2015; Evangelista et al. 2015). Agriculture, a key sector in the country, is highly vulnerable to climate-related hazards, with rice production being the most affected. Rice is a major crop and a staple food in the Philippines. It plays a vital role in the national economy, contributing an average of 23.4% to the gross value added of the Agriculture, Forestry, and Fishing (AFF) sector from 2000 to 2020[1]. However, climate change can highly affect rice production as it is one of the most sensitive agroecosystems to climate variability (Lansigan et al. 2000; Saud et al. 2023). The effects of climate-related hazards pose significant risks to food security and the livelihoods of rice farmers, as these hazards can damage rice production and even wipe out production depending on the intensity, duration, and timing.

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[1] Author's calculation of PSA annual data at constant 2018 prices (https://openstat.psa.gov.ph/Database/Agriculture-Forestry-Fisheries).

Typhoons and extreme temperatures can severely damage rice harvests and threaten farmers' incomes. According to Lansigan et al. (2000), 82% of the loss to rice production from 1970 -1990 was due to typhoons, floods, and droughts. In addition, typhoons have been the cause of the production loss of 12.5 million tons of rice since 2001(Blanc and Stobhl 2016). On the other hand, Wang et al. (2021), Diaz et al. (2021), and Sharma et al. (2022) have demonstrated the negative impact of rising temperatures on rice yields.

Rice production is a main source of income for most Filipinos in rural areas (Rebojo et.al. 2023), and exposure to various climate-related hazards and damage to rice harvest leads to significant loss of farmers' income. Most rice farmers in the Philippines are small-scale farmers, each owning an average of 1.2 hectares of farmland (Arnaoudov, V. et al. 2015). According to IPCC, smallholder farmers are highly vulnerable to the impacts of climate change due to limited financial resources and increased exposure to extreme weather events (Evangelista et al. 2015).

Despite various government efforts, rice farmers continue to suffer significant losses when faced with climate-related hazards. This highlights the need to identify a refined strategy to minimize the effects and damages from future hazards. The vulnerability index has been identified for targeted intervention and prioritization, serving as a basis or framework for evaluating specific adaptation and input monitoring efforts (Balica et al., 2012; Downing et al., 2005). The estimation of the vulnerability index of rice farmers serves as a critical basis for evidence-informed policymaking aimed at enhancing their resilience to climate change. According to Hoddinott and Quisumbing (2003), most studies on vulnerability assessment utilize econometric approaches such as Vulnerability as Expected Poverty (VEP), Vulnerability as Expected Utility (VEU), and Vulnerability as Uninsured Exposure to Risk (VER). This study also offers an alternative approach to vulnerability assessment by using the probability of ruin to determine the likelihood that a farmer’s financial resources, such as capital, assets, or income, will be depleted, which may hinder the continuity of farming operations.

In a developing country like the Philippines, limited physical, financial, and institutional resources pose significant challenges in effectively addressing climate-related challenges (Defiesta and Rapera 2014). Vulnerability assessment offers a robust foundation for identifying suitable adaptation strategies and supports evidence-based planning. Prior studies have assessed the vulnerability of rice farmer households, primarily within a specific local scope (Tran et al. 2022; Ho et al. 2021). This study seeks to examine the vulnerability of rice farmer households at a broader scale and introduces an alternative methodological approach to vulnerability assessment.

Theoretical Framework. In this paper, vulnerability is defined as the likelihood that a farmer will suffer a devastating loss after encountering climate change-related hazards such as heavy rainfall, strong winds, and extreme temperatures. This loss could leave the farmer with extreme difficulty in continuing rice farming, posing significant challenges to their livelihood. Mathematically, VI is defined as

$$VI = P(lr > lr_0)$$

where

VI = Vulnerability index
lr = worst loss ratio
lr_0 = threshold loss ratio

This VI is analogous to the concept of ruin probability in mathematics. The probability of ruin is used in various fields such as insurance and finance (Firouzi et al. 2025). In the actuarial field, the probability of ruin is a measure of the likelihood that an insurance company will become ruined or bankrupt, meaning its capital will drop below zero. The loss ratio is defined as

$$lr = \frac{ny - ws}{ny} = \frac{L}{ny} \tag{1}$$

where:

lr = worst loss ratio
ws = worst harvest due to climate-related hazards (kg)
ny = normal year harvest (kg)
L = highest rice harvest loss experienced due to climate-related hazards (kg)

The worst loss ratio measures the percentage of harvest lost due to unfavorable weather conditions under the worst-case scenario. The threshold loss ratio is the minimum loss ratio that will lead to a devastating loss. The concept of loss ratio originates in the insurance field. It is a key financial metric that represents the percentage of earned premiums an insurer spends on paying claims and other expenses related to claims. It's calculated by dividing the total amount of losses (claims paid, plus adjustment expenses) by the total premiums earned.

MATERIALS AND METHODS

Study sites. The municipalities included in this study were Mangatarem, Pangasinan (Region 1), Solana, Cagayan (Region 2), Minabalac, Bicol (Region 5), Pototan, Iloilo (Region 6), Mahayag, Zamboanga del Sur (Region 9), Malaybalay, Bukidnon (Region 10), and Mlang, Cotabato (Region 12). Data from the Philippine Statistics Authority (PSA 2024) show the regions included in this study collectively contribute approximately 53% of the Philippines' total annual rice output, reflecting their critical importance to national rice production. Within these regions, the selected municipalities represent the top one or two rice-producing areas in their respective provinces. On average, these municipalities account for about 11% of provincial rice production (PhilRice 2024).

Sampling procedure. Multi-stage stratified random sampling was employed in the selection of respondents for this study. Multi-stage stratified random sampling improves representativeness by proportionally including key subgroups, reducing sampling bias and enhancing estimate accuracy (Cochran 1977). Its multi-stage design increases efficiency and feasibility in large, dispersed populations while lowering fieldwork costs and maintaining randomness within strata (Lohr 2022).

The strata were based on the Manila Observatory's classification of provinces according to climate change risk of high, medium, and low. Rice-producing provinces were randomly selected from each stratum, with Regions 2 and 5 classified as high-risk, Regions 2 and 9 as medium-risk, and Regions 6, 10, and 12 as low-risk. A rice-producing municipality was then randomly chosen in each of the provinces. Respondents in the chosen municipality were randomly selected from a list of rice farmers provided by the Municipal Agriculture Office of each local government unit in this survey. If a selected respondent could not be contacted, they were replaced with another randomly chosen sample from the same stratum.

Data collection. A survey of 100 rice farmers was conducted using a structured questionnaire in coordination with the municipal agriculture offices of selected local government units. The relatively small sample size is justified by the use of multi-stage stratified random sampling, which ensured adequate representation across key strata despite the limited number of respondents. As Mooi et al. (2018) stated, the strength of samples comes from selecting samples accurately, rather than their sizes. Moreover, practical constraints such as time, financial resources, and the geographic dispersion of farming communities further limited the feasible sample size, a common challenge in field-based empirical research (Creswell and Creswell 2018; Etikan and Bala 2017).

The structured questionnaire was constructed to obtain information on the socio-demographic characteristics of the farmers, their households, and rice production information. Other questions associated with climatic stress were obtained to determine exposure for the last 10 years (i.e., number of extreme climatic stresses, loss of rice harvest, and worst rice harvest due to climatic stresses). The questionnaire was pretested with five rice farmers in Bay, Laguna, over two sessions to evaluate clarity, relevance, and consistency of responses. Feedback from participants was used to refine questions wording and structure, ensuring the instrument's validity and suitability for the main survey.

Data analysis. A fractional logit regression model was utilized to determine the farmer's loss ratio. Fractional regression is appropriate when the dependent variable is a proportion bounded between 0 and 1, such as indices, in this case loss ratio. It ensures predicted values remain within valid limits and provides consistent estimates, unlike linear regression models that may yield invalid predictions (Papke and Wooldridge 1996). The specification of the model is presented below:

$$ln\left(\frac{lr_i}{1-lr_i}\right) = \beta_0 + \beta_1 gender_i + \beta_2 SFI_i + \beta_3 loan_i + \beta_4 livestock_i + \beta_5 crop\_ins_i + \beta_6 training_i + \beta_7 typhoon_i + \beta_8 dought_i + \beta_9 assist_i + \varepsilon \quad (2)$$

where:

lr_i = worst loss ratio
gender =Dummy;1= male, 0 = otherwise
SFI_i= share of rice farming income to total HH income
$loan_i$= amount of existing loan
$livestock_i$ =Dummy; 1= own livestock, 0 = otherwise
$crop\_ins_i$= Dummy; 1= with crop insurance, 0 = otherwise
$training_i$ = Dummy; 1=attended at least 1 training related to agriculture in the last 10 years, 0 = otherwise
$typhoon_i$ = nbr of typhoons experienced in the last 10 years
$drought_i$ = number of drought events experienced in the last 10 years
$assist_i$ = Dummy; 1= availed government assistance, 0 = otherwise
i = farmer

Various regression models were conducted with different combinations of variables. The regression model chosen was determined based on the goodness of fit of the various fractional regression models as measured by the Akaike Information Criterion (AIC) and the Bayesian Information Criterion (BIC). The model with the lowest AIC and BIC was chosen. The vulnerability index was then determined using a standard normal approximation for the distribution of the loss ratio.

RESULTS AND DISCUSSION

Profile of the respondents. Table 1 provides an overview of the characteristics of the surveyed rice farmers. It shows that the rice farmer respondents were primarily male, accounting for 85% of the sample size. This indicates that agriculture is still a male-dominated sector. The average age is 54, with the youngest being 23 years of age and the oldest 78 years old. This implies a high proportion of older rice farmers in the country. On average, they have 27 years of farming experience. The mean number of years of education is 11, indicating that most farmers have at least a year of tertiary education.

The mean household size is 4.34, where the minimum is 2 and the maximum is 11. The average share of farm income relative to total household income is 75% as some younger family members choose non-agricultural employment. Additionally, 63% of respondents have outstanding loans, with the mean amount of PhP 75,100. Approximately 41% of the respondents own livestock. On average, the farmer respondents reported experiencing about 23 typhoons and 11 drought events over the past decade. However, only 9% of the respondents have crop insurance, while 93% have access to government assistance and have participated in at least one training course on agriculture.

Table 1. Socio–demographic characteristics of respondents

Variable	Mean	Std. Dev.	Min	Max
Gender	0.85	0.36	0	1
Age	53.66	10.75	23	78
Years of schooling	11.12	2.60	4	17.5
Farming experience	26.83	12.41	3	60
Household size	4.34	1.60	1	11
Farm Size	5.74	13.88	0.4	127
Ownership of farm	0.62	0.488	0	1
Share of rice farming income to total income	74.68	30.50	10.53	100
Loan	75,100	303,404	0	3,000,000
Livestock	0.41	0.49	0	1
Crop insurance	0.09	0.29	0	1
Typhoon	22.87	15.00	6	52
Drought	10.99	7.19	3	30
Training	0.93	0.26	0	1
Access govt program	0.93	0.26	0	1

Regression results. Table 2 displays the regression results for the model that yielded the lowest Akaike Information Criterion (AIC) among the estimated models with various combinations of explanatory variables. The model with the smallest AIC and BIC score is determined to be the better-fit model (Fabozzi et al. 2014). In addition, the model results indicate a good overall fit, with the chi-square test (Prob > χ^2 = 0.0000) showing that the explanatory variables jointly contribute significantly to the model. The pseudo R^2 value of 0.3256 suggests that about 32.6% of the variation in the dependent variable is explained by the predictors, which is acceptable for cross-sectional data (McFadden 1974). The log pseudolikelihood (–35.457) indicates a satisfactory model fit (Greene 2018).

Table 2. Fractional logistic regression results

Variable	Loss Ratio
Gender	-0.812
	(0.509)
Share of rice farming income to total HH income	0.0101**
	(0.00479)
Loan	-7.06e-07***
	(1.10e-07)
Livestock	-0.236
	(0.347)
Crop insurance	1.643**
	(0.746)
Training	-1.600***
	(0.307)
Typhoon	0.0189*
	(0.0114)

Variable	Loss Ratio
Drought	0.383***
	(0.0532)
Access to government assistance	-1.483*
	(0.877)
constant	0.889
	(1.074)
Prob >chi^2	0.0000
Psuedo R^2	0.3256
Log pseudolikelihood	-35.457352
AIC	90.9147
BIC	116.9664

Notes: Standard errors in parentheses
* p<0.1 ** p<0.05 *** p<0.01"
Source: Author's calculation

Marginal effects of the dependent variable. Table 3 presents the marginal effects, which represent the change in the probability of an outcome resulting from a one-unit change in a predictor variable, while holding other variables constant (Long and Freese 2014). Results show that a 1 percentage point increase in the share of rice farming income to total household income is associated with a 0.10 percentage point increase in the loss ratio. This shows that rice farmer households that rely mainly on rice farming income are more vulnerable to losses. Akhtar et al. (2018) and Khan et al. (2022) state that farmer households with off-farm income have a positive attitude towards implementing new strategies such as new rice varieties and better fertilizer management to improve yield and better resistance to the impact of climate change. This shows that adaptive capacity increases as off-farm income increases. Farmers who depend entirely on farming income are more susceptible to climatic shocks and face significant financial loss.

Loan, on the other hand, has a negative relationship with the loss ratio. The marginal effect of –8.02E–08 ($p < 0.01$) indicates that an increase in loan amount is associated with a small but statistically significant reduction in the loss ratio. This finding is consistent with the results of Adzawla and Baumüller (2020) and Ho et al. (2022). The negative relationship between the loan and the loss ratio of harvest reflects the utilization of the loaned amount to improve resilience and recover from natural hazards (Debesai et al. 2019; Adzawla and Baumüller 2020; Ho et al. 2022). In addition, Khan et al. (2022) noted that access to financial capital, like a loan, can enhance a farmer's adaptive capacity and decision-making.

Farmers with crop insurance exhibited a 119 percentage-point increase in the loss ratio. These results are consistent with the findings of Smith and Goodwin (1996) and Fadhliani et al. (2019), who observed that crop insurance coverage may reduce input use and risk-reducing activities, resulting in lower yield. According to previous studies of Wu et al. (2019) and Clarke and Dercon (2016), this pattern may reflect moral hazard, wherein the security provided by insurance leads farmers to adjust their behavior by lowering farm inputs and reducing investment in risk-mitigation practices. Additionally, the crop losses experienced by other farmers may stem from the choice of the insured farmers to cultivate riskier crops or varieties (Yu and Sumner 2018). In this study, respondents reported that rice production losses were mainly due to typhoons and droughts, yet most did not modify their farming practices. Consequently, the absence of adaptive measures among insured farmers exposed to these hazards likely contributes to higher loss ratios.

There was a positive correlation between climate-related factors, including typhoons and droughts, and loss ratio or damage in rice production. Specifically, each additional typhoon and drought increased the loss ratio by 0.20 and 4.4 percentage points, respectively. Typhoons, characterized by strong winds and heavy rainfall, negatively impacted rice production in the Philippines. Research results of Koide et al. (2012), as cited in Blanc and Strobl (2016), found a negative correlation between typhoons and rice production. Furthermore, a study by Defeista and Mediodia (2016) emphasized the detrimental impact of typhoons and droughts on rice production in the Philippines.

Training and access to government assistance also have a negative relationship with the loss ratio. A unit increase in attendance to training and access to government assistance experienced an 18.6 and 17.2 percentage point decrease in the loss ratio, respectively. The results aligned with those of Issahaku et al. (2022), who also indicated that training rice farmers can improve their yields. Ituriaga et al. (2024) noted that informing farmers about new farming techniques is crucial, as it can significantly enhance their agricultural practices and increase crop yields. Government assistance comes in various forms, including financial assistance, training programs, and the provision of agricultural inputs. Consequently, the effect of government assistance is parallel to that of loans and training. The provision of inputs to production also aligned with the results of studies by Thanapan (2019), Azumah and Zakaria (2019), Nasrin et al. (2018), and Yang et al. (2023). This suggests that government aid helps mitigate agricultural losses.

Table 3. Marginal effects of the dependent variables

Variable	Loss Ratio
Gender	-0.094
	(0.573)
Share of rice farming to total HH income	0.001**
	(0.001)
Loan	-8.02E-08***
	(1.06E-08)
Livestock	-0.027
	(0.040)
Crop insurance	1.191**
	(0.088)
Training	-0.186***
	(0.039)
Typhoons	0.002*
	(0.001)
Drought	0.044***
	(0.005)
Access to government assistance	-0.172*
	(0.102)
Constant	0.889
	(1.074)

Robust standard errors in parentheses

*** p<0.01, ** p<0.05, * p<0.1

Vulnerability of rice farmer households. The vulnerability classification used in this study was adapted from IPCC (2014) and Balica (2012), wherein the original five categories ("very low," "low," "moderate," "high," and "very high") were simplified into low, moderate, and high to better align with the data distribution. This study posits that households with a vulnerability index (VI) of less than or equal to 0.4 are categorized as having low vulnerability, while those with a VI between 0.41 and 0.6 are considered moderately vulnerable, and those with a VI greater than 0.6 are classified as highly vulnerable. The mean vulnerability decreases as the threshold increases (Table 4). The threshold represents the amount of damage that rice farmer households can withstand. The mean vulnerability for each threshold indicates that, on average, the probability of farmers facing ruin after experiencing losses of 50%, 75%, and 90% are 0.82, 0.67, and 0.57, respectively. As expected, the number of instances of low vulnerability increased with a rising threshold, while the opposite is true for households with high vulnerability. In addition, a substantial number of rice farmer households fall into the highly vulnerable category.

Table 4. Descriptive statistics of vulnerable rice farmer households by threshold level

Threshold	VI (All Rice Farmer Households)		
	50%	**75%**	**90%**
Mean	0.82	0.67	0.57
Standard Deviation	0.36	0.43	0.46
Minimum	0.00	0.00	0.00
Maximum	1.00	1.00	1.00
Incidence of Low Vulnerability (%)	15.00	29.00	40.00
Incidence of Moderate Vulnerability (%)	3.00	3.00	1.00
Incidence of High Vulnerability (%)	82.00	68.00	59.00

Characteristics of rice farmer households by vulnerable group and threshold level. Table 5 shows the characteristics of the respondents by vulnerability group using the three thresholds. It shows that the high-vulnerable group has the largest share of rice farming income in total household income compared to the other two groups at all thresholds. This aligns with the findings of Tran et al. (2022) and Ho et al. (2022), which demonstrate that households with alternative sources of income and reduced reliance on farming income lessen their vulnerability. However, the results show that the moderate vulnerability group exhibits the lowest share, while the highly vulnerable group maintains a higher share by a slight difference compared to the low vulnerable group. This probably shows that some other factors affect the vulnerability of the moderate group besides the share of rice farming income to total household income.

The low-vulnerable group had the highest average loan amount of all thresholds. This finding underscores the critical role of access to adequate credit in recovering from climate-induced losses and strengthening farmers' adaptive capacity and resilience. This is consistent with previous studies that reported improved credit access is associated with reduced vulnerability to climate change (Ho et al. 2022; Adzawla et al. 2020; Debesai et al. 2019). Furthermore, the results support the argument that limited access to credit remains a significant constraint to climate adaptation and agricultural development (Ndamani and Watanabe 2015; Adzawla et al. 2020).

The rice farmer households in the low and medium vulnerable groups had no crop insurance across all thresholds. However, 11%, 14%, and 15 % of the high vulnerable group had crop insurance across all thresholds. This shows that farmers with crop insurance were more vulnerable to climate-related hazards than those without crop insurance. Crop insurance may lead to moral hazard, causing farmers to decrease investment in their farms or adopt risk-reducing practices because they feel financially protected (Clarke and Dercon 2016). Reduced investment in farm inputs and risk-reducing practices results in lower yields (Smith and Goodwin 1996; Fadhliani et al. 2019) and decreased rice farming income. However, while the literature identifies several factors contributing to the high vulnerability of insured farmers, respondents indicated that they had not modified their farming practices. Typhoons and droughts were cited as the main causes of rice production losses. As most insured farmers have not adopted adaptive measures and remain highly exposed to these climatic hazards, their loss ratios are likely to increase. This, combined with inaccurate crop damage assessment by the Philippine Crop Insurance Corporation (PCIC) and the delay in claim payouts (Rola and Aragon 2018), can heighten farmers' vulnerability. The program was advantageous for farmers recovering from natural disasters; however, its coverage was insufficient for smallholder farmers (Reyes and Mina et al. 2019). In addition, crop insurance offers immediate financial relief but does not effectively mitigate long-term vulnerabilities to climate-related shocks (Conrado et al. 2017).

On climate-related hazards such as typhoons and droughts, the group with high vulnerability had the highest incidents for both hazards, followed by the moderate and low vulnerability groups. Typhoons can damage rice and reduce harvest. This shows that exposure to climate-related hazards increases rice farmers' vulnerability. Studies have revealed the damage to rice production due to typhoons (Lansigan et al. 2000; Blanc and Strobl 2016), and the positive relationship between drought and vulnerability (Ho et al. 2022), with drought-prone communities being more vulnerable (Manalo et al. 2020)

All rice farmers in the low and moderate vulnerability groups in all thresholds attended successfully training sessions and accessed government assistance. In contrast, only 88% to 91% of rice farmers in the high vulnerability group participated in at least one training course, while 88% to 92% accessed government support. Access to government assistance can offer farmers essential training and financial support, enabling them to recover from damage to their rice farms, particularly in the face of climate-related hazards. The provision of training to farmer households is a crucial factor that can enhance their ability to reduce vulnerability (Tran et al. 2022).

The group identified as highly vulnerable exhibited the most significant percentage share of income derived from farming, albeit by a marginal difference compared to the low vulnerability group. Furthermore, this highly vulnerable group possessed the lowest total amount of loans among the three groups analyzed; however, the average loan amount constitutes the highest percentage share of their income. Additionally, it is noteworthy that the highly vulnerable group was the only cohort with the lowest percentage of respondents who participated in agricultural training and had access to government assistance compared to the other two groups.

Table 5. Characteristics of rice farmer households by vulnerability and threshold level

Variable	**Threshold**	**Vulnerability**		
		Low	**Moderate**	**High**
Share of rice farming to total HH income (%)	50	70.93	73.95	75.40
	75	75.73	37.76	75.86
	90	71.63	40.00	77.16

Variable	Threshold	Vulnerability		
		Low	**Moderate**	**High**
Loan (Php)	50	224,533	23,333	49,659
	75	129,103	66,667	56,034
	90	106,026	50,000	52,881
Crop ins (%)	50	0	0	11
	75	0	0	14
	90	0	0	15
Attended Training (%)	50	100	100	91
	75	100	100	88
	90	100	100	88
Typhoon	50	13.20	30.33	24.37
	75	17.10	22.33	23.75
	90	18.74	20.00	25.80
Drought	50	4.20	4.67	12.46
	75	4.93	8.00	11.58
	90	5.44	9.00	14.73
Access to Government (%)	50	100	100	91
	75	100	100	92
	90	100	100	88

Characteristics of respondents with high vulnerability. The results revealed that rice farmers, classified as highly vulnerable, were respondents with a significant proportion of their income derived from rice farming. In addition, the group with high vulnerability was the only group with farmers who had crop insurance coverage. As insured farmers frequently experience typhoons and droughts, but have not implemented adaptive measures.

Among the three groups, the group with the highest vulnerability was the most exposed to natural disasters, particularly typhoons and droughts, followed by the moderately vulnerable group. Further disaggregation of the data revealed that respondents with high vulnerability had endured more instances of rice farm flooding and flood damage. Furthermore, the high-vulnerability group experienced an average maximum crop loss of 94% due to climate-related hazards across thresholds, and the low and moderate vulnerability groups suffered average losses of 49% and 56%, respectively. Moreover, the group with high vulnerability was the only cohort with the lowest percentage of respondents who participated in agricultural training programs and had limited access to government assistance.

In addition, the group with high vulnerability consists of 47% of rice farmers who lived in the area classified by Manila Observatory as low-risk provinces, and 29% and 23% live in the medium and high-risk provinces, respectively. This supports the assertion by IPCC 2014 that vulnerability is not solely driven by a single factor, such as climate-related hazards, but by a combination of concepts and elements, including exposure to hazards, sensitivity, and adaptive capacity.

CONCLUSION

This study demonstrated an alternative approach to assessing the vulnerability of rice farmers. By using the concepts of probability of ruin and worst loss ratio, the study identified the factors that affect farmers' vulnerability and determined their vulnerability index.

The share of farming income to total household income, crop insurance coverage, exposure to hazards such as typhoons and droughts, insufficient training in rice farming and agriculture, and limited access to government assistance programs contributed significantly to the vulnerability of rice farmers. Furthermore, while crop insurance is anticipated to mitigate farmers' vulnerability, issues such as limited coverage and operational inefficiencies must be addressed. In addition, the results also show that the group with high vulnerability has the lowest percentage of respondents who have participated in agricultural training programs and have limited access to government assistance. The vulnerability index developed for rice farmers offers critical evidence-based information for designing targeted and informed climate adaptation policies. Building on this, further research should examine the specific variables that contribute to vulnerability to refine intervention strategies. Moreover, accurately identifying the farmers' training needs and the appropriate forms of assistance can significantly enhance their capacity to adapt and reduce overall vulnerability to climate-related risks.

To strengthen the resilience of rice farmers, policies should promote balanced livelihood diversification supported by targeted training and capacity-building programs that equip farmers with the skills to engage in profitable off-farm and value-adding activities without compromising farm productivity. Training modules should integrate climate risk management, sustainable water use, and crop diversification strategies to enhance both income stability and adaptive capacity. Furthermore, improving access to government assistance through digitalized platforms and transparent targeting can ensure that support reaches farmers in the most climate-vulnerable areas in a timely and equitable manner.

Enhancing credit access via simplified loan procedures and cooperative-based financing will enable farmers to invest in adaptive technologies. Likewise, the crop insurance program should be rationalized and simplified to enhance administrative efficiency and promote broader farmer participation through more accessible enrollment and claims procedures. In addition, implementing comprehensive awareness and information campaigns can increase farmers' understanding of insurance benefits and procedures. Expanding coverage and strengthening protection against climate-induced shocks would further enhance the program's effectiveness as a risk management tool.

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TECHNICAL EFFICIENCY AND TECHNOLOGY GAP OF SMALLHOLDER OIL PALM FARMERS: ISPO AND NON-ISPO IN RIAU, INDONESIA, USING A STOCHASTIC META-FRONTIER APPROACH

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ABSTRACT

This study examined how smallholder oil palm plantations in Indonesia's Riau Province were affected by Indonesian Sustainable Palm Oil (ISPO) certification in terms of technical efficiency and technological gaps. Data were collected from July 2023 to February 2024 from 177 farmers (87 ISPO-certified and 90 non-certified) in Siak District. The technical efficiency and technology gap ratios were estimated using the Stochastic Meta-Frontier (SMF) technique, considering the technological heterogeneity among the farmer groups. Results revealed that production among ISPO-certified farmers was significantly influenced by chemical fertilizer use, tree age, and interactions between land size and tree age, as well as between tree age and organic fertilizer application. Non-certified farmers' production was affected by tree age, labor input, chemical fertilizers, and interactions between tree age and chemical fertilizers. ISPO-certified farmers demonstrated higher technical and meta-technical efficiency, indicating more optimal input use and closer adherence to the best-practice production frontier. Technology gap ratios below one for both groups highlighted the potential for further technological improvements. These findings provide empirical evidence that ISPO certification enhances resource use efficiency and supports sustainable management practices among smallholder oil palm farmers, providing insightful information to extension services and policymakers looking to increase sector sustainability and productivity.

Key words: Indonesian Sustainable Palm Oil, input allocation

INTRODUCTION

The palm oil sector is a vital component of Indonesia's agricultural economy, making a substantial contribution to both regional and national economic expansion. According to Statistics Riau Province (2025), 83% of Indonesia's total non-oil and gas export revenue came from palm oil exports in 2021, which totaled over USD 35 billion. In addition to its macroeconomic contributions, the industry provides for the livelihoods of more than 17 million people and, thanks to the mandated biodiesel policy, is essential to the country's energy security. This highlights the crucial role that palm oil plays in socioeconomic elements and solidifies Indonesia's dominance as the world's top palm oil producer.

The amount of palm oil produced nationwide has been steadily increasing, and in 2023 it reached 47.08 million tons, up 0.57% from the year before. The five leading producing provinces, including Riau, contribute approximately 68.02% of the national production. Riau Province holds a strategic position with a production volume of 9.24 million tons, representing 19.59% of the national output, and a plantation area spanning 3.04 million hectares (Statistics Indonesia 2024). Most palm oil plantations in Riau are managed by smallholder farmers, who control 67.28% of the total plantation area (2.28 million hectares) and contribute 57.03% (5.26 million tons) of production. The remainder is managed by large private companies (30.50%) and state-owned plantations (2.22%) (Statistics Riau Province 2025). Palm oil is the preferred commodity among farmers in Riau due to its relatively higher profitability than alternatives such as rubber and coconut. The transition from rubber to palm oil reflects farmers' adaptation to market dynamics and agricultural development policies (Riau Plantation Office 2021). Data indicate that approximately 830,038 smallholder households cultivate palm oil, with an average annual income of IDR 46 million, significantly higher than those in rubber and coconut farming.

Nonetheless, the smallholder palm oil sector faces several challenges that hinder productivity and sustainability. Smallholders in Riau encounter constraints such as limited access to capital, low adoption of agricultural technologies, and suboptimal input management. Factors including technological changes, technical efficiency, farm scale, and plantation age structure are key determinants of productivity. Smallholder productivity in Riau remains relatively low, averaging only 3,183 kg/ha, substantially below the productivity of large plantations (Statistics Riau Province 2025). The primary causes include inadequate implementation of Good Agricultural Practices (GAP), limited knowledge, poor access to information, technology, capital, and managerial capacity. Moreover, the industry faces increasing international pressure, particularly from the European Union, regarding environmental concerns such as deforestation and greenhouse gas emissions. These issues have triggered trade restrictions and reputational risks, highlighting the necessity of implementing more efficient and sustainable production methods.

In response to increasing international pressure and to address the issue of low productivity in smallholder palm oil plantations in Indonesia, the Indonesian government made the Indonesian Sustainable Palm Oil (ISPO) certification mandatory to promote palm oil production that is both sustainable and socially responsible (Anwar et al. 2014; Ernah et al. 2019; Apriyanto et al. 2020). The ISPO program targets smallholders by encouraging compliance with labor and environmental standards, optimizing input use, and improving plantation management practices. However, adoption among smallholders remains very low. As of mid-2021, only 760 ISPO certificates had been issued nationwide—most of them to large companies—while very few were held by smallholders. Only 19 certificates had been issued in Riau Province, covering 9,344 hectares across four districts (Riau Plantation Office 2021). Key barriers include limited knowledge and training, restricted access to capital, and the complexity of ISPO requirements, which are often difficult for self-managed smallholders to implement (Hutabarat 2017; Apriyanto et al. 2020; Majid et al. 2021).

The limited success of ISPO implementation is often attributed to a mismatch between the certification's principles and requirements and smallholders' practical realities and socio-economic conditions. Factors such as older age, low levels of formal education, limited access to capital, and insufficient technical knowledge further exacerbate the challenges of adoption (Hidayat et al. 2018; Schoneveld et al. 2019; Apriyanto et al. 2020; Majid et al. 2021). In addition, Liana et al. (2023), in a literature review, highlighted several key challenges smallholder palm oil farmers face in Indonesia regarding sustainability certification. These challenges include limited understanding of sustainability concepts—particularly Good Agricultural Practices (GAP), weak institutional capacity among farmers, perceptions that certification is only accessible to wealthier farmers due to high costs, and uncertainty regarding the tangible benefits of certification. Their findings suggest that current regulations may not fully reflect smallholders' practical conditions and constraints, indicating a need for policy adjustments to enhance adoption.

Previous studies have demonstrated that inadequate adherence to sustainability standards and suboptimal farming practices pose significant challenges to the competitiveness of smallholder farmers, highlighting the need to assess the real-world effectiveness of ISPO certification thoroughly. While several studies have investigated the economic impacts of ISPO (Hutabarat 2017; Rohdiah et al. 2019; Christiawan 2020), there remains a notable research gap regarding the technical efficiency of smallholders in implementing ISPO.

Technical efficiency, defined as maximizing output from a given set of inputs by adopting best practices (Coelli et al. 2005), is critical for enhancing productivity and sustainability in agriculture. Traditional methods for measuring technical efficiency, such as stochastic frontier analysis, typically assume homogeneous production technologies among farmers. However, this assumption is increasingly questioned in heterogeneous agricultural settings. Ignoring technological heterogeneity can result in biased efficiency estimates, especially in contexts characterized by diverse institutional, ecological, and socio-economic conditions (Battese and Rao 2002; Rao et al. 2003; Battese et al. 2004; O'Donnell et al. 2008; Huang et al. 2014). Such heterogeneity is particularly relevant for ISPO-certified and non-certified smallholders in Riau, who operate under distinct production environments.

To address these limitations, the stochastic meta-frontier (SMF) approach has been developed. The SMF method estimates a meta-frontier representing the potential production boundary across all groups, alongside group-specific frontiers that capture unique technological contexts. The Technology Gap Ratio (TGR), derived from the SMF model, measures the extent to which a group's production frontier deviates from the meta-frontier, offering valuable insights into the potential for technological improvement (Huang et al. 2014). The SMF framework has been widely applied in efficiency studies of staple crops such as maize (Ng'ombe 2017), rice (Tinaprilla 2012; Junaedi 2016), and others (Alem 2021; Miriti et al. 2021; Kosarova and Pokrivcak 2023). However, its application in the palm oil sector remains limited, with only a few studies examining technological efficiency among smallholder oil palm farmers operating independently or in partnerships (Varina et al. 2020b).

Building on this framework, the present study employs the meta-frontier approach to examine technology gaps and variations in technical efficiency between ISPO-certified and non-certified smallholder oil palm plantations in Riau Province, Indonesia. Additionally, it investigates the key factors influencing productivity among these farmers. Through this analysis, the study aims to provide a comprehensive understanding of how technological heterogeneity and differences in management practices associated with certification status affect productivity outcomes.

RESEARCH METHODOLOGY

Research location. This research was carried out in Siak District, Riau Province, Indonesia (Fig. 1), which was purposively chosen due to its status as a key area for smallholder oil palm plantations and as the province's foremost center for ISPO-certified smallholders, with 11 certificates issued at the time of the study. The diverse farming systems and certification status variations among Siak's smallholders provide an ideal setting to analyze differences in farm management, technical efficiency, and sustainable cultivation adoption. Additionally, Siak's socio-economic profile broadly represents oil palm smallholders across Indonesia, enhancing the study's generalizability.

Data types and sources. Primary data were collected from 177 smallholder farmers in Siak District, Riau Province, Indonesia, through field observations and structured interviews between July 2023 and February 2024. The sample included 87 ISPO-certified and 90 non-certified farmers. ISPO-certified farmers were purposively sampled based on active plantation management and a minimum of three years' certification to ensure data reliability. Non-certified farmers were selected using justified sampling, focusing on active plantation managers without ISPO or other certifications.

Secondary data from regional agricultural offices, ISPO bodies, and government reports supplemented the primary data to enhance analysis robustness.

Figure 1. Study area location map

Data analysis. This research utilized a two-stage Stochastic Meta-Frontier (SMF) method by Huang et al. (2014) to assess and compare the technical efficiency (TE) and technology gap ratio (TGR) between ISPO-certified and non-certified smallholder oil palm farmers. This method effectively accounts for heterogeneity among groups operating under varying technological environments. Data analysis was performed using STATA MP 17 software.

Stage 1: Group-specific stochastic frontier analysis. In the initial phase, stochastic production frontiers were separately estimated for two categories of smallholder oil palm farmers: those holding Indonesian Sustainable Palm Oil (ISPO) certification and those uncertified. This differentiation accounts for potential variations in production technologies and management practices between the groups, thereby enhancing the precision of technical efficiency estimations.

Using the Stochastic Frontier Analysis (SFA) framework, this stage analyzes the factors influencing production output and inefficiency levels within each group, offering insights into efficiency disparities related to certification status.

The general specification of the stochastic production frontier is:

$$Y_{ji} = f^j(X_{1ji}, X_{2ji}, X_{3ji}, \ldots, X_{nji})e^{v_{ji}-u_{ji}} \text{ ; j = farmers group} \quad (1)$$

In its logarithmic form, the model becomes:

$$\ln Y_i = \beta_0 + \sum_{j=1}^{6} \beta_j \ln X_{ji} + \frac{1}{2}\sum_{j=1}^{6}\sum_{k=1}^{6} \theta_{jk} \ln X_{ji} \ln X_{ki} + (v_i - u_i) \quad (2)$$

The production of fresh fruit bunches (FFB), denoted as Y_i and measured in kilograms per year, is modeled as a function of several inputs. These inputs include land area (X_1) measured in hectares, age of palm trees (X_2) in years, chemical fertilizer application (X_3) in kilograms per year, organic fertilizer usage (X_4) in kilograms per year, pesticide use (X_5) in liters per year, and labor input (X_6) measured in person-hours per year. The model accounts for statistical noise, represented by v_i, which is assumed to be normally distributed with mean zero and variance $\sigma^2_{v_j}$. Additionally, an inefficiency term, u_i, captures deviations from the frontier and is assumed to follow a truncated normal distribution.

The model was estimated using maximum likelihood estimation (MLE) to obtain consistent and efficient parameter estimates. A positive β signified a positive marginal impact of inputs on output, while interaction terms reflected synergistic effects between inputs, improving the explanatory capacity of the production function. The SFA model separated the composite error term into a symmetric random error (v_i), representing statistical noise arising from measurement errors and external shocks, which was assumed to be independently and identically distributed:

$$v_i \sim N\left(0, \sigma_{vj}^2\right) \tag{3}$$

Conversely, the inefficiency term (u_i) was modeled as a truncated normal distribution, capturing deviations from the frontier due to inefficiencies in management and technology:

$$u_i \sim N^+\left(\mu_j (Z_{ji}), \sigma_{uj}^2\right) \tag{4}$$

The term N^+ refers to a normal distribution truncated at zero, ensuring the non-negativity of inefficiency scores.

Inefficiency model specification. Technical inefficiency among smallholder oil palm plantations was modeled using the following equation:

$$u_i = \delta_0+\delta_{1i}Z_{1i}+\delta_{2i}Z_{2i}+\delta_{3i}Z_{3i}+\delta_{4i}Z_{4i}+\delta_{5i}Z_{5i}+\delta_{6i}Z_{6i} \tag{5}$$

Where Z_{1i} represents the age of the *i*-th farmer in years, Z_{2i} denotes formal education measured in years, and Z_{3i} indicates farming experience in years. The number of family dependents is captured by Z_{4i}, measured as the number of people. Z_{5i} is a dummy variable for farm management type, where 1 indicates partnership (plasma farmers) and 0 represents self-managed (independent farmers). Lastly, Z_{6i} is a dummy variable for ISPO certification status, with 1 indicating ISPO-certified farmers and 0 for non-certified ones.

Positive δ values indicate increased inefficiency, while negative values reflect efficiency gains. A dummy variable differentiates farm management types: self-managed (independent) and partnership-based (plasma) farmers. Partnership farmers typically have better access to inputs, technical support, and markets, potentially boosting efficiency. This classification helps evaluate how management affects performance and access to resources. This distinction is key for ISPO certification, as awareness is higher among self-managed farmers linked to farmer groups, while many independent, non-certified farmers remain unaware. Thus, management type highlights institutional gaps affecting sustainable practice adoption and certification compliance.

Technical efficiency analysis. Technical efficiency (TE) for individual smallholder oil palm farmers in a group was estimated using the following expression:

$$TE_i^j = \frac{Y_{ji}}{f^j(X_{ji})e^{v_{ji}}} = e^{-u_{ji}} \tag{6}$$

Where TE_{ji} represents the technical efficiency score of the *i*-th farmer in group *j* Y_{ji} denotes the observed output measured as fresh fruit bunch production in kilograms per year, and $f_j(X_{ji})$ refers to the deterministic component of the production function specific to group *j*. The vector X_{ji} contains the inputs the *i*-th farmer utilizes within group *j*.

Technical efficiency (TE) values range from 0 to 1, where a value of 1 represents full efficiency, indicating that inputs are used optimally to achieve maximum output. Scores below 1 reflect varying degrees of inefficiency. A TE value above 0.7 is considered relatively high (Kumbhakar and Lovell 2000). Meanwhile, technical efficiency is categorized into three levels: low (TE < 0.6), medium (TE between 0.6 and 0.8), and high (TE > 0.8) (Tanjung 2003). This classification serves as a valuable framework for assessing the performance of smallholder oil palm farmers and identifying areas in need of targeted development interventions.

Stage 2: Meta-frontier production function and technology gap analysis. To reflect the best available technology across all groups, a stochastic meta-frontier was estimated in the second step to encapsulate the group-specific frontiers. This is how the meta-frontier production function was defined:

$$f^j X_{ji} = \ln(f^M(X_{ji})) \cdot e^{-u_{ji}^M}, \forall j,i \tag{7}$$

Where, $f^M(X_{ji})$ denotes the meta-frontier production function that includes the frontiers of both ISPO-certified and non-certified farmers, implying that $f^M(X_{ji}) \geq f^j(X_{ji})$. The term $u_{ji}^M \geq 0$ reflects the inefficiency relative to the meta-frontier caused by the technological gap.

The ratio of the group-specific frontier output to the meta-frontier output was measured by the Technology Gap Ratio (TGR), which was expressed as follows:

$$TGR_i^j = \frac{f^j(X_{ji})}{f^M(X_{ji})} = e^{-u_{ji}^M}, \; 0<TGR_{ji}\leq 1 \tag{8}$$

The Technology Gap Ratio (TGR) quantified how closely farmers employed the optimal production technology. A TGR of 1 signified that farmers operated on the meta-frontier, fully adopting the sector's most efficient production methods. In contrast, a TGR below 1 reflected a technological shortfall, which led to less-than-optimal output due to restricted access to advanced production technologies. Understanding TGR is crucial for identifying opportunities to enhance productivity through improved production efficiency, including better access to modern technologies that can help reduce disparities among smallholder farmers. In this context, the term u_{ji}^M in Equation (8) represents the degree of access to or utilization of best-practice technologies.

Meta-Technical Efficiency (MTE) assessed the overall efficiency of farmers in relation to the meta-frontier by combining both input use efficiency and the degree of technology adoption. Formally, MTE was defined as:

$$MTE_i^j = \frac{Y_{ji}}{f^M(X_{ji}) \cdot e^{V_{ji}}} = TGR_i^j \cdot TE_i^j \tag{9}$$

An MTE value of 1 indicated that farmers had fully optimized production by applying best-practice technologies and efficiently utilizing resources, achieving the highest efficiency relative to the meta-frontier. Conversely, an MTE value less than 1 signified opportunities for improvement among smallholder oil palm farmers, reflecting technological inefficiencies and gaps compared to the meta-frontier.

RESULTS AND DISCUSSION

Socio-demographic profile of smallholder oil palm farmers in Riau. Table 1 compared the characteristics between ISPO-certified and non-certified smallholder farmers in Riau Province. Significant differences were observed in organizational membership and access to training, which were closely associated with certification status and farm management quality. Case evidence from Siak District showed that ISPO-certified farmers benefited from enhanced institutional support and access to information, which likely improved productivity and encouraged the adoption of sustainable practices. These findings aligned with prior research indicating that farmer organizations facilitated compliance and sustainability through better institutional access (Nuliza et al. 2019), that training and incentives increased willingness to adopt certification (Reich and Musshoff 2025), and that organizational participation often served as a prerequisite for engaging in sustainability schemes (Jelsma et al. 2024).

Table 1. Socio-demographic characteristics oil palm smallholder farmers in Riau

Soico-demographic characteristics	ISPO certified farmers	Non-ISPO certified farmers
Farmer age (years)	51.78	48.94
Education level (years)	9.59	9.10
Farming experience (years)	24.21	23.57
Family dependents (persons)	3.00	3.00
Farmers' participation in agricultural organizations	87.00	45.00
Access to agricultural training	87.00	28.00
Characteristic smallholder oil palm plantations		
Land area (hectare)	1.94	2.49
The cultivation age of oil palm trees (years)	15.67	18.49
Planting density (trees/ha)	127.00	132.00
Input use patterns		
Fertilizer (kg/ha/year)	392.90	439.88
Pesticide (liter/ha/year)	12.77	5.37
Labor (HOK/ha/year)	35.61	32.37
Productivity and selling price		
Fresh Fruit Bunches (FFB) (kg/ha/year)	18,011.64	20,243.24
Selling price (Rp/kg)	2,879.00	1,997.00

Source: primary data on the field (2024) (own survey)

Age of farmers. Most smallholder oil palm farmers in Riau Province, whether ISPO-certified or not, were within the productive age group. ISPO-certified farmers had a slightly higher average age (51.78 years) than non-certified farmers (48.94 years). While the age gap was modest, it carried social and psychological implications. Older farmers might have been more inclined toward certification due to greater farming experience and stronger social networks. However, age-related physical and cognitive decline could have limited their adaptability to technical innovations (Ngaisset and Jia 2020). Hence, targeted extension and support services were essential to facilitate the adoption of sustainable practices among ageing farmer populations.

Education level of farmers. Formal education was a critical factor influencing the adoption of sustainability certification. ISPO-certified and non-certified farmers in Riau Province had comparable average education levels—9.59 and 9.10 years, respectively—equivalent to junior high school. Although the difference was insignificant, education enhanced farmers' understanding of sustainability concepts, certification procedures, and access to modern agricultural information and technologies. Higher education also promoted engagement in training, extension services, and institutional support, all essential for farm development. Better-educated farmers were more receptive to innovation and implemented Good Agricultural Practices (GAP), thereby improving productivity and sustainability (Alwarritzi et al. 2015). Thus, continuous investment in formal and non-formal education through training and extension was vital to increasing ISPO certification uptake among smallholders.

Farming experience. Most smallholder oil palm farmers in Riau, whether ISPO-certified or not, showed considerable farming experience, with an average exceeding 23 years. This experience constituted valuable social capital, enhancing local knowledge and supporting sustainable management practices. However, experience alone did not ensure improved farm performance without complementary access to training, technological innovations, and market incentives. Thus, integrating farming experience with institutional support such as technical training and extension services was critical to translating traditional knowledge into modern practices that complied with ISPO certification standards.

Family dependents. The average household size of smallholder oil palm farmers in Riau, irrespective of their ISPO certification status, was three dependents, ranging from one to six. This suggests that household size may have influenced their participation in ISPO certification. Farmers with more dependents faced greater economic pressure, motivating them to seek additional income through certification, which offered benefits like higher fresh fruit bunch (FFB) prices and better market access. Certified farmers gained premium prices, improved competitiveness, and stronger bargaining power, encouraging certification, especially among those with larger families. However, certification costs, administrative hurdles, and technical training remained barriers. Hence, institutional support through subsidies, training, and assistance was essential to help farmers, particularly those with many dependents, complete the certification process.

Farmers' participation in agricultural organizations. Significant differences in training participation between ISPO-certified and non-ISPO farmers reflected disparities in involvement with agricultural institutions. Most ISPO farmers were members of active organizations such as farmer group associations (Gapoktan) or cooperatives that facilitated training, extension, and technical assistance. This involvement provided broader access to information, production inputs, and administrative support critical for certification and sustainable cultivation practices.

In contrast, non-ISPO farmers, especially independent smallholders, often had weak institutional ties, limiting their access to training and support. This hampered their capacity to adopt sustainable practices and meet certification standards. This aligned with previous studies highlighting the importance of institutions in certification adoption. Nuliza et al. (2019) noted that farmer organizations improved compliance and access to support. Reich and Musshoff (2025) showed that training and incentives boosted smallholders' willingness to certify, while Jelsma et al. (2024) stressed institutional participation as key for sustainability efforts. However, Najmi et al. (2019) pointed out challenges such as low education and limited institutional capacity for financing, especially in South Aceh. The perceived low benefits reduced farmers' motivation to join organizations. Thus, strengthening farmer institutions was crucial as technical-administrative support and a strategy to increase sustainable practice adoption and certification participation among smallholder palm oil farmers.

Access to agricultural training. Table 1 revealed a significant difference in training participation between ISPO-certified and non-ISPO palm oil farmers. While all ISPO farmers attended Good Agricultural Practices (GAP) training, non-ISPO farmers primarily received training only through company partnerships. This disparity reflected gaps in technical capacity and institutional access, influencing farmers' readiness to adopt sustainable practices aligned with ISPO.

Training enhanced farmers' technical, administrative, and institutional skills and was a vital channel for the diffusion of agricultural innovation (Rogers et al. 2009). According to the Diffusion of Innovations Theory, adopters ranged from innovators to laggards. Training improved knowledge in environmental management, farm record-keeping, and certification compliance, thereby increasing production efficiency (Asaad et al. 2022). It also empowered farmers to become early adopters and change agents within their communities. Institutional training delivered through cooperatives or farmer groups was more effective than individual-based approaches. These findings highlighted the importance of strengthening institutional training and extension systems to broaden ISPO certification adoption, particularly among independent non-certified farmers with limited access to information and support.

Profile of smallholder oil palm plantations in Riau. This study examined smallholder oil palm plantations in Riau Province by comparing ISPO-certified and non-certified farmers and evaluating plantation size, oil palm age, and land ownership (Table 1).

Land area. ISPO-certified farmers managed smaller plantations (an average of 1.94 ha) than non-ISPO farmers (2.49 ha), with most plantations ranging between 2 and 2.5 hectares, classified as small to medium scale. This small-scale, individually managed structure was typical in the Indonesian smallholder sector, often limiting access to technology and markets. Consequently, farmers relied heavily on external support such as replanting programs, technical assistance, financing, and partnerships with palm oil mills (PKS). Participation in farmer groups (Gapoktan) was key to disseminating ISPO certification information among smallholders in Riau.

The cultivation age of oil palm trees. The distribution of plant ages among responses indicated that ISPO-certified and non-certified farmers cultivated oil palm trees of varying ages. The average plant age for ISPO farmers was 15.67 years, while non-ISPO farmers had older plantations, averaging 18.49 years. Agronomically, plant age was a critical factor affecting oil palm productivity. Optimal production typically occurred between 7 and 18 years, peaking around 9–14 years (Tampubolon 2016). Productivity declined gradually after this period, with significant decreases usually observed after 22 years (Lubis and Iskandar 2018). Nonetheless, sound agronomic management could mitigate the adverse effects of aging trees (Risza 2009). Therefore, effective management of plant age was essential to enhance production efficiency and sustainability, particularly for farmers aiming to comply with certification standards like ISPO.

Planting density. The study revealed differences in planting density practices between ISPO-certified and non-certified farmers. ISPO-certified plantations had an average density of 127 palms per hectare, while non-ISPO plantations averaged 132 palms per hectare. Both values fell within the technical recommendations set by the Directorate General of Plantations (2014), which ranged from 125 to 150 palms per hectare. These findings aligned with previous studies by Nainggolan and Fitri (2024) in Muaro Jambi and Chaira et al. (2024) in Batanghari, which reported similar density ranges. Although higher planting densities may have offered short-term benefits through increased early yields (Chalil et al. 2023), long-term productivity depended largely on agronomic practices aligned with sustainable cultivation principles. Therefore, optimizing planting density needed to be integrated with technical standards to maintain consistent production throughout the productive lifespan of the palms.

Input use patterns. Table 1 illustrated the differences in input usage between ISPO-certified and non-certified smallholder farmers in Riau.

Fertilization. Fertilization is critical in oil palm cultivation because it directly influences vegetative and generative growth, ultimately affecting fresh fruit bunch (FFB) yields. Budiargo et al. (2015) highlighted that inadequate or imbalanced fertilization often reduces productivity among smallholders, particularly when fertilizer application does not correspond to plant nutritional requirements. Similarly, Khalida and Lontoh (2019), in their study of independent smallholders in Sungai Sagu, Riau, emphasized that efficient fertilizer management is essential for optimal plantation performance. However, it is often constrained by limited technical knowledge and financial capacity.

Findings from this study (Table 1) show that neither ISPO-certified nor non-certified farmers fully complied with the recommended fertilizer application rates established by the Directorate General of Plantations (2014). ISPO-certified farmers applied an average of 392.90 kg/ha/year, below the recommended 471.35 kg/ha/year, possibly reflecting environmentally conscious practices encouraged through certification. Non-ISPO farmers applied 439.88 kg/ha/year, slightly below the recommended 448.86 kg/ha/year.

These findings were consistent with Varina (2020a), who reported that fertilization practices among smallholders remained suboptimal nationwide, both in quantity and in accordance with plant age and nutrient requirements. Jelsma et al. (2019) further observed that independent smallholders tended to apply fertilizers in unbalanced proportions and lower quantities than scheme-linked farmers, mainly due to their limited access to agronomic guidance and market incentives. In addition, Liana et al. (2023), in their literature review, found that farmers' limited knowledge in implementing Good Agricultural Practices (GAP) was closely linked to their restricted access to affordable production inputs and inadequate transportation for fresh fruit bunches (FFB) during harvest. These structural limitations might have indirectly affected fertilization efficiency, as farmers prioritized cost and accessibility over adherence to recommended nutrient management practices.

Pesticide. ISPO-certified farmers applied more pesticides (12.77 litres/ha/year) than non-certified farmers (5.37 litres/ha/year), likely because of the mandatory Integrated Pest Management (IPM) protocols under ISPO standards. IPM required controlled pesticide use to optimize pest control while minimizing environmental impacts. Improper herbicide use in Pelalawan, Riau, was reported to have reduced productivity by damaging tree health and soil conditions (Alwarritzi et al. 2015). However, differences in pesticide use did not necessarily indicate substantial gaps in cultivation quality, as some non-certified farmers followed similar practices but faced barriers such as certification costs and limited access to information. Thus, variations in pesticide use reflected differences in standard operating procedures and access to certification, rather than fundamental disparities in management quality. These findings highlighted the need for training and information dissemination among non-certified farmers to promote effective and environmentally responsible pest control and equitable access to certification.

Labor. Labor input was slightly higher among ISPO-certified farmers, averaging 35.61 workdays/ha/year, compared to 32.37 workdays/ha/year for non-certified farmers. This difference may have reflected more intensive management practices or additional tasks required to comply with certification standards. Despite the higher labor input, such practices could have enhanced farm productivity and sustainability through improved management efficiency.

Productivity and Fresh Fruit Bunch (FFB) Selling Price. The results revealed that the average productivity of ISPO-certified farmers was 18,011.64 kg/ha/year, slightly lower than that of non-ISPO farmers, who averaged 20,243.24 kg/ha/year. Hutabarat (2018) similarly found that productivity varied among smallholders, with RSPO-certified farmers producing 20.30 tons/ha/year, non-certified farmers 15.50 tons/ha/year, and plasma-certified farmers 13.50 tons/ha/year.

However, ISPO-certified farmers received higher FFB prices (IDR 2,879/kg) than non-ISPO farmers (IDR 1,997/kg), indicating a market preference for sustainable practices. This finding aligned with Hidayat et al. (2016) and Siregar (2023), who reported premium pricing for sustainably produced palm oil. Nevertheless, buyer–farmer partnerships also influenced price formation, suggesting that the direct impact of ISPO certification on price premiums warranted further investigation. ISPO was often regarded more as a mechanism for technical and managerial improvement than as a direct price driver (Rohdiah et al. 2019), while inconsistent compliance with sustainability standards continued to limit smallholders' access to premium markets (Schoneveld et al. 2019).

Reich and Musshoff (2025) identified price incentives and market access as key drivers motivating smallholder certification, although debates regarding ISPO's market effectiveness persisted. In this context, Mustofa et al. (2025) emphasized that ISPO was critical in promoting Good Agricultural Practices (GAP) and environmental stewardship, thereby improving production standards. Conversely, Pramudya et al. (2022) argued that ISPO's strong regulatory orientation might have constrained innovation and value creation among smallholders. These contrasting perspectives suggested that, while ISPO contributed to improved farming practices, its influence on economic incentives remained ambiguous and may have varied depending on market dynamics and the quality of implementation.

Estimation of SFA Model: Factors affecting Fresh Fruit Bunch (FFB) production. In order to examine the varying effects of input variables on FFB production between ISPO-certified and non-ISPO smallholder oil palm farmers in Riau Province, this study used a Translog production function calculated by Stochastic Frontier Analysis (SFA). The findings are compiled in Table 2.

Table 2. Estimation of factors affecting fresh fruit bunch (FFB) production and inefficiency of smallholder oil palm plantations by ISPO certification status

Variables	Stage I							
	ISPO certified				Non-ISPO certified			
	Coefficients	Z	P>|Z|		Coefficients	Z	P>|Z|	
Constant	-54.301	-2.68	0.007		1.377	0.30	0.762	
lnLand (lnX_1)	-17.389	-1.15	0.251		-1.051	-0.58	0.563	
lnAge (lnX_2)	6.066	1.37	0.170		3.590	3.10	0.002	***
lnChem (lnX_3)	11.875	2.41	0.016	**	-1.787	-2.11	0.035	**
lnOrg (lnX_4)	-0.684	-1.78	0.075	*	0.094	1.17	0.240	
lnPest (lnX_5)	7.998	1.33	0.183		1.244	1.39	0.164	
lnLab (lnX_6)	7.889	1.57	0.116		3.683	2.09	0.037	**
Quadratic variables:								
lnLand ^{squared}	1.059	0.50	0.618		0.109	0.39	0.693	
lnAge ^{squared}	2.146	1.72	0.086	*	-0.642	-7.97	0.000	***
lnChem ^{squared}	-0.302	-0.76	0.445		0.309	4.45	0.000	***
lnOrg ^{squared}	0.005	0.70	0.486		0.002	1.14	0.256	
lnPest ^{squared}	0.055	0.37	0.715		0.043	1.03	0.301	
lnLab ^{squared}	0.201	0.38	0.701		0.179	0.57	0.568	
Interaction variables:								
lnLand x lnAge	6.948	2.01	0.045	**	0.069	0.35	0.723	
lnLand x lnChem	0.418	0.13	0.896		-0.266	-0.80	0.426	

Variables	Stage I							
	ISPO certified				Non-ISPO certified			
	Coefficients	Z	P>|Z|		Coefficients	Z	P>|Z|	
lnLand x lnOrg	-0.097	-0.70	0.481		-0.008	-0.40	0.687	
lnLand x lnPest	-1.259	-0.93	0.354		0.059	0.29	0.772	
lnLand x lnLabor	1.592	0.58	0.564		0.598	1.05	0.292	
lnAge x lnChem	-0.370	-0.73	0.468		0.218	3.60	0.000	***
lnAge x lnOrg	0.417	1.74	0.082	*	-0.004	-0.68	0.494	
lnAge x lnPest	-6.216	-1.93	0.054	*	-0.170	-2.19	0.028	**
lnAge x lnLab	0.053	0.09	0.930		-0.292	-1.18	0.240	
lnChem x lnOrg	0.007	0.19	0.852		-0.009	-0.93	0.351	
lnChem x lnPest	-0.080	-0.13	0.894		0.029	0.29	0.779	
lnChem x lnLab	-1.720	-2.13	0.034	**	-0.587	-1.88	0.060	*
lnOrg x lnPest	0.017	0.73	0.466		-0.008	-0.96	0.336	
lnOrg x lnLab	0.015	0.44	0.663		-0.002	-0.12	0.908	
lnPest x lnLab	0.395	0.48	0.633		-0.279	-1.30	0.194	
Inefficiency variables:								
Constant	0.098	1.63	0.104		-5.667	-2.71	0.007	
Farmer age (Z_1)	-0.005	-0.45	0.650		0.036	0.81	0.419	
Education level (Z_2)	0.002	0.04	0.965		0.018	0.23	0.822	
Farming experience (Z_3)	0.001	0.04	0.971		-0.036	-0.91	0.363	
Family dependents (Z_4)	-0.002	-0.31	0.756		-0.059	-0.28	0.777	
Management pattern dummy (Z_5)	0.007	0.41	0.683		1.162	1.91	0.056	*
Statistics model:								
Sigma_u	0.051				0.112			
Sigma_v	0.098				0.068			
Lambda	0.519				1.645			
Log likelihood	68.801				63.458			

***, **, * significant at the α levels of 1%, 5%, and 10%, respectively.
Source: Own computation using STATA/MP17.0

ISPO certified farmers. The SFA results indicated that chemical fertilizer use (ln X_3) significantly and positively influenced FFB production, with a coefficient of 11.875 ($p < 0.05$). This underscored the critical role of chemical fertilizers as primary nutrient sources supporting palm physiological processes from vegetative growth to fruit formation. These findings reinforced previous studies by Welda et al. (2020); Ariyanto et al. (2020); Mustari et al. (2020); Syuhada et al. (2022); and Jamhari et al. (2025) that highlighted the importance of fertilizer inputs in enhancing productivity and technical efficiency in oil palm cultivation. The application of organic fertilizers ($\ln X_4$), on the other hand, had a significantly negative impact (-0.684; $p < 0.10$), which could be related to ISPO-certified farmers' inefficient usage practices and limited supply. However, in the medium and long term, organic inputs remain strategically valuable for advancing sustainable horticulture.

The squared term of plant age ($\ln X_2^2$) had a positive and statistically significant effect on production (coefficient 2.146; $p < 0.10$), indicating a nonlinear relationship where FFB yields increase at an accelerating rate as the oil palm trees mature. This reflected the variation in plantation age phases among ISPO-certified farmers—from early production stages (3–4 years) to peak productivity (12–18 years)—highlighting the need for age-specific management strategies to optimize yield and sustainability. Significant interaction effects revealed synergistic dynamics within the production system. For example, the interaction between land area and plant age ($\ln X_1 \times \ln X_2$) was positive and significant ($p < 0.05$), emphasizing effective land management during peak productive periods. Similarly, interactions between plant age and pesticide use ($\ln X_2 \times \ln X_5$) and between chemical fertilizer and labor ($\ln X_3 \times \ln X_6$) showed significant impacts, underscoring the importance of labor quality in enhancing the effectiveness of agronomic inputs in labor-intensive smallholder systems.

Overall, the production structure among ISPO-certified farmers was complex and nonlinear, requiring integrated input management approaches that consider input interdependencies rather than isolated input intensification. These results provide important implications for designing targeted policy and management strategies to enhance productivity and promote sustainable practices within the framework of ISPO certification.

Non-ISPO certified farmers. For non-ISPO-certified farmers, plant age ($\ln X_2$) positively and significantly affected FFB production (coefficient 3.590; $p < 0.01$), consistent with previous studies identifying 7–18 years as the optimal productive age range (Tampubolon, 2016). Labor input ($\ln X_6$) also had a positive impact on production (coefficient 3.683; $p < 0.05$), reflecting the essential role of manual labor due to limited mechanization.

The quadratic terms for plant age ($\ln X_2^2$) and chemical fertilizer ($\ln X_3^2$) were both significant but with contrasting signs: plant age squared was negative (−0.642; $p < 0.01$), indicating declining productivity beyond peak age, while chemical fertilizer squared was positive (0.309; $p < 0.01$), suggesting a nonlinear response that supports optimizing fertilizer dosage to avoid inefficiencies. Notably, the interaction between plant age and chemical fertilizer ($\ln X_2 \times \ln X_3$) positively influenced production (coefficient 0.218; $p < 0.01$), highlighting the importance of age-specific fertilization strategies to maximize efficiency. Significant adverse effects were observed in some input variables and interactions—such as between plant age and pesticide use, chemical fertilizer and labor, and pesticide and labor—indicating inefficiencies likely caused by suboptimal input combinations or timing. These results underscore the complexity and nonlinearity of production processes in non-ISPO farms, paralleling ISPO-certified farms, and emphasize the need for integrated, adaptive input management to enhance productivity sustainably.

Technical inefficiency of smallholder oil palm plantations in Riau. The second stage of the Stochastic Frontier Analysis (SFA) revealed significant differences in technical inefficiency between ISPO-certified and non-ISPO smallholder oil palm farmers. For ISPO-certified farmers, the lambda (λ) value of 0.519 indicated that output deviations were primarily caused by random noise rather than inefficiency. The low inefficiency variance ($\sigma_u = 0.051$) and insignificant effects of socio-economic variables (age, education, farming experience, family dependents) suggested that ISPO certification effectively standardized cultivation practices through Good Agricultural Practices (GAP). This standardization minimized variation in farm management and reduced dependency on individual farmer characteristics, fostering more uniform and efficient production.

Conversely, for non-ISPO farmers, a higher lambda ($\lambda = 1.645$) indicated that technical inefficiency was the dominant source of output variation. The inefficiency variance ($\sigma_u = 0.112$) exceeded the stochastic error variance ($\sigma_v = 0.068$), reflecting less efficient farm operations. The significant effect of farm management patterns (dummy variable coefficient = 1.162, $p < 0.10$) highlighted that traditional, experience-based practices without formal technical support contributed to inefficiency. These results highlighted how crucial institutional support and technical guidance were to raising farm efficiency.

Overall, the analysis underscored that institutional frameworks and standardized management practices were critical in reducing technical inefficiency among smallholder oil palm farmers. Enhancing managerial capacity and promoting access to extension services and training could mitigate inefficiencies and improve productivity, especially for non-ISPO farmers.

Estimation of SMF model: Factors affecting meta-frontier production. The SMF framework thoroughly analyzed efficiency levels and technological disparities between ISPO-certified and non-ISPO farmers by estimating a meta-frontier production function that accounted for technological differences across groups. The meta-frontier production function represented the highest achievable output by integrating all group-specific production frontiers. The SMF results presented in Table 3 showed that key inputs significantly influenced the meta-frontier output in Riau's smallholder oil palm sector, with plant age and labor identified as the most influential factors.

Table 3. Stochastic meta-frontier parameter estimates for smallholder oil palm plantations in Riau

Variables	**Stage II Stochastic Meta-frontier *(SMF)***			
	Coefficients	**Z**	**P>|Z|**	
Constant	1.429	0.41	0.684	
lnLand (lnX_1)	-0.432	-0.27	0.787	
lnAge (lnX_2)	2.365	4.87	0.000	***
lnChem (lnX_3)	-0.129	-0.18	0.861	
lnOrg (lnX_4)	0.041	0.64	0.520	
lnPest (lnX_5)	-0.005	-0.01	0.994	
lnLab (lnX_6)	2.502	2.21	0.027	**
Quadratic variables:				
lnLand ^{squared}	0.564	2.35	0.019	**
lnAge ^{squared}	-0.529	-8.89	0.000	***
lnChem ^{squared}	0.353	5.43	0.000	***
lnOrg ^{squared}	0.001	0.26	0.797	
lnPest ^{squared}	0.026	0.73	0.467	
lnLab ^{squared}	0.673	2.84	0.005	***
Interaction variables:				
lnLand x lnAge	0.046	0.44	0.658	
lnLand x lnChem	0.352	1.23	0.219	
lnLand x lnOrg	-0,010	-0,59	0,554	

Variables	Stage II Stochastic Meta-frontier *(SMF)*			
	Coefficients	**Z**	**P>|Z|**	
lnLand x lnPest	-0,247	-1,51	0,132	
lnLand x lnLabor	-0,496	-1,15	0,251	
lnAge x lnChem	0,111	1,91	0,056	*
lnAge x lnOrg	-0,003	-0,91	0,364	
lnAge x lnPest	-0,001	-0,01	0,993	
lnAge x lnLab	-0,083	-0,91	0,364	
lnChem x lnOrg	-0,011	-1,23	0,220	
lnChem x lnPest	-0,024	-0,27	0,789	
lnChem x lnLab	-1,125	-3,95	0,000	***
lnOrg x lnPest	-0,003	-0,54	0,589	
lnOrg x lnLab	0,015	1,10	0,270	
lnPest x lnLab	0,054	0,43	0,667	
Statistics model:				
Sigma_u	0,113			
Sigma_v	0,086			
Lambda	1,322			
Log likelihood	105,964			

***, **, * significant at the α levels of 1%, 5%, and 10%, respectively.
Source: Own computation using STATA/MP17.0

Specifically, plant age positively influenced output (coefficient = 2.365, $p < 0.01$), consistent with agronomic literature indicating peak production around 14 years of age, followed by a decline after 22 years (Tampubolon 2016; Lubis and Iskandar 2018). Additionally, labor input significantly increased productivity (coefficient = 2.502, $p < 0.05$), confirming previous research that highlighted the essential role of skilled labor in oil palm farming (Bankole et al. 2018; and Jamhari et al. 2025). Non-linear effects were observed for land area, chemical fertilizer, and labor variables, showing increasing marginal returns. Meanwhile, the squared term of plant age negatively impacted yield, indicating a decline after the optimal growth period.

Interaction effects revealed that fertilizer application synchronized with plant age significantly improved yields (interaction coefficient between plant age and chemical fertilizer: 0.111, $p < 0.10$), reflecting enhanced nutrient uptake during specific growth phases (Dubos et al. 2022). Conversely, a negative interaction between chemical fertilizer and labor (-1.125, $p < 0.01$) indicated that fertilizer effectiveness heavily depended on the availability of skilled labor for proper management. These findings emphasized the importance of balanced input management and human resource capacity development to optimize production efficiency. Overreliance on increasing input quantities without considering supporting factors may lead to resource wastage and long-term efficiency losses (Yanita and Suandi 2021).

Overall, the SMF analysis provided valuable insights into the factors influencing technical efficiency and technology gaps among smallholder oil palm farmers in Riau. Optimizing resource allocation, particularly through coordinated management of labor and inputs, was crucial for bridging technology gaps and enhancing productivity at the meta-frontier level. This study offers theoretical and practical contributions that can guide policy formulation to improve the productivity and sustainability of the smallholder oil palm sector, especially in Riau

Technical efficiency and technology gap by ISPO certification status. This study evaluated the technical efficiency and technology gap ratio of smallholder farmers in Riau, Indonesia, using the Stochastic Meta-Frontier (SMF) method. The three primary indicators were assessed: technical efficiency (TE), technology gap ratio (TGR), and meta-technical efficiency (MTE); the results were presented in Table 4.

Technical efficiency (TE). The SMF estimation showed that smallholder oil palm farmers with ISPO certification exhibited a higher average technical efficiency of 0.932. In contrast, non-ISPO farmers had an average TE of 0.893. This finding provided empirical evidence that ISPO certification positively influenced farmers' capacity to manage production inputs optimally, resulting in TE values approaching unity. Previous studies reinforced this conclusion. Varina et al. (2020b) found that farmers receiving external support (partner farmers) exhibited higher TE (0.713) compared to independent farmers (0.679). Similarly, Yuhendra et al. (2022) reported higher TE values for oil palm farmers integrating cattle farming in Riau Province, achieving 94.49% efficiency compared to 82.40% for non-integrated farmers. Compared to these studies, the TE values found in this research, particularly among ISPO-certified farmers, were notably higher, highlighting the positive impact of certification on technical efficiency.

Table 4. Estimated TE, TGR, and MTE of smallholder farmers by ISPO Certification

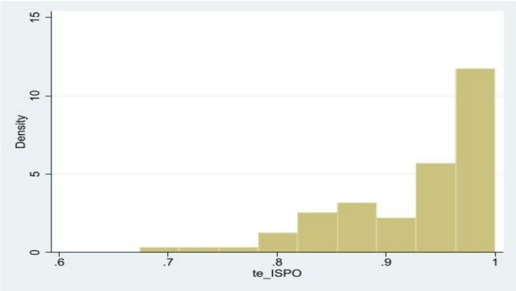
Indicator	Mean	Std. Dev.	Min.	Max.
ISPO certified:				
Technical efficiency (TE)	0.932	0.073	0.674	1
Technology gap ratio (TGR)	0.891	0.104	0.556	1
Meta-technical efficiency (MTE)	0.836	0.149	0.421	1
Non-ISPO certified:				
Technical efficiency (TE)	0.893	0.099	0.606	1
Technology gap ratio (TGR)	0.889	0.105	0.591	1
Meta-technical efficiency (MTE)	0.803	0.167	0.374	1

Source: Own computation using STATA/MP17.0

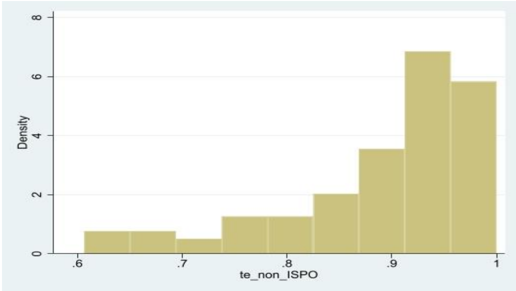
Figure 2 displayed the distribution of technical efficiency values among smallholder oil palm plantations in Riau according to ISPO certification status. The TE scores of ISPO-certified farmers ranged from 0.674 to 1, indicating greater and more reliable efficiency. In contrast, non-certified farmers displayed a wider TE range, from 0.606 to 1, reflecting greater variability and lower average efficiency. These results suggested that ISPO certification was associated with better technical performance, likely due to improved management practices, enhanced input access, and adoption of advanced technologies. The narrower TE range observed among certified farmers reflected more uniform efficiency, which could be attributed to structured support and compliance with ISPO standards.

Differences in technical efficiency indicated that ISPO-certified smallholder oil palm farmers possessed superior managerial capacity and institutional support, enabling them to operate closer to their potential production frontier. Although absolute production levels, measured in Fresh Fruit

Bunches (FFB), tended to be lower among ISPO farmers, their higher TE values reflected more efficient input utilization. This finding aligns with the production frontier theory proposed by Coelli et al. (2005), which conceptualizes technical efficiency as a relative measure of output maximization given a specific input combination, emphasizing productive efficiency rather than output quantity alone. The study empirically demonstrated that ISPO certification significantly enhanced technical efficiency among smallholder oil palm farmers in Riau Province. Certified farmers demonstrated more effective input management compared to their non-certified counterparts. Therefore, strengthening certification programs and providing continuous technical assistance were essential to improve efficiency further and support sustainable smallholder oil palm production.



a) Technical efficiency for ISPO certified



b) Technical efficiency for non- ISPO

Figure 2. Technical efficiency histogram categorized by ISPO certification status
Source: Own computation using STATA/MP17.0

Technology gap ratio (TGR). The TGR measures the degree of alignment between farmers' technology and the highest technological frontier (meta-frontier). It is calculated as the group's technical efficiency ratio to the meta-frontier efficiency. A TGR value close to one indicated a minimal technology gap and near-optimal technology use. The results showed that ISPO-certified farmers had a slightly higher average TGR (0.891) than non-ISPO farmers (0.889), suggesting that certification contributed to reducing the technology gap by encouraging the adoption of better agricultural technologies. Although the difference was marginal, it supported the notion that ISPO certification facilitated the transition from traditional to improved practices, aligning farmers closer to the best available technology.

These findings aligned with previous studies (e.g., Varina et al. 2020b), highlighting that technology adoption varied by support mechanisms and institutional arrangements. The ongoing technology gap highlighted the necessity for focused policies to improve the dissemination and adoption of technology, aiming to achieve optimal efficiency at the meta-frontier level and foster sustainable competitiveness among smallholder oil palm farmers.

Meta-technical efficiency (MTE). Meta-Technical Efficiency (MTE) comprehensively assessed farmers' ability to optimize input use relative to the meta-frontier, reflecting the highest achievable production technology. ISPO-certified farmers demonstrated a higher average MTE (0.836) than non-ISPO farmers (0.803), indicating superior efficiency not only in managing inputs (TE) but also in operating closer to the best available technology (TGR). This suggested that ISPO certification strengthened both technical and technological capabilities among smallholders.

However, MTE and TGR values below one revealed existing efficiency gaps, attributable to technological access, managerial skills, and institutional support limitations. Therefore, improving MTE required expanding the adoption of appropriate technologies and enhancing farmers' technical capacity through continuous training and extension services. Furthermore, fostering farmer institutions and multi-stakeholder partnerships—including financial institutions, cooperatives, extension agents, and private sector actors—was essential for knowledge transfer and sustainable technology innovation. Such collaboration was vital to bridging the technology gap and promoting long-term efficiency improvements in smallholder oil palm production.

CONCLUSIONS AND RECOMMENDATIONS

This study was the first to investigate technical efficiency differences between ISPO-certified and non-certified smallholder farmers in Riau Province, addressing a notable empirical gap in the literature. Its primary objective was to assess whether ISPO certification enhances resource use efficiency and plantation management among smallholder oil palm farmers. Using the stochastic meta-frontier (SMF) method, this study comprehensively analyzed technical efficiency and technology gaps across various farmer groups. By evaluating technical efficiency (TE) and technology gap ratio (TGR), the research offers robust evidence on the productivity and development potential of smallholder oil palm plantations in Riau, thereby supporting policy formulation for sustainable palm oil development in Indonesia, focusing on Riau.

Among ISPO-certified farmers, oil palm production was influenced significantly by using chemical fertilizers, the age of palm trees, and the interaction between land size, tree age, and organic fertilizer application. In contrast, the production performance of non-ISPO farmers was affected by tree age, labor input, chemical fertilizer use, and their interactions. While socio-economic factors did not significantly impact technical inefficiency, farm management practices played an important role in shaping the performance of non-ISPO farmers.

Meta-frontier analysis revealed higher technical efficiency (TE) among ISPO-certified farmers (0.932) compared to non-certified ones (0.893). However, technology gap ratios (TGR) below one in both groups indicated room for improvement through technology adoption. The higher meta-technical efficiency (MTE) in ISPO farmers reflected better technology implementation. Overall, ISPO certification improved technical efficiency and technology uptake among smallholder oil palm farmers, yet substantial potential remained for further gains through targeted technological assistance and sustainable management practices.

Moving forward, continuous training and adoption of Good Agricultural Practices (GAP) should be prioritized to enhance production efficiency and sustainability, emphasizing critical inputs such as fertilization and the management of palm tree age. Moreover, bridging technology gaps will require expanded access to training programs, advanced technologies, financial support, and the establishment of multi-stakeholder farmer organizations. Offering incentives to farmers who successfully adopt modern technologies could further reduce these gaps. These measures are essential for improving the performance of smallholder farmers within the ISPO certification framework in Indonesia, particularly in Riau Province.

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FRESH BANANA EXPORT PERFORMANCE: A COMPARATIVE ANALYSIS BETWEEN THE PHILIPPINES AND THAILAND

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ABSTRACT

Despite the Philippines' historical leadership in global banana exports, recent trends suggest its declining competitiveness, while Thailand has steadily been gaining market share. This study, conducted at the University of the Philippines Los Baños in 2024, examined the export competitiveness of fresh bananas from the Philippines and Thailand, two major players in Asia's tropical fruit trade. A multi-index framework was applied to address gaps in comparative trade analysis, using the Revealed Comparative Advantage (RCA), Trade Intensity Index (TII), and Trade Complementarity Index (TCI) to evaluate performance across key markets based on trade data covering 1990–2022. The study also assessed export stringency and policy environments to contextualize the indices. Findings revealed that Thailand consistently recorded higher TCI in major markets, reflecting stronger alignment with its importing country standards made possible by government support. In contrast, the Philippines has struggled to adapt its exports to meet diverse market quality standards and residue limits. Recommendations for the Philippines include: aligning quality standards with export market requirements; diversifying export markets and enhancing trade partnerships; and improving governance and infrastructure to support export competitiveness.

Key words: comparative advantage, trade indices, stringency

INTRODUCTION

Bananas are among the most commercially traded fruits worldwide and serve as a significant source of income for many tropical economies. In Asia, the Philippines has historically been the leading exporter of fresh bananas, especially the Cavendish variety, supplying high-demand markets such as Japan, China, and South Korea (OECD/FAO 2025). However, this dominance has been increasingly threatened by production challenges, including disease outbreaks like Fusarium wilt, climate-related disruptions, trade tensions, and growing competition from neighboring exporters (OECD/FAO 2025; Rivera 2023; Arcalas 2019).

Thailand is not among the world's largest banana exporters by volume but it has strengthened its foothold in major Asian markets such as China and Japan (Suvittawatt 2014) and has also expanded shipments to other destinations in the region, including Hong Kong (OOSGA 2023). Suvittawatt (2014) attributed this progress to the improvements in banana supply chain management, including enhanced post-harvest handling, more efficient distribution systems, and government-backed farmer support programs (e.g., low-interest credit) that help maintain product quality and competitiveness. While the OOSGA (2023) report does not specifically mention bananas, it provides broader context on Thailand's trade policy environment such as the establishment of Export Processing Zones, Special Economic Zones, and participation in multiple Free Trade Agreements—that facilitates agricultural exports, including bananas. These factors collectively underscore Thailand's emerging competitiveness in the regional banana trade, particularly within the context of ASEAN integration and shifting global market dynamic (OOSGA 2023). These developments highlight an evolving competitive landscape in the regional banana trade, particularly in the context of ASEAN integration and global market diversification.

It is strategic to compare the Philippines and Thailand not only due to their similar agro-climatic conditions but also because of their contrasting trade trajectories and policy environments (Larson et al. 2004; Dy 2014). The Philippines remains heavily dependent on banana exports for agricultural income (TradeImeX 2025; PSA 2025) whereas Thailand has diversified its fruit export portfolio and increasingly competes in markets once dominated by the Philippines (Dy 2014). This context provides a unique opportunity to examine how differences in trade policy, quality compliance, and market access strategies influence export competitiveness.

Despite the shifting dynamics, limited research exists that directly compares the export competitiveness of the Philippines and Thailand using standardized trade indices. Most studies focus either on national production trends or use broader agricultural trade indicators without isolating the banana sector. This study fills this gap by applying a multi-index approach to assess banana export performance of the two countries using the Revealed Comparative Advantage (RCA), Trade Intensity Index (TII), and Trade Complementarity Index (TCI), taking off from the methodologies of the World Bank (2010) and Balassa (1989) to a commodity-specific, long-term (1990–2022) assessment. . These indices provide a comprehensive view of each country's export specialization, trade intensity with key partners, and the alignment between export supply and market demand.

Specifically, the study aimed to analyze the trends in banana exports of the Philippines and Thailand, evaluate the competitiveness of the Philippines and Thailand in major banana-importing markets, and draw implications based on the results of the trade indices to inform evidence-based policy recommendations.

In this study, import competitiveness refers to the ability of Philippine and Thai bananas to penetrate and compete within the importing markets of their trading partners (e.g., Japan, China, Singapore). This was assessed through the TII, which measures the strength of bilateral trade with each partner, and the TCI, which measures how well the countries' export structures align with the import demand of those partners.

RESEARCH METHODOLOGY

Type and sources of data. This study applied a combination of descriptive and comparative research designs to analyze the performance of the Philippines and Thailand in the export of fresh bananas (HS Code 0803.90) using FAOSTAT data on production, area harvested, and trade volume and values from 1990-2022. The 33-year data range was chosen to capture long-term export trends, structural shifts, and competitiveness patterns across changing policy and trade environments. The study also incorporated a document review approach to evaluate the stringency of import requirements of trade partners affecting banana exports from the Philippines and Thailand. Relevant technical regulations, food safety standards such as Maximum Residue Limits (MRLs) and import protocols were examined using official documents from the Codex Alimentarius, national sanitary and phytosanitary (SPS) authorities of

Japan, China, Singapore, and Hong Kong, as well as the Philippine National Standards (PNS) and Thailand Agricultural Standards (TAS).

Methods. The Spearman Rank Correlation was used to assess the association between RCA values of Philippines and Thailand. The TII and TCI were also calculated to measure the depth of bilateral trade and how well a country's export composition matches the import demand of its trading partners, respectively, thus serving as indicators of import competitiveness in those markets. All three indices were computed using standard formulas as follows:

$$\textbf{RCA} = \frac{\frac{x_{ij}}{X_{it}}}{\frac{x_{wj}}{X_{wt}}} \qquad \textbf{TII} = \frac{\frac{x_{ij}}{X_{it}}}{\frac{x_{wj}}{X_{wt}}} \qquad \boldsymbol{TCI} = \left(1 - \sum \frac{|m_{ik} - x_{ij}|}{2}\right) x\ 100$$

Where x refers to exports, m to imports of banana; X represents total exports; the subscript t denotes the total value of exports, such that X_{it} and X_{wt} represent the total exports of country i and of the world, respectively; and the subscripts i, j, and w represent the reporting country, trading partner, and world totals, respectively.

RESULTS AND DISCUSSIONS

Global overview of fresh banana production and trade. Global banana production in 2022 reached approximately 127 million metric tons (mt), growing at an average annual rate of 4.6% since 1990 despite frequent disruptions from climate events and disease outbreaks. Of this total, only an average of 14.5% entered international trade over the 33-year period, generating approximately US $237.76 billion in export revenues (FAOSTAT 2024). The combined upward trends in both area planted, and total output led to an average yield of 12.1 tons per hectare. However, production growth has fluctuated over the years. Notable surges occurred in 1992 (6.12%), 1997 (5.8%), 2007 (5.56%), 2014 (5.15%) and 2020 (5.7%) largely driven by rising global demand for fresh bananas. In contrast, significant declines were recorded in 1996 (-0.26%), 2000 (-1.6%), 2008 (-0.53%), and 2016 (-2.92%) (FAOSTAT 2024) (Fig. 1), mostly associated with adverse weather events (Voora et al. 2023), disease outbreaks such as Fusarium wilt TR4 and Black Sigatoka and macroeconomic disruptions like inflation in major producing countries (FAO 2021). The Cavendish variety represents nearly half of global production and remains the most traded banana type due to its longer shelf life and transport resilience (FAO 2025).

The global banana production is heavily concentrated in ten countries: India, Uganda, Mainland China, the Philippines, Ecuador, Brazil, Indonesia, Colombia, Cameroon, and the Republic of Congo. These countries collectively contributed approximately 76% of the world's total fresh banana output, (author's calculations using the 33-year data from FAOSTAT 2024). However, high production does not always equate to export strength. Of the top world producers, only Ecuador and the Philippines are major exporters with the top three producers (India, Uganda, and Mainland China) participating minimally in global banana trade since their production primarily satisfies domestic demand (OECD/FAO 2025).

According to Dodo (2014), the global banana production follows two main systems: family farming and plantation production. Family farms are small-scale, use traditional methods, and yield less, mainly serving local and regional markets. In contrast, plantation systems, common in countries like Costa Rica, Honduras, and Mexico, are large-scale, capital-intensive, and geared toward high-yield export production, often managed by multinational corporations.

On the other hand, global banana export volumes have been at a generally increasing trend although some fluctuations are notable such as in 2015 where it dipped from 10.7 million mt in 2014 to 9.6 million mt. In 2022, total exports were reported at 24.37 million mt, representing a 4% decline from 2021, largely attributed to adverse weather conditions in Latin America and Asia. In terms of export value, global banana shipments generated approximately US $13.06 billion in 2020, with a slight decline to US $13.02 billion by 2022 due to falling unit prices (FAOSTAT 2024). Meanwhile, the global net banana imports fell by about 1.94% in 2022, amounting to a drop of nearly 1.1 M mt, resulting to a reduction of US $376 million in total import value (FAOSTAT 2024).

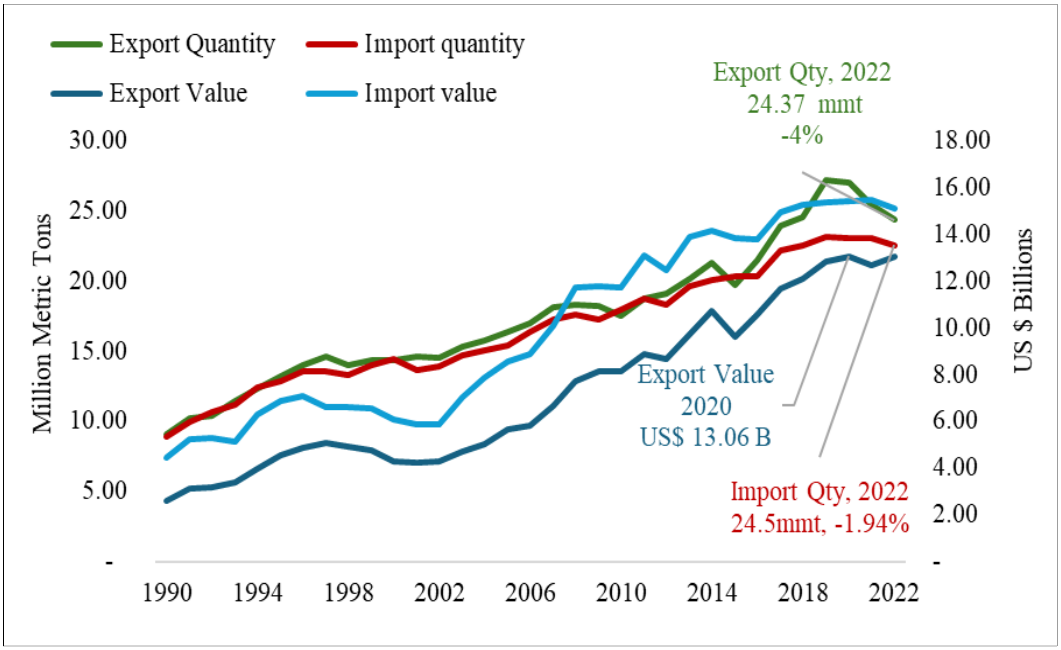

Figure 1. Global banana export and import volume and value trends, 1990-2022
Source of basic data: FAOSTAT 2024

Fresh banana production and exports (Philippines and Thailand*).* The Philippines has consistently ranked among the top global producers of fresh bananas, with production averaging 5.9 million mt annually from 1990 to 2022 (FAOSTAT, 2024). Major production areas include Davao Region, Northern Mindanao, and SOCCSKSARGEN, where large-scale plantations and corporate growers are concentrated (PCAARRD 2023). The country's export-oriented production model has enabled it to supply major Asian markets, particularly China, Japan, and South Korea (Dodo 2014). Its production volumes have been almost steadily increasing (except for a dip in 1998), until 2012 (9.23 M mt) and had an unprecedented decline for the next couple of years, to stabilize at only more than 5.9 million mt in 2022. Such declines were attributed to Fusarium wilt outbreaks, erratic weather, and increasing compliance requirements in importing countries (Arcalas 2019; FAO 2021). In 2020, a marked drop in export-quality bananas coincided with China's tightened import scrutiny characterized by increased rejections and reduced orders from Chinese importers. These disruptions underscored the vulnerability of the Philippine banana sector to phytosanitary and quality-control failures, intensifying the need for stronger regulatory compliance and logistical support (Henry 2020; Ochave 2020; Miraflor 2020).

In contrast, Thailand has historically been a domestically-oriented banana producer, with smaller-scale farms spread across multiple provinces. From 1990 to 2004, its production volumes were stable but relatively low. Beginning 2005, production has been fluctuating along with area planted but it reached approximately 1.2 million metric tons in 2022 (FAOSTAT 2024). Supported by investments in GAP certification and postharvest handling improvements (JETRO 2011; OOSGA 2023), especially in 2012 to 2014, yield has surged to a maximum of 379,730 100g per hectare or 37.97 tons per hectare surpassing that of the Philippines. However, beginning 2015, the Philippines regained its lead in yield performance. For the last 33 years, the Philippines had an average yield of 194,906 100g per hectare or 19.49 mt per hectare while Thailand had 162,979 100g per hectare or 16.30 tons per hectare (Fig. 2).

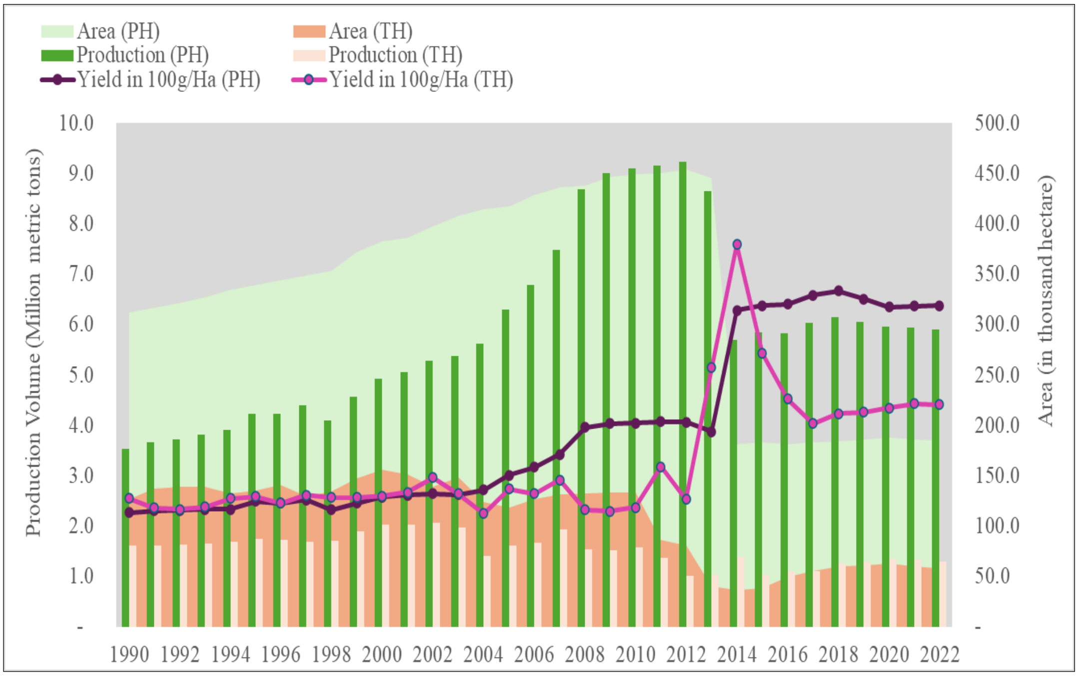

Figure 2. Philippines and Thailand banana area planted, production and yield, 1990-2022
Source of basic data: FAOSTAT 2024

In both countries, Cavendish remains the primary export variety. In the Philippines, it accounts for 50% of total banana output, followed by Saba (29%) and Lakatan (11%) (PCAARRD 2023). Thailand also exports Cavendish, but its domestic markets favor varieties like Kluai Namwa (Musa ABB), particularly the *Mali Ong* variety, prized for sun-dried banana production due to its sweetness and texture (Wongwaiwech et al. 2022). However, recent supply instability has led producers to shift to alternatives like *Nuanchan*.

The Philippine Banana Growers and Exporters Association (PBGEA) plays a central role in coordinating the export sector, comprising 22 companies across 15 provinces in Mindanao, including multinational firms like Del Monte and Dole (PBGEA n.d.). In Thailand, major exporters include Plaengyai Kluay Hom Thong Sukpaiboon Co., Ltd (Freshdi 2025), Chiquita Thailand, Dole Thailand, Del Monte Thailand, Golden Banana Co., Ltd.(ESSFeed 2025), among others

In recent years, the Philippines has continued with a large-scale, vertically integrated model vulnerable to shocks, while Thailand has advanced through product differentiation and gradual integration into regional value chains. Figure 3 illustrates the changes in the shares of the Philippines and Thailand over the past 33 years (Fig. 3). The chart highlights the dominant share of the Philippines as one of the key contributors and Thailand having a relatively smaller participation. These contrasting approaches reflect key factors underlying their divergent export performance, which are further analyzed using the RCA, TII, and TCI indices in the following sections.

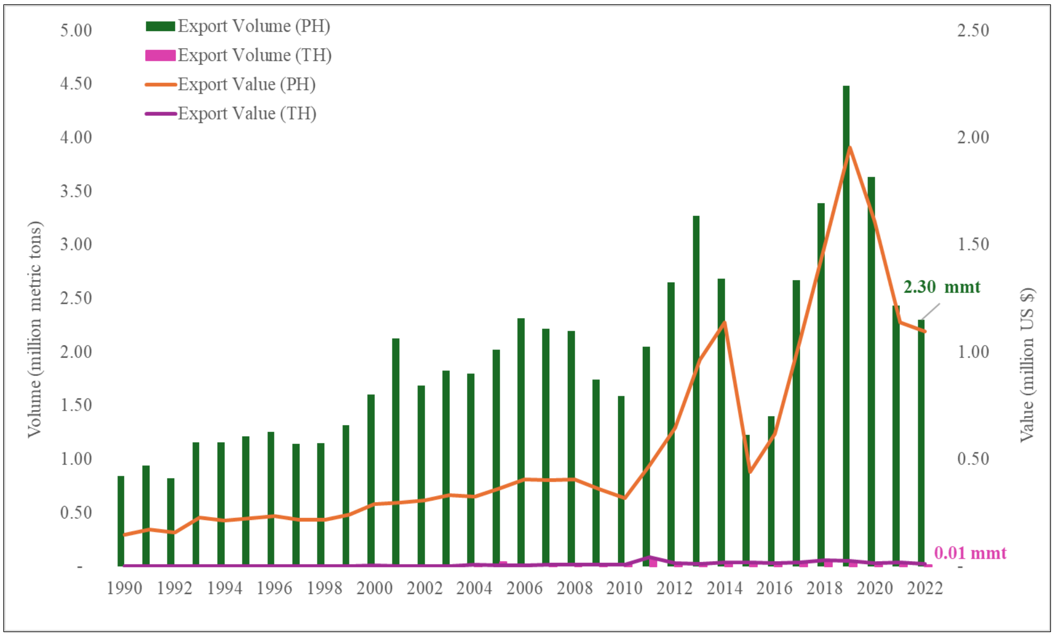

Figure 3. Philippines and Thailand banana exports volume and exports value, 1990-2022
Source of basic data: FAOSTAT 2024

Export policies and stringency measures of the Philippines and Thailand. In order to fully understand what could have possibly caused the variabilities in the banana exportation of both countries, stringency analysis was performed, comparing regulatory frameworks governing the export and import of bananas among their importing partners (Japan, China, Singapore, and Hong Kong). In this context, stringency refers to how strict importing countries are in imposing requirements for incoming products which may include, among others, pesticide residue limits, shape and size standards, labeling, and inspections and how exporting countries rigorously conform to these requirements before products are shipped. It reflects how "picky" buyers are and how "strict" sellers must be to gain and maintain market access (Hejazi et al. 2022; Engemann et al. 2024).

A related study by Fiankor et al. (2021) utilized residue level data as continuous indicators of relative stringency for specific products, allowing direct comparison across standards applied by different countries. For instance, a Maximum Residue Limit (MRL) of 0.01 ppm for a particular pesticide reflects a stricter standard than an MRL of 0.50 ppm established for the same pesticide elsewhere.

Data gathered for this study revealed that the Philippines' PNS/BAFPS 64:2008 – Banana: Grading and Classification contains provisions covering minimum quality requirements, size and class specifications, tolerances, sampling, packaging, labeling, hygiene, and other aspects of product quality. Information on contaminants and pesticide residues, including MRLs and heavy metals, is addressed in separate PNS document. In contrast, Thailand's TAS 136-2008 – Banana outlines key provisions, which include maturity, appearance, defects, size, color, trimming standards, and explicitly incorporate contaminants and pesticide residues. Both standards set quality requirements emphasizing fruit shape, cleanliness, and freedom from decay, bruises, blemishes, or latex burns. The Philippine PNS defines "Extra Class" bananas as those of superior quality with only slight superficial defects permitted, while Thailand's TAS provides the same technical parameters but supplements them with photo documentation showing acceptable and unacceptable fruit conditions. This visual feature promotes consistency in interpretation and enforcement of standards, which is not yet incorporated in the

Philippine PNS documentation (BAFPS 2008; National Bureau of Agricultural Commodity and Food Standards 2005).

In terms of MRLs, the Philippines has more MRLs for bananas (75), reflecting also the standards required by Australia, Canada, Japan, Korea, the European Union, and the Codex Alimentarius (BAFPS 2021). In contrast, Thailand listed 34 MRLs, adopting those established by the Codex and other international benchmarks (National Bureau of Agricultural Commodity and Food Standards 2005). For their major partner countries, Japan enforces MRLs for 189 pesticide active substances in bananas, China includes 69 substances (Zou et al. 2015), Hong Kong has 70 (Center for Food Safety 2025), and Singapore has 24 (Singapore Food Agency 2020).

While the Philippines listed more pesticide active ingredients with established MRL for bananas than Thailand, this alone does not imply greater regulatory stringency. It is emphasized that meaningful comparison requires evaluating the specific residue limits and concentrations of each chemical used (Fiankor et al. 2021). Based on the respective standards, only a limited number of active ingredients are common between the two countries (6 chemicals with MRLs) (Table 1).

A comparison reveals that Thailand applied a lower standard than the Philippines for certain pesticides, such as chlorothalonil (0.01 ppm versus 2.00 ppm). However, for other commonly used pesticides such as bitertanol, cadusafos, and chlorpyrifos, both countries adopt identical limits, while variations with importing partners like Japan or Singapore are often more pronounced. This suggests that regulatory stringency varies by active ingredient. Both the Philippines and Thailand demonstrate conformity and alignment depending on the pesticides and MRLs whether based on the Codex Alimentarius, data from local residue studies, or the importing country's specific regulations.

Table 1. Comparison of Maximum Residue Limits (MRLs) for selected pesticides in bananas across the Philippines, Thailand, CODEX, and major trading partners.

Common Pesticide Residue Limits	Thailand[1]	Philippines[3]	Japan[4]	China[5]	Hongkong[6]	Singapore[7]	CODEX Alimentarius (FI 0327)
Bitertanol	0.50	0.50	0.50	-	0.5	-	0.50
Cadusafos	0.01	0.01	0.01	-	0.01	-	0.01
Carbofuran	0.01	0.01	-	0.02	0.10	0.10	0.01[8]
Chlorothalonil	**0.01**	**2.00**	0.20	-	0.01	0.20	15.00
Chlorpyrifos	2.00	2.00	2.00	-	2.00	-	T 0.50[8]
Ethephon	2.00[2]	2.00	2.00	2.00	2.00	-	T 0.05[8]

Sources:

(1) *Thai Agricultural Standard 6-2005 Bananas*
(2) *Thai Agricultural Standard 9002-2013 Pesticide Residues: Maximum Residue Limits*
(3) *PNS/BAFS 160:2021 Banana – Product Standard – Maximum Residue Limits (MRLs) of Pesticides*
(4) *The Japan Food Chemical Research Foundation*
(5) *Zou et al. 2015*
(6) *Centre for Food Safety - Hong Kong Pesticide MRL Database*
(7) *Singapore Food Agency*
(8) *Agricultural and Veterinary Chemicals Code (MRL Standard) Instrument 2019*
    a. *A 'T' denotes that the MRL use is temporary*

It is important to note that Thailand's standards cannot be considered less stringent or of lower safety simply because it has fewer imposed MRLs. This is mainly due to the fact that fewer pesticides are registered for use on bananas in Thailand. Conversely, the Philippines has more registered pesticides in banana means that there are more pesticides registered for use in banana. However, the number of MRLs does not reflect the actual level of pesticide use. Instead, it indicates a broader range of approved crop protection products available to growers, allowing flexibility in pest management strategies and supporting resistance management over time.

In terms of regulation, the Philippine banana industry has pursued a range of institutional and policy-based strategies to remain competitive. One of the key approaches is sectoral diversification, including intercropping Cavendish with Saba bananas to cater to rising global demand for frozen bananas and banana chips. This strategy, backed by the Philippine Chamber of Commerce and Industry (PCCI), promotes product diversification and expands market access (Mangarin 2023).

In the Philippines, quality assurance initiatives such as farm registration, irrigation upgrades, and control of stray animals are in place, while outreach programs provide growers with technical training, although limited in scale and impact. These limitations stem from the fact that many smallholders are outside the coverage of large associations, like PBGEA and have less access to sustained support (PBGEA n.d.; PCAARRD 2023). For instance, while GAP training modules are available, only a small proportion of banana farms are formally registered and certified. In contrast, Thailand provides wider-reaching support through structured GAP certification programs, subsidies, and SEZ/EPZ incentives, enabling more consistent compliance at the smallholder level (OOSGA 2023). Long-term competitiveness will depend on sustained public investment in research, disease control, and environmental resilience (Mangarin 2023).

Thailand promotes fruits (including bananas) export competitiveness through strict phytosanitary measures under the Hazardous Substances Act, backed by incentives such as duty exemptions in Export Processing Zones (EPZs) and logistical support in Special Economic Zones (SEZs). Trade liberalization under AFTA and other agreements has further enhanced access to key markets. Aside from these incentives, Thailand also provides extensive government support for compliance with international SPS requirements and quality standards, including a structured farm-to-export traceability system and expanded MRL testing capacity through public–private collaboration (OOSGA 2023). In contrast, while the Philippines also participates in AFTA and bilateral agreements such as the Japan–Philippines Economic Partnership Agreement (Lima and Bathan 2016), government facilitation for banana exports is more limited, with tariff negotiations and compliance responsibilities largely carried out by private industry groups such as PBGEA (BAFPS 2013; PCAARRD 2023). The Philippines regulates SPS measures through its National Plant Quarantine Services and Bureau of Agriculture and Fisheries Product Standards, but enforcement capacity at the smallholder level remains weak. These differences help explain why Thailand has been more effective in ensuring compliance, resulting in fewer SPS-related rejections and stronger positioning in high-value markets (JETRO 2011; OOSGA 2023). These regulatory and policy dimensions provide essential context for interpreting the comparative trade indicators (TCI, RCA, TII) discussed in the following section.

Comparative analysis of Philippines and Thailand export competitiveness and trade performance. Each index used in this study has inherent strengths and limitations. The RCA (Balassa) index captures export specialization and offers a clear, consistent, and historically comparable measure of comparative advantage, making it widely applied in long-term, cross-country trade analysis due to its simplicity and interpretability (Hoen and Oosterhaven 2006; Cai et al. 2009). However, it does not account for economy size and may overstate competitiveness when exports are highly concentrated. The TII reflects the strength of bilateral trade relationships but may be influenced by market size or historical trade ties rather than pure competitiveness. Meanwhile, the TCI measures how well a country's exports align with partner-country import demand but does not capture price competitiveness or non-tariff barriers. Despite these limitations, combining RCA, TII, and TCI provides a more holistic perspective on export performance by integrating insights on specialization, trade intensity, and market alignment across the 33-year period analyzed in this study.

The Philippines maintained a strong comparative advantage in fresh banana exports from 1990 to 2022, with RCA values consistently above 1 (20.73), reaffirming its global competitiveness, particularly in markets like Japan and China (FAOSTAT 2024). In contrast, Thailand's RCA remained below 1 (0.04) for most of the period but has steadily increased since the early 2010s, indicating growing regional presence (Fig. 4). The Philippines' edge is attributed to its large-scale production, established export infrastructure, and contract farming models linking small growers to multinational firms like Del Monte and Dole (PBGEA n.d.; BAFS 2013). The suitable agro-climatic conditions of the country and its strategic location relative to trading partners are adding to these advantages. Contrastingly, Thailand's lower RCA reflects limited prioritization of bananas, which rank only 16th among its fruit exports in 2022 (FAOSTAT 2024). Prioritization of the other top export earners over bananas in the use of resources might have contributed to the comparative disadvantage of the latter relative to the Philippines.

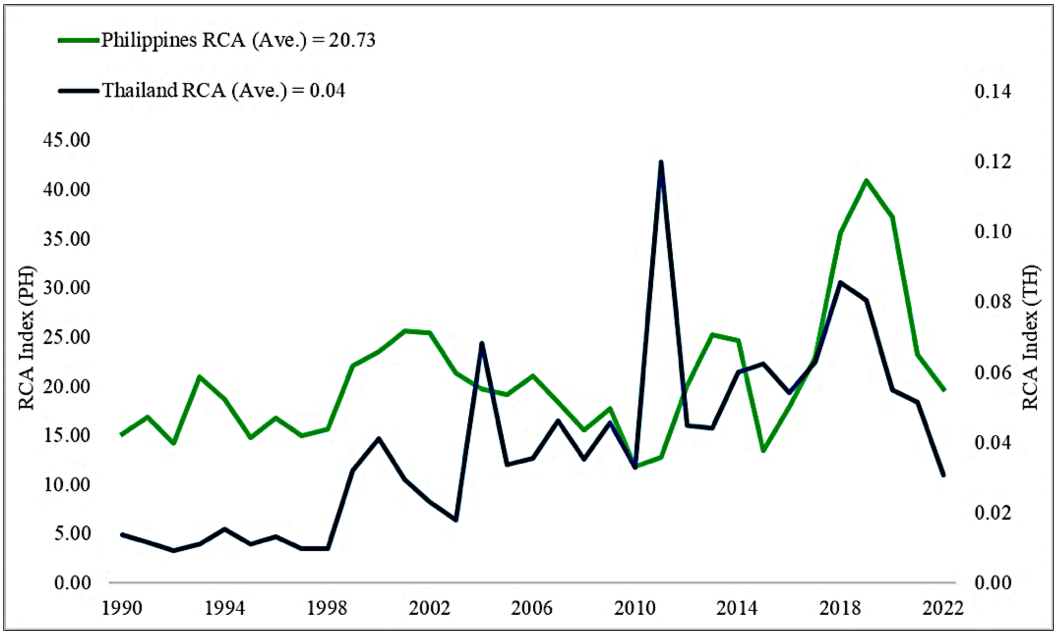

Figure 4. Revealed comparative advantage and growth rates, Philippines and Thailand banana industry, 1990-2022
Source of basic data: FAOSTAT, 2024

The Spearman rank correlation (ρ = 0.364, $p < 0.05$) suggests a moderate positive relationship between the RCA rankings of both countries, implying shared responses to regional and global market dynamics while also reflecting country-specific differences in production scale, policies, and export capacity. The low correlation coefficient could be due to the low export volume of Thailand but nevertheless could be reflective of its movement toward the export trajectory of the Philippines as bolstered by the computed TII and TCI.

In the determination of the TII and TCI of both countries, focus was on four major trading partners: Japan, China, Singapore, and Hongkong. These markets were selected due to their established roles as consistent importers and conduits of banana trade in the Asia-Pacific region. While both TII and TCI are commonly used for multi-product analysis, this study, however, applied them specifically to fresh bananas, a commodity in which both the Philippines and Thailand hold significant export specialization to provide an illustrative assessment of bilateral trade strength (TII) and market demand alignment (TCI). This approach is intended to complement, not replace, aggregate-level analyses, and highlights specific dynamics in a key export sector.

Following this approach, the Philippines shows historically strong TII with Japan and later with Singapore, although it declined after 2012 as Philippine exporters shifted trade routes following the ASEAN–China FTA and stricter Chinese import rules (Lima and Bathan 2016; Higgins 2012) (Fig. 5). Thailand, however, demonstrates high TII values with China, Hong Kong, and Singapore, bolstered by the Thailand–China FTA, growing demand, and improved logistics like the China–Laos railway (Wei and Sukhotu 2022; OOSGA 2023). Proximity, trade hubs, and product quality contribute to Thailand's growing integration into these markets (Yu 2024; Ploetz 2015).

Figure 5. Trade intensity index of Philippines and Thailand to Japan, Hongkong, China, and Singapore, 1990-2022
Source of basic data: FAOSTAT, 2024

TCI results further reinforce Thailand's increasing competitive edge, averaging 99.70 across the four trading partners indicating near-perfect alignment with import demands. The Philippines, while still competitive, recorded a lower average TCI of 91.93, suggesting some misalignment in product-market fit. Thailand's higher TCI may have stemmed from superior quality, pricing, and trade facilitation, while the Philippines faces constraints related to supply chain inefficiencies and stricter compliance issues in key markets.

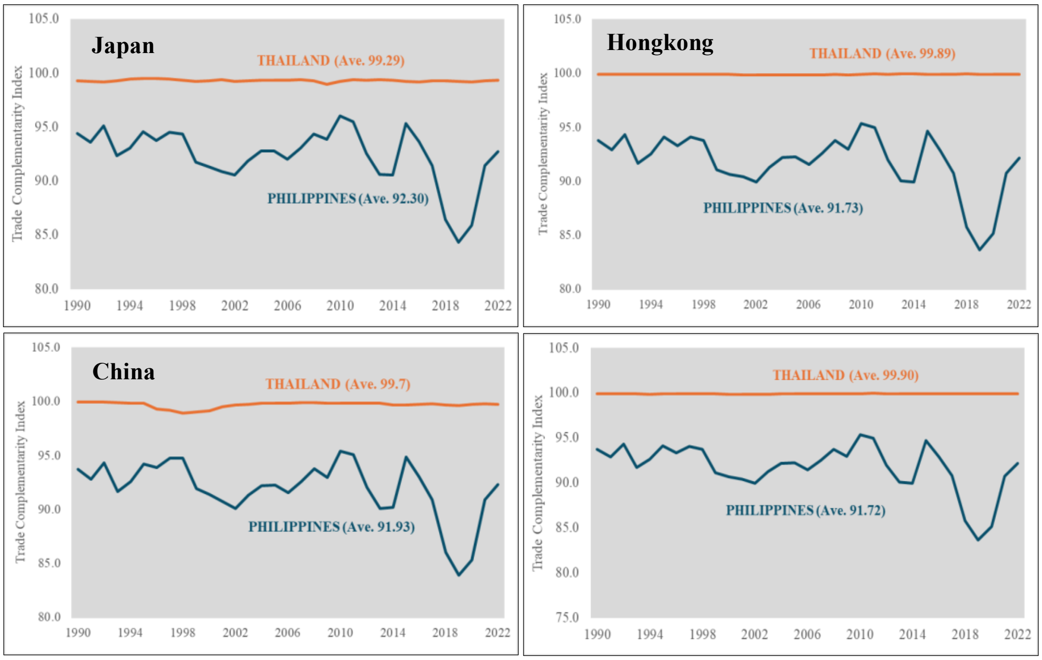

Figure 6. Trade complementarity index of Philippines and Thailand to Japan, Hongkong, China, and Singapore, 1990-2022
Source of basic data: FAOSTAT, 2024

These results highlight strategic contrasts: the Philippines excels in scale and infrastructure but faces growing risks from disease outbreaks, climate disruptions, and tightening importing country SPS standards. Thailand, meanwhile, leverages product differentiation, trade agreements, and logistics to penetrate regional markets more effectively (Ploetz 2015; Ministry of Foreign Affairs of the People's Republic of China 2018; Yu 2024). These patterns are synthesized in Table 2, which presents a comparative summary of RCA, TII, and TCI values for the Philippines and Thailand averaged over the 33-year period (Table 2).

Table 2. Comparative summary table of export competitiveness based on indicators (computed as average of 33-year data).

Indicator	Market	Philippines	Thailand
RCA > 1 = Strong comparative advantage	All Markets	**20.73** Strong comparative advantage across markets, especially with Japan and China	**0.04** Modest to moderate advantage; rising; reflecting improving export capability
TII >1 = intense trade relationship	Japan	**3.11** Very strong trade ties; reflects large volume	**2.63** Strong; reflects limited but stable trade relationship

Indicator	Market	Philippines	Thailand
	China	**1.04** Strong, but declining post-2020 due to phytosanitary issues	**2.75** Growing intensity due to increasing exports since 2010
	Hongkong	**1.38** Moderate and declining	**2.26** High and rising, likely due to proximity and quality differentiation
	Singapore	**2.46** Low and declining	**3.24** Moderate and stable, supported by geographic proximity
TCI Closer to 100 = high trade complementarity	Japan	**92.30** High but modest decline (96.01 in 2010 → 84.32 in 2019 → 92.73 in 2022) Slight weakening, with recovery in recent years; competitiveness remains strong but should be reinforced	**99.29** Exceptionally high and stable; indicating better structural match with Japan's import needs
	China	**91.93** Declining (95.41 in 2010 → 83.92 in 2019 → 92.32 in 2022); Weakened complementarity, indicating need to align exports with China's import needs	**99.70** Exceptionally high and stable; High complementarity due to increased export diversity
	Hongkong	**91.73** Downward trend 95.34 in 2010 → 83.63 in 2019 → 92.17 in 2022; Needs improved alignment with Hongkong import demand	**99.89** Exceptionally high; near perfect stability likely due to Thailand's product match and quality standards
	Singapore	**91.72** Declining 95.34 in 2010 → 83.63 in 2019 → 92.17 in 2022; Needs improved alignment with Singaporean import demand	**99.90** Exceptionally high near perfect stability; reflecting both direct demand and re-export role

Source of basic data: FAOSTAT, 2024

CONCLUSIONS AND RECOMMENDATIONS

This study examined the export competitiveness of the Philippines and Thailand in the fresh banana trade, highlighting how production capacity, SPS measures, and trade partnerships shape their performance. The Philippines maintains a strong production base and historical comparative advantage but faces declining export competitiveness due to disease outbreaks, climate disturbances, rising costs, and trade tensions. Thailand, though lacking a similar production advantage, has gained ground through strict quality enforcement, trade agreements, and improved logistics, enabling access to high-value markets such as Japan and China. Both countries share vulnerabilities to pests and climate variability, yet Thailand's proactive standardization and market strategies have strengthened its position. If structural and policy gaps in the Philippines remain unaddressed, Thailand may eventually overtake it in the regional banana trade.

To sustain and strengthen its competitiveness, the Philippines should align its national standards with importing-country requirements while continuing to base its MRLs on locally generated residue data that reflect actual production conditions. Establishing standardized testing facilities near production hubs will enhance compliance and product consistency to meet global market demand, while promoting organic and climate-resilient farming practices will support sustainable market access. Expanding trade partnerships beyond traditional markets such as Japan, China, South Korea, and Europe, can help reduce vulnerability to global market shifts. In parallel, the government should foster stronger governance and infrastructure support through public–private partnerships, empower industry organizations such as PBGEA, and invest in cold storage, transport, and export facilities. Learning from Thaland's use of export processing zones and strategic branding could help Philippines create a premium banana niche and enhance export competitiveness taking advantage of its high RCA. These measures will enable smallholders to participate more effectively in export chains, enhance quality assurance, and ensure long-term resilience of the Philippine banana industry.

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ECONOMIC, CLIMATIC, AND INPUT DETERMINANTS OF AGRICULTURAL PRODUCTION: EVIDENCE FROM 33 COUNTRIES ACROSS INCOME GROUPS

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ABSTRACT

This study examines the long- and short-run relationships between economic, climatic, and agricultural input factors and agricultural production value (AGPVI) across 33 countries classified by income level: high-, upper-middle-, and lower-middle-income. Using the Panel ARDL model, supported by DOLS and FMOLS estimations, the study identifies both dynamic and cointegrated relationships among variables. In the long run, fertilizer consumption (FRTZQ) consistently shows a positive and significant effect on agricultural production across all income groups, while GDP (GDPII) and rainfall (RAINI) exhibit varying impacts depending on income level. Agriculture in high-income countries is largely technology- and efficiency-driven, whereas in upper- and lower-middle-income countries, growth relies more on input intensification and macroeconomic factors. In the short run, GDP and agricultural inputs significantly influence production fluctuations, while climatic factors are more prominent in lower-middle-income countries. The negative and significant ECM values confirm a stable adjustment process toward long-run equilibrium. Overall, the results support structural transformation theory, indicating that as income rises, agriculture's role shifts from being a primary growth driver to ensuring economic stability and food security. Policy recommendations emphasize technological innovation in high-income countries, input-efficient growth in upper-middle-income countries, and stronger climate adaptation in lower-middle-income countries.

Key words: agricultural sector, ARDL, DOLS, FMOLS

INTRODUCTION

Climate change poses a significant threat to the agricultural sector worldwide, as this sector is highly sensitive and profoundly affected by climatic shifts (Chandio et al. 2021; Iizumi et al. 2025). Numerous empirical studies have documented the adverse consequences of climate change for agricultural development. For example, Khan et al. (2022) show that across all income groups, agricultural growth has declined due to climatic pressures. Kalkuhl and Wenz (2020) further highlight that rising global temperatures and extreme weather events threaten agricultural productivity and, consequently, food security (Hogan and Schlenker 2024). However, while these studies emphasize the negative effects, there remains limited consensus on how specific climatic and economic variables interact to shape agricultural performance across different income groups. This research gap provides an opportunity for a more nuanced investigation that links climate change indicators with conventional production and macroeconomic factors.

The agricultural sector is deemed vital due to its dual strategic roles: as a provider of food for consumption and as a source of employment for 36% of the global workforce. According to (FAO 2021), climate change could lead to a 10–25% annual reduction in crop yields, driven by natural disasters and pest outbreaks (Xue et al. 2024). Such impacts exacerbate poverty, which still affects over 800 million people globally. If unaddressed, climate change is likely to further aggravate global poverty (Carattini et al. 2020). Hence, understanding how climate-related variables and economic drivers jointly affect agricultural production is critical to formulating effective policy responses.

This study contributes by providing a stronger conceptual framework for the explanatory variables. Gross Domestic Product (GDP) is considered a proxy for macroeconomic capacity, which supports investments in agricultural technology, infrastructure, and adaptation strategies. Fertilizer use reflects the role of modern agricultural inputs in enhancing yields, though with potential environmental trade-offs. Irrigation represents an adaptation measure that reduces reliance on rainfall variability and enhances production stability. Rainfall is both a direct production input and an indicator of climate variability. Finally, CO_2 emissions serve as a proxy for anthropogenic climate change pressures that may indirectly affect agriculture through global warming and extreme weather patterns. By integrating these variables, the framework allows us to capture both environmental and economic drivers of agricultural performance.

Regarding country selection, this study focuses on 33 of the world's leading agricultural commodity producers. The selection is based on their consistently high agricultural production values, their significant contribution to global GDP, and the share of agriculture in their national economies. Collectively, these countries account for more than 85% of global GDP and around 8% of agricultural value-added worldwide (FAO 2024). While this approach ensures that the analysis captures the majority of global agricultural output, it may exclude smaller, agriculture-dependent economies that are highly vulnerable to climate change (Heikonen et al. 2025). This limitation is acknowledged, but the focus on large producers is justified to provide insights into the performance of countries that shape global food supply and trade. Future research may extend the analysis to smaller economies to better capture vulnerability in marginal contexts.

In sum, this study seeks to address existing gaps by examining the combined influence of climatic and economic variables on agricultural performance across different income classifications. The results are expected to provide region- and income-specific policy implications for building resilience in the agricultural sector against climate change.

RESEARCH METHODOLOGY

Data types and sources. To achieve its research objectives, this study utilized the Augmented Autoregressive Distributed Lag (ARDL) model. According to (Anh et al 2023), the ARDL model offers several advantages: (1) it effectively addresses issues of endogeneity and serial correlation, (2) it accommodates variables that are integrated at order zero [I(0)], order one [I(1)], or a mix of both, (3) it allows some regressors to be endogenous, (4) it performs well with relatively small sample sizes, and (5) it simultaneously estimates short-term and long-term effects.

Based on these strengths, the study constructs five single-equation models, categorized according to the income levels of countries, as follows:

Model I: High Income
$AGPVI = f(RAINI, GDPII, CO2WD, FRTZQ)$

Model II: Lower Middle Income

$AGPVI = f(INPIX, TFPIX, LBORQ)$

Model III: Upper Middle Income
$AGPVI = f(RAINI, GDPII, CO2WD, IRRIQ)$

Model IV: All Countries
$AGPVI = f(GDPII, FRTZQ, RAINI, IRRIQ)$

The theoretical foundation of this study is rooted in production economics and climate change theory. From the production economics perspective, agricultural output is determined not only by conventional inputs such as labor, land, fertilizer, and irrigation, but also by environmental and climatic factors that directly affect productivity. Gross agricultural production value (AGPVI) reflects the aggregate outcome of combining these inputs, while climate variability introduces risks that can alter both efficiency and long-term sustainability.

To ensure consistency across the analysis, all data were harmonized. The time coverage was standardized to the period 1990–2020 for all models and country groups, and the number of countries was fixed at 33 major producers. These 33 countries were selected based on their consistently high agricultural production values and their collective contribution of more than 85% to global GDP and approximately 8% to global agricultural value added (FAO 2024). Although this approach excludes some smaller countries highly dependent on agriculture, it ensures a representative global coverage of agricultural output while acknowledging that results may not fully capture the vulnerability of small, agriculture-dependent economies.

The explanatory variables were carefully defined and adjusted for comparability. GDP (GDPII) was expressed in constant 2015 US dollars to align with the dependent variable (AGPVI), which is reported in constant 2014–2016 US dollars. Agricultural inputs were normalized to improve cross-country comparability: fertilizer use was expressed per hectare of arable land, irrigation was measured as irrigated area relative to total arable land, and labor was scaled as agricultural labor force per hectare. These adjustments reduce bias due to scale differences among countries and enhance the robustness of the analysis. Table 1 presents the operational definitions of variables after these adjustments.

Table 1. Operational definition of variables

Notation	Description	Unit	Sources
AGPVI	Gross Agricultural Production Value	Constant 2014–2016 thousand USD	FAOSTAT
LBORQ	Agricultural Labor Force	Workers per hectare of arable land	FAOSTAT
INPIX	Index of total agricultural input	Index, 2015=100	USDA ERS
TFPIX	Index of agricultural TFP	Index, 2015=100	USDA, ERS
GDPII	Gross Domestic Product	Constant 2015 US$	WDI
FRTZQ	Quantity of total agricultural fertilizer	Metric tons per hectare of inorganic N, P, K and organic N	FAOSTAT
IRRIQ	Quantity of total area equipped for irrigation	1000 hectares	USDA, ERS

Notation	Description	Unit	Sources
GHGMI	Greenhouse Gas Emissions	CO_2 equivalents	Our World in Data
RAINI	Precipitation	Millimeters per year	World Bank
CO2WD	Total CO_2 Emissions	Kiloton (kt)	World Bank

The focus of this study was to examine 33 major countries with the highest average Gross Agricultural Production Value (GPV). The countries included in the analysis were: Algeria, Argentina, Australia, Bangladesh, Brazil, Canada, Chile, Colombia, Egypt, France, Germany, Greece, Indonesia, Iran, Italy, Japan, Kenya, Malaysia, Mexico, Netherlands, New Zealand, Nigeria, Pakistan, the Philippines, Poland, Republic of Korea, South Africa, Spain, Thailand, Türkiye, the United Kingdom, the United States, and Viet Nam. Collectively, these 33 nations represented an average of 85.63% of global GDP over the 1990–2020 period. Additionally, they had an average agricultural sector share of 8.41% of their respective national GDPs (FAO 2024). The income classification criteria followed those established by the World Bank.

This study employed the Panel Autoregressive Distributed Lag (ARDL) framework to estimate the short-run and long-run relationships between climate and economic variables and agricultural production. The ARDL approach is appropriate when the underlying variables are integrated of mixed orders, I(0) and I(1), but not I(2). Importantly, while ARDL can accommodate regressors with different integration orders, it requires regressors to be weakly exogenous in the long run; therefore, it does not solve endogeneity problems in a strict econometric sense. Instead, the method assumes that explanatory variables do not respond contemporaneously to short-run shocks in the dependent variable. This distinction is important for interpreting the results, as it highlights the limitations of ARDL relative to instrumental variable or structural approaches. Table 2 displays the descriptive statistics of the variables used in this study.

Table 2. Descriptive statistics

Variables	Mean	Median	Maximum	Minimum	Std. Dev.	Coefficient of Variation (%)
AGPVI	1,732,209	1,730,088	1,973,088	1,574,137	0.76	0.00
CO2WD	1,220,064	1,236,915	1,556,919	8,698,064	1,196,623	98.08
FRTZQ	1,424,749	1,434,351	1,697,681	1,088,329	1,020,519	71.63
GDPII	2,691,434	2,668,949	3,063,470	2,413,876	1,274,581	47.36
INPIX	4,524,703	4,570,898	5,065,978	3,792,875	0.19	0.00
IRRIQ	7,448,381	7,560,601	1,020,618	3,988,984	1,334,124	17.91
LBORQ	7,830,821	7,714,771	1,066,993	4,961,445	1,483,715	18.95
RAINI	6,671,643	6,685,861	8,179,760	2,302,585	1,016,822	15.24
TFPIX	4,477,716	4,513,084	4,836,025	3,894,737	0.16	0.00

To evaluate the stationarity of the data, this study applied the Augmented Dickey-Fuller (ADF), Phillips-Perron (PP), and Kwiatkowski-Phillips-Schmidt-Shin (KPSS) tests. These three tests were employed to ensure robustness in assessing stationarity, as the ADF and PP tests operate under the null hypothesis of non-stationarity (presence of a unit root), while the KPSS test uses the null hypothesis of stationarity. By combining these complementary approaches, potential biases or weaknesses in individual tests—such as sensitivity to serial correlation in ADF or heteroskedasticity in PP—could be mitigated, providing a more reliable confirmation of whether the series are stationary or require differencing. All variables included in the ARDL model were converted into their natural logarithmic forms to stabilize variance and facilitate interpretation in terms of elasticities. Additionally, a cointegration test was performed to verify the existence of a long-run relationship among the variables. The outcomes of the stationarity tests are summarized in Table 3.

Table 3. Panel unit root test results (ADF, PP, and KPSS)

Country Groups	Variables	ADF Test		PP Test		KPSS Test	
		Level	1st Diff.	Level	1st Diff.	Level	1st Diff.
High-income countries	AGPVI	46.99**	232.84*	96.29*	1,313.50*	0.41***	0.11***
	RAINI	125.03*	280.43*	504.98*	3,343.78*	0.78***	0.05***
	GDPII	159.11*	274.06*	233.83*	3,611.03*	3.14***	0.28***
	CO2WD	6.64	87.95*	3.76	191.41*	0.46***	0.07***
	FRTZQ	41.55***	180.50*	57.68*	519.37*	0.48***	0.09***
Lower-middle countries	AGPVI	12.10	71.46*	23.09***	193.93*	0.74***	0.05***
	INPIX	4.49	61.19*	8.24	616.62*	0.15***	0.03***
	TFPIX	10.49	62.38*	21.35***	399.84*	0.21***	0.05***
	LBORQ	4.17	30.18*	3.61	72.49*	0.45***	0.09***
Upper-middle countries	AGPVI	37.99**	205.24*	50.51*	931.16*	0.17***	0.08***
	GDPII	299.35*	1,368.79*	1,597.11*	2,684.20*	2.85***	0.05***
	FRTZQ	37.14**	150.77*	37.28**	623.95*	0.37***	0.10***
	RAINI	62.73*	181.95*	124.66*	2,078.52*	0.32***	0.12***
All countries	AGPVI	97.09*	509.55*	169.89*	2,438.59*	0.21***	0.02***
	GDPII	39.78	160.84*	31.01	473.33*	0.17***	0.02***
	FRTZQ	97.08*	436.22*	128.14*	2,024.92*	0.30***	0.04***
	RAINI	229.36*	579.26*	740.69*	7,095.22*	0.37***	0.02***
	IRRIQ	351.35*	434.80*	113.44*	534.86*	0.14***	0.02***

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

The stationarity test results in Table 3 indicate that the variables across different income groups are integrated at mixed orders, namely I(0) and I(1). The combination of I(0) and I(1) integration levels justifies the use of the ARDL approach, which can appropriately handle regressors with mixed orders of integration but not I(2). This finding further confirms the robustness of the subsequent cointegration test and supports the validity of employing the Panel ARDL model to capture both short-run and long-run dynamics among the variables.

The general ARDL (p, q_1, …, q_k) model can be written as:

$$AGPVI_{it} = \alpha_i + \sum_{j=1}^{p} \phi_{ij}\, AGPVI_{i,t-j} + \sum_{m=1}^{k}\sum_{j=0}^{q_m} \beta_{imj}\, X_{m,i,t-j} + \varepsilon_{it}$$

where AGPVI denotes the agricultural production value for country i at time t; X_m represents the explanatory variables (GDP, fertilizer use, irrigation, rainfall, etc.); and ε_{it} is the error term.

The short-run dynamics are captured through the corresponding Error Correction Model (ECM), in which the coefficient of the lagged error correction term (ECM_{t-1}), denoted by λ, measures the speed of adjustment toward the long-run equilibrium. A significant and negative λ confirms the existence of a stable long-run relationship.

The ARDL bounds testing approach was applied to identify both short run and long-run effects, which are represented in the following linear equation:

High income

$$\begin{aligned}\Delta AGPVI_t = {} & \alpha_0 + \alpha_1 AGPVI_{t-1} + \alpha_2 RAINI_{t-1} + \alpha_3 GDPII_{t-1} + \alpha_4 CO2WD_{t-1} + \alpha_5 FRTZQ_{t-1} \\ & + \sum\nolimits_{i=1}^{p} \alpha_{6i} \Delta AGPVI_{t-i} + \sum\nolimits_{i=1}^{q} \alpha_{7i} \Delta RAINI_{t-i} + \sum\nolimits_{i=1}^{r} \alpha_{8i} \Delta GDPII_{t-i} \\ & + \sum\nolimits_{i=1}^{s} \alpha_{9i} \Delta CO2WD_{t-i} + \sum\nolimits_{i=1}^{t} \alpha_{10i} \Delta FRTZQ_{t-i} + u_t\end{aligned}$$

Lower middle income

$$\begin{aligned}\Delta AGPVI_t = {} & \alpha_0 + \alpha_1 AGPVI_{t-1} + \alpha_2 INPIX_{t-1} + \alpha_3 TFPIX_{t-1} + \alpha_4 LBORQ_{t-1} \\ & + \sum\nolimits_{i=1}^{p} \alpha_{5i} \Delta AGPVI_{t-i} + \sum\nolimits_{i=1}^{q} \alpha_{6i} \Delta INPIX_{t-i} + \sum\nolimits_{i=1}^{r} \alpha_{7i} \Delta TFPIX_{t-i} \\ & + \sum\nolimits_{i=1}^{s} \alpha_{8i} \Delta LBORQ_{t-i} + u_t\end{aligned}$$

Upper middle income

$$\begin{aligned}\Delta AGPVI_t = {} & \alpha_0 + \alpha_1 AGPVI_{t-1} + \alpha_2 GDPII_{t-1} + \alpha_3 FRTZQ_{t-1} + \alpha_4 RAINI_{t-1} \\ & + \sum\nolimits_{i=1}^{p} \alpha_{6i} \Delta AGPVI_{t-i} + \sum\nolimits_{i=1}^{q} \alpha_{7i} \Delta GDPII_{t-i} + \sum\nolimits_{i=1}^{r} \alpha_{8i} \Delta FRTZQ_{t-i} \\ & + \sum\nolimits_{i=1}^{s} \alpha_{9i} \Delta RAINI_{t-i} + u_t\end{aligned}$$

All countries

$$\begin{aligned}\Delta AGPVI_t = {} & \alpha_0 + \alpha_1 AGPVI_{t-1} + \alpha_2 GDPII_{t-1} + \alpha_3 FRTZQ_{t-1} + \alpha_4 RAINI_{t-1} + \alpha_5 IRRIQ_{t-1} \\ & + \sum\nolimits_{i=1}^{p} \alpha_{6i} \Delta AGPVI_{t-i} + \sum\nolimits_{i=1}^{q} \alpha_{7i} \Delta GDPII_{t-i} + \sum\nolimits_{i=1}^{r} \alpha_{8i} \Delta FRTZQ_{t-i} \\ & + \sum\nolimits_{i=1}^{s} \alpha_{9i} \Delta RAINI_{t-i} + \sum\nolimits_{i=1}^{t} \alpha_{10i} \Delta IRRIQ_{t-i} + u_t\end{aligned}$$

Where Δ denotes the change in the variable, and p, q, r, s, and t represent the optimal lag lengths for each respective variable.

Following this, the short-run dynamics within the ARDL framework are represented by the equation below:

High income

$$\Delta AGPVI_t = \alpha_{11} + \sum_{i=1}^{p} \alpha_{12i} \Delta AGPVI_{t-i} + \sum_{i=0}^{q} \alpha_{13i} \Delta RAINI_{t-i} + \sum_{i=0}^{r} \alpha_{14i} \Delta GDPII_{t-i} + \sum_{i=0}^{s} \alpha_{15i} \Delta CO2WD_{t-i} + \sum_{i=0}^{t} \alpha_{16i} \Delta FRTZQ_{t-i} + \lambda ECM_{t-1} + u_t$$

Lower middle income

$$\Delta AGPVI_t = \alpha_{11} + \sum_{i=1}^{p} \alpha_{12i} \Delta AGPVI_{t-i} + \sum_{i=0}^{q} \alpha_{13i} \Delta INPIX_{t-i} + \sum_{i=0}^{r} \alpha_{14i} \Delta TFPIX_{t-i} + \sum_{i=0}^{s} \alpha_{15i} \Delta LBORQ_{t-i} + \lambda ECM_{t-1} + u_t$$

Upper middle income

$$\Delta AGPVI_t = \alpha_{11} + \sum_{i=1}^{p} \alpha_{12i} \Delta AGPVI_{t-i} + \sum_{i=0}^{q} \alpha_{13i} \Delta RAINI_{t-i} + \sum_{i=0}^{r} \alpha_{14i} \Delta GDPII_{t-i} + \sum_{i=0}^{s} \alpha_{15i} \Delta CO2WD_{t-i} + \sum_{i=0}^{t} \alpha_{16i} \Delta IRRIQ_{t-i} + \lambda ECM_{t-1} + u_t$$

All countries

$$\Delta AGPVI_t = \alpha_{11} + \sum_{i=1}^{p} \alpha_{12i} \Delta AGPVI_{t-i} + \sum_{i=0}^{q} \alpha_{13i} \Delta GDPII_{t-i} + \sum_{i=0}^{r} \alpha_{14i} \Delta FRTZQ_{t-i} + \sum_{i=0}^{s} \alpha_{15i} \Delta RAINI_{t-i} + \sum_{i=0}^{t} \alpha_{16i} \Delta IRRIQ_{t-i} + \lambda ECM_{t-1} + u_t$$

Based on the equation, a negative and statistically significant coefficient of ECM_{t-1} (λ) indicates the existence of cointegration within the model. This reflects the speed at which any temporary deviation in the relationship between the dependent and independent variables returns to the long-run equilibrium. Table 4 presents the results of the panel cointegration test.

Table 4. Panel cointegration test results (Pedroni and Kao Tests)

Country Groups	Panel v-stat.	Panel rho-stat.	Panel PP-stat.	Panel ADF-stat.	Group rho-stat.	Group PP-stat.	Group ADF-stat.	Kao ADF-stat.
High-income countries	-2.16	2.63	1.51	4.26	1.68	-1.88*	2.47	2.42*
Lower-middle countries	6.23**	-4.04**	-6.39*	-0.49	-1.43***	-4.36*	-0.47	-3.62*

Upper-middle countries	-2.48	0.61	-1.49	1.20	1.39	-1.34***	1.75	-3.30*
All countries	-1.11	0.21	-1.36***	1.57	1.29	-1.07	2.65	-1.25***

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

The results of the Pedroni and Kao residual cointegration tests confirm the presence of a long-run equilibrium relationship among the variables across most country groups. Several Pedroni statistics, both within and between dimension, are significant for high-income, upper-middle-income, and the full sample, while the Kao test also consistently rejects the null of no cointegration. Although the evidence is weaker for lower-middle-income countries, at least one of the tests indicates cointegration. These findings validate the suitability of the Panel ARDL model, which is capable of capturing both short-run dynamics and long-run relationships in the presence of cointegration.

Three dynamic panel estimators were considered: the Mean Group (MG), the Pooled Mean Group (PMG), and the Dynamic Fixed Effects (DFE). The MG estimator allows full heterogeneity across groups, while the PMG restricts long-run coefficients to be homogeneous but permits heterogeneous short-run dynamics. The DFE estimator imposes homogeneity on both long- and short-run coefficients. To determine whether PMG is appropriate, Hausman tests were conducted, comparing PMG against MG to test the null hypothesis that the long-run coefficients are homogeneous across groups. If the null is not rejected, PMG is preferred due to its efficiency gains, while rejection of the null suggests that the MG estimator, which allows for full heterogeneity, provides more reliable estimates.

Lag length selection was based on the Akaike Information Criterion (AIC), balancing goodness of fit and parsimony across specifications. Consistent lag lengths were applied across groups to facilitate comparability.

Because climate and market shocks often affect many countries simultaneously, the possibility of cross-sectional dependence was formally tested. Robustness checks were conducted using the Common Correlated Effects (CCE) ARDL specification, which augments the standard ARDL with cross-sectional averages of the dependent and independent variables. This specification accounts for unobserved common factors, ensuring that global shocks do not bias long-run coefficients. The CCE approach is widely recognized as a reliable method to address cross-sectional dependence in panel data, particularly in studies involving global phenomena such as climate change. By incorporating common factors, the CCE-ARDL provides more consistent and unbiased estimates, allowing the results to better reflect both country-specific dynamics and shared global shocks.

Overall, the empirical strategy involved four steps: (1) testing for stationarity and cointegration, (2) estimating panel ARDL models across income groups, (3) conducting robustness checks with alternative estimators (MG, PMG, DFE, CCE), and (4) validating results through Hausman tests and sensitivity analyses. This comprehensive methodological framework ensures that the estimated effects of climate and economic factors on agricultural production are reliable and robust across model specifications.

RESULTS AND DISCUSSION

After confirming cointegration, the subsequent step involved identifying and estimating the short-run and long-run effects. The long-run ARDL estimation results are reported in Table 5, complemented by robustness checks using the Dynamic Ordinary Least Squares (DOLS) and Fully Modified Ordinary Least Squares (FMOLS) methods. Table 6 reports the short-run ARDL results. All tables have been reformatted to ensure clarity, with units, measures, and standard errors reported in parentheses. Each table is now self-contained and designed to be interpretable without reference to the main text, thereby allowing readers to directly assess the magnitude, significance, and robustness of the estimated coefficients across country groups.

Table 5. Long-run Estimation Results Using ARDL, DOLS, and FMOLS

Country Groups	Variables	ARDL		DOLS		FMOLS	
		Coefficient	t-Statistics	Coefficient	t-Statistics	Coefficient	t-Statistics
High income	RAINI	0.57* (0.02)	23.05	0.09 (0.14)	0.64	0.05 (0.06)	0.83
	GDPII	-0.02* (0.00)	-3.79	-0.01 (0.01)	-0.48	0.00 (0.00)	0.03
	CO2WD	0.15 (0.02)	7.00	0.26* (0.07)	3.69	0.25* (0.04)	5.23
	FRTZQ	0.40* (0.02)	23.87	0.26* (0.06)	4.79	0.25* (0.04)	5.98
	Constant	6.54* (0.37)	17.88				
	R2			0.99		0.99	
	Adjusted R2			0.99		0.99	
	Standard error of the estimate			0.08		0.09	
Lower middle income	RAINI	-0.10*** (0.05)	-1.82	0.08 (0.12)	0.63	0.01 (0.08)	0.09
	FRTZQ	0.03 (0.09)	0.27	0.37* (0.07)	5.56	0.49* (0.06)	8.16
	LBORQ	0.19 (0.15)	1.27	0.12 (0.13)	0.88	0.25** (0.11)	2.25
	GHGMI	-0.02 (0.14)	-0.15	0.65* (0.08)	8.28	0.53* (0.07)	7.51
	Constant	15.93* (4.46)	3.57				
	R2			0.98		0.96	
	Adjusted R2			0.97		0.95	
	Standard error of the estimate			0.09		0.11	
Upper middle income	GDPII	0.20** (0.10)	2.09	0.06 (0.09)	0.65	0.02* (0.02)	1.04
	FRTZQ	0.76* (0.22)	3.43	0.74* (0.06)	12.06	0.71 (0.05)	15.13
	RAINI	0.69 (0.32)	2.17	0.20 (0.25)	0.80	0.17 (0.13)	134
	Constant	-2.33 (5.69)	-0.41				

Country Groups	**Variables**	**ARDL**		**DOLS**		**FMOLS**	
		Coefficient	**t-Statistics**	**Coefficient**	**t-Statistics**	**Coefficient**	**t-Statistics**
	R2			0.97		0.96	
	Adjusted R2			0.96		0.96	
	Standard error of the estimate			0.04		0.06	
All countries	GDPII	0.28* (0.02)	14.52	0.37* (0.02)	16.32	0.37* (0.02)	20.56
	FRTZQ	0.36* (0.02)	16.83	0.27* (0.03)	10.09	0.28* (0.02)	13.12
	RAINI	0.45* (0.03)	17.36	0.08 (0.06)	1.35	-0.00 (0.03)	-0.02
	IRRIQ	0.22* (0.01)	16.17	0.23* (0.03)	7.72	0.23* (0.03)	8.48
	Constant	0.10 (0.48)	-0.20				
	R2			0.99		0.99	
	Adjusted R2			0.99		0.99	
	Standard error of the estimate			0.00		0.02	

Note: *, **, and *** denote significance at the 1%, 5%, and 10% levels, respectively. Standard errors are reported in parentheses.

Long-Run Analysis

High-income countries. Based on the long-run estimation results of the ARDL model for the high-income country group, it was found that rainfall (RAINI), gross domestic product (GDPII), and fertilizer consumption (FRTZQ) have a significant influence on agricultural production (AGPVI), while carbon emissions (CO2WD) show no significant effect (Ruane et al. 2024). The positive and significant coefficient of rainfall (0.57) indicates that a 1% increase in rainfall can raise agricultural production by 0.57%. This finding suggests that although developed countries possess advanced irrigation and water management technologies, rainfall availability remains a vital factor in maintaining the stability of their agricultural systems. Meanwhile, the GDPII variable exhibits a negative and significant coefficient (-0.02), indicating an inverse relationship between economic growth and the contribution of the agricultural sector. This result is consistent with the structural transformation theory proposed by Kuznets (1955) and Timmer (1988), which explains that as income levels and industrialization rise, the share of agriculture in total economic output tends to decline due to the reallocation of labor and capital toward the industrial and service sectors. In contrast, fertilizer consumption (FRTZQ) shows a strong and significant positive relationship with agricultural production (coefficient 0.40), confirming that agricultural intensification through modern inputs remains a key factor in sustaining land productivity in developed economies (Bracho-Mujica et al., 2024).

In contrast, the DOLS estimation results reveal variations in the level of significance across variables. In this model, only carbon emissions (CO2WD) and fertilizer consumption (FRTZQ) have a positive and significant impact on agricultural production, whereas rainfall and GDP are statistically insignificant. The positive and significant coefficient of CO2WD (0.26) suggests that higher carbon emissions, which typically result from energy-intensive economic activities, are associated with increased agricultural productivity (Li et al. 2025). This may reflect the higher levels of modernization and mechanization in developed countries, where the use of energy and fossil-fuel-based machinery contributes to greater production efficiency. Meanwhile, the insignificance of rainfall and GDP in the DOLS model indicates that after accounting for short-run dynamics and time trends, these variables no longer serve as dominant factors in explaining variations in agricultural output among high-income countries.

A relatively consistent pattern is also observed in the FMOLS model, where carbon emissions (CO2WD) and fertilizer consumption (FRTZQ) continue to exert a positive and significant effect on agricultural production, while rainfall (RAINI) and GDP (GDPII) remain insignificant. The insignificance of rainfall in both the DOLS and FMOLS models reinforces the notion that agricultural systems in advanced economies have become relatively insulated from climatic fluctuations through the adoption of adaptive technologies such as greenhouses, precision irrigation systems, and climate-resilient crop varieties. Similarly, the insignificance of GDP in explaining agricultural production implies that agriculture in developed countries is no longer the main driver of economic growth but rather a technologically advanced and mature sector with stable output that is relatively independent of macroeconomic dynamics.

A comparison of the three models shows that fertilizer consumption (FRTZQ) consistently exerts a positive and significant effect on agricultural production, emphasizing the importance of modern input factors in advanced agricultural systems. Meanwhile, carbon emissions (CO2WD) become significant only in the DOLS and FMOLS models, suggesting that the impact of agricultural modernization on productivity becomes more apparent when long-run relationships and cointegration effects are taken into account. Conversely, rainfall and GDP, which are significant in the ARDL model but not in the DOLS and FMOLS estimations, appear to have more short-term and transitional effects. Hence, the differing patterns of significance across models illustrate a structural shift from dependence on climatic and economic factors toward the predominance of technological and efficiency-related drivers in the agricultural systems of high-income countries.

These findings strengthen the argument that at higher income levels, agriculture has entered a post-productivist phase, where productivity growth is increasingly driven by innovation, energy efficiency, and environmental sustainability rather than traditional economic and climatic variables. Overall, fertilizer use—representing technological advancement—emerges as the principal factor reinforcing the resilience of the agricultural sector in developed economies against climate change. This aligns with Aggarwal et al. (2019), who emphasize the importance of technological innovation, and Kadanali and Yalcinkaya (2020), who advocate for greater collaboration among developed nations in reducing greenhouse gas emissions. High-income countries should therefore utilize their fiscal capacities effectively and efficiently, enabling them not only to strengthen domestic agricultural resilience but also to contribute to global climate finance—such as the US$100 billion annual commitment pledged by developed countries at COP15 to support mitigation and adaptation efforts in developing nations (Abebaw et al. 2025).

Lower-middle-income countries. The long-run estimation results of the ARDL model for the lower-middle-income country group reveal that most independent variables do not significantly affect agricultural production (AGPVI), except for rainfall (RAINI), which is marginally significant at the 10% level. The rainfall coefficient of -0.10 indicates a negative relationship between rainfall and agricultural production, suggesting that an increase in rainfall tends to reduce agricultural productivity in lower-middle-income countries. This finding resonates with the case of Nepal, where rice production fell by 0.01% due to rainfall (Chandio et al. 2021). This can be explained by the fact that most countries in this group possess limited agricultural infrastructure and irrigation systems, making them vulnerable to excessive rainfall that often leads to flooding, soil erosion, and farmland degradation. Consequently, climatic variables that should ideally serve as productive resources may instead become destructive forces when not accompanied by adequate adaptive capacity and water management systems. Other variables such as fertilizer consumption (FRTZQ), agricultural labor (LBORQ), and greenhouse gas emissions (GHGMI) show no significant effect in the ARDL model. This indicates that at the lower-middle-income level, key production factors such as labor and modern inputs have yet to optimally enhance agricultural productivity due to persistent inefficiencies, limited access to capital, and low technological adoption.

However, the DOLS estimation results show a notable shift in both the direction and magnitude of variable influences on agricultural production. In this model, fertilizer consumption (FRTZQ) and greenhouse gas emissions (GHGMI) have a positive and significant impact on agricultural output at the 1% level. The fertilizer consumption coefficient of 0.37 suggests that increased fertilizer use directly contributes to higher agricultural output. This finding aligns with the theory of agricultural intensification, which posits that increased utilization of modern inputs is a primary strategy for enhancing productivity in developing countries. Meanwhile, the positive and significant coefficient of greenhouse gas emissions (0.65) indicates a link between more intensive agricultural activities and higher carbon emissions. This can be interpreted as evidence that productivity growth in lower-middle-income countries is still achieved through input expansion that remains energy-intensive and environmentally inefficient. These results highlight that agriculture in these countries is still in the early stages of industrialization, where production growth is often accompanied by rising emissions and environmental degradation.

The FMOLS model produces a pattern nearly identical to that of DOLS, reinforcing the evidence that the relationship between modern input use and agricultural production is long-term in nature. In this model, fertilizer consumption (FRTZQ), agricultural labor (LBORQ), and greenhouse gas emissions (GHGMI) all exert positive and significant effects on agricultural output. The fertilizer coefficient of 0.49 confirms a strong and consistent positive influence on agricultural productivity, while the labor coefficient of 0.25 underscores that the agricultural sector in lower-middle-income countries remains labor-intensive. The significance of labor also indicates that mechanization has not yet fully replaced human labor, meaning that output growth still heavily depends on the availability and intensity of the agricultural workforce. Furthermore, the positive and significant coefficient of greenhouse gas emissions (0.53) once again emphasizes that economic expansion and intensive agricultural activities remain the main drivers of productivity—though at the cost of increasing environmental pressure.

The varying levels of significance across the ARDL, DOLS, and FMOLS models illustrate the structural dynamics currently unfolding in lower-middle-income countries. In the ARDL model, rainfall exerts a negative and marginally significant effect, suggesting that the agricultural sector in these countries remains highly vulnerable to climatic variability and weather uncertainty. However, when long-run correction models (DOLS and FMOLS) are employed, the rainfall effect disappears, and stronger relationships emerge between modern inputs, emissions, and agricultural productivity. This shift indicates a transition from dependence on natural factors toward reliance on production inputs. In other words, although agriculture in lower-middle-income countries continues to depend heavily on climatic conditions, in the long run, productivity is increasingly determined by the extent to which these countries can enhance the use of modern inputs and productive labor.

Conceptually, these findings indicate that the agricultural sector in lower-middle-income countries remains in an input-driven growth phase rather than an innovation-driven growth phase. The dominant influence of fertilizer and labor variables suggests that productivity is not yet supported by technological efficiency or sustainable agricultural systems. Moreover, the positive relationship between carbon emissions and agricultural output indicates a trade-off between economic growth and environmental sustainability. Therefore, agricultural development policies in this country group should be directed toward two main strategies: (1) Improving input efficiency through environmentally friendly technologies and sustainable farming practices, and (2) Strengthening adaptive capacity to climate change to reduce dependence on extreme weather conditions.

Overall, the findings empirically confirm that in lower-middle-income countries, agricultural development remains heavily constrained by structural limitations and incomplete economic transitions. In the long run, agricultural productivity will largely depend on these countries' ability to balance output growth with sustainable environmental management, while gradually transforming toward an innovation- and efficiency-based agricultural system.

Empirical evidence from previous studies supports these conclusions. Islam et al. (2019) highlight the vulnerability of the agriculture and fisheries sectors in Bangladesh to the impacts of climate change. Raihan et al. (2022) and Yousaf Raza et al. (2023) find that economic growth, energy use, and urbanization significantly influence agricultural productivity and climatic conditions in Bangladesh. In Egypt, Raihan et al. (2023) report that higher agricultural productivity contributes to improved environmental quality through reductions in CO_2 emissions, underscoring the importance of climate-smart agricultural practices.

These findings reinforce the urgency of an integrated strategy that combines technological innovation, institutional strengthening, and international cooperation to balance productivity growth with environmental sustainability.

Upper-Middle-Income Countries. The long-run estimation results using the ARDL model for the upper-middle-income country group reveal that gross domestic product (GDPII), rainfall (RAINI), and fertilizer consumption (FRTZQ) all contribute positively to agricultural production (AGPVI). Among these variables, only GDP and fertilizer consumption are statistically significant. The GDP coefficient of 0.20, significant at the 5% level, indicates that economic growth positively influences agricultural output in upper-middle-income countries. This finding suggests that economic expansion in this income group is still partially supported by the substantial contribution of the agricultural sector, where increases in domestic income enhance investment in agricultural infrastructure and technological capacity. The result reinforces the argument that agriculture continues to play a strategic role in the process of industrialization and economic development at the intermediate stage.

In addition, fertilizer consumption (FRTZQ) exhibits a strong and highly significant positive effect on agricultural production (coefficient 0.76, significant at 1%). This result implies that the intensification of modern input use, such as chemical fertilizers, remains a primary determinant of agricultural productivity in upper-middle-income countries. Such dependence on input-based growth indicates that productivity improvements are driven more by factor accumulation than by technological efficiency or systemic innovation. Meanwhile, rainfall (RAINI) also shows a positive coefficient of 0.69, although its significance is borderline (t-statistic 2.17). This suggests that climatic conditions—particularly rainfall—still play an important role in supporting agricultural productivity in upper-middle-income economies, most of which retain land-based production structures and are situated in tropical or subtropical climate zones.

Cross-regional empirical evidence supports the complexity of interactions between climate, economic growth, and agriculture. In Malaysia, climate change has significantly affected rice production over the period 1980–2019, with rainfall and agricultural land area exerting positive effects on yields, while extreme temperature and precipitation variability reduce productivity (Q. Zhang et al. 2023). In China, H. Zhang et al. (2023) find that a 1% increase in agricultural output contributes to a 0.14% rise in agricultural CO_2 emissions in the long run, highlighting the linkage between agricultural intensification and environmental impact. Conversely, Raihan et al. (2022) report that in Indonesia, a 1% increase in agricultural productivity leads to a 0.24% reduction in CO_2 emissions in the long run, reflecting the benefits of cleaner and more efficient farming practices.

The DOLS model results reveal that although the direction of relationships among variables remains consistent, the level of statistical significance changes. GDP (GDPII) continues to have a positive relationship with agricultural production, but its effect becomes statistically insignificant, while fertilizer consumption (FRTZQ) remains significant with a coefficient of 0.74. The loss of GDP significance in the DOLS model suggests that when long-run cointegration relationships and autocorrelation corrections are taken into account, the contribution of economic growth to the agricultural sector diminishes. This may be explained by ongoing economic diversification in upper-middle-income countries, where non-agricultural sectors—particularly industry and services—are becoming increasingly dominant. Hence, while agriculture continues to grow, it no longer serves as a primary driver of macroeconomic expansion.

The FMOLS model produces results broadly similar to those of the DOLS estimation. Fertilizer consumption (FRTZQ) remains the most significant variable (coefficient 0.71), whereas GDP (GDPII) and rainfall (RAINI) retain positive but statistically insignificant effects. The consistent significance of FRTZQ across all three models (ARDL, DOLS, and FMOLS) confirms that modern agricultural inputs remain a key determinant of agricultural productivity in upper-middle-income countries. However, the insignificance of GDP and rainfall in the DOLS and FMOLS models indicates a structural transition in which agriculture becomes less dependent on macroeconomic and climatic factors, and increasingly reliant on technological and input-based drivers of production.

The differences in significance levels across the three models carry both methodological and substantive implications. The ARDL model captures short-run dynamics and adjustments to economic or climatic shocks, thereby revealing significant effects of GDP and rainfall that may reflect short-term economic fluctuations or seasonal weather conditions. However, once long-run cointegration corrections are incorporated in the DOLS and FMOLS models, only variables with strong and persistent relationships—such as fertilizer consumption—remain significant. This finding underscores that, at the upper-middle-income stage, agricultural productivity is more strongly determined by internal production-system factors than by external influences such as macroeconomic growth or annual climate variation.

Overall, these results suggest that the agricultural sector in upper-middle-income countries is undergoing a transition from traditional farming toward a modern, input-intensive production system. The high dependence on fertilizers indicates that intensification remains the dominant strategy, while technological innovation and adaptive efficiency have not yet fully substituted for physical input use. In the long-term development context, this condition implies the need for policy strategies focused on improving fertilizer-use efficiency, enhancing production technologies, and strengthening adaptive capacity to climate change—thereby promoting agricultural growth that is both sustainable and less reliant on material input intensification.

All Countries (33 Countries). The long-run estimation results for the *All Countries* group—which includes 33 countries across high-, upper-middle-, and lower-middle-income levels—reveal that nearly all variables in the ARDL model exert a positive and significant influence on agricultural production (AGPVI). GDP (GDPII), fertilizer consumption (FRTZQ), rainfall (RAINI), and irrigation (IRRIQ) all display positive coefficients and are statistically significant at the 1% level. This indicates that, in aggregate, economic growth, agricultural input intensification, climatic factors, and irrigation infrastructure are the main drivers of agricultural production across countries. The GDP coefficient (0.28) suggests that economic growth remains directly associated with higher agricultural output. In other words, as national income increases, countries tend to expand investments in agriculture—

through enhanced physical inputs, improved access to agricultural finance, and the adoption of modern technologies.

Fertilizer consumption (FRTZQ), with a positive and highly significant coefficient (0.36 at the 1% level), confirms that modern input use remains a dominant determinant of agricultural productivity across income groups. This finding reinforces evidence from the previous country-group analyses, establishing fertilizer as the most consistent and significant variable explaining variations in agricultural output. Rainfall (RAINI), with a coefficient of 0.45, also exhibits a positive and significant effect, suggesting that climatic factors continue to play a crucial role in global agricultural systems—particularly in developing countries where agricultural infrastructure remains underdeveloped. This finding underscores that climatic stability remains a fundamental prerequisite for aggregate agricultural productivity. Likewise, irrigation (IRRIQ) has a positive and significant relationship (coefficient 0.22), emphasizing the importance of water management infrastructure as a primary adaptation instrument to climate variability.

However, the DOLS and FMOLS estimation results reveal shifts in the level of significance among variables. In the DOLS model, GDP, fertilizer consumption, and irrigation remain positive and significant, whereas rainfall becomes insignificant. Once cointegration and autocorrelation corrections are introduced, the influence of rainfall on agricultural output becomes statistically negligible—indicating that short-term climatic fluctuations do not exert stable long-term effects on productivity when structural and technological factors are accounted for. The FMOLS results echo this pattern, with GDP, fertilizer use, and irrigation remaining significant, while rainfall loses significance. These changes suggest that rainfall effects are short-term and context-dependent, whereas long-run agricultural productivity is more strongly driven by economic, technological, and infrastructural factors.

Conceptually, the consistent significance of GDP, fertilizer consumption, and irrigation in the DOLS and FMOLS models underscores the combined importance of macroeconomic and input-related factors in sustaining agricultural production across nations. Rising GDP reflects a country's capacity to invest in agriculture through infrastructure development, technological innovation, and farmer financing. The persistent significance of fertilizer use across all models confirms that input intensification remains a widespread strategy to boost productivity, even though its long-term effectiveness depends on usage efficiency. Meanwhile, the strong role of irrigation highlights the centrality of water management infrastructure in reducing dependency on rainfall—particularly in tropical and semi-arid regions.

A comparison of the ARDL, DOLS, and FMOLS models reveals that differences in coefficient magnitude and significance reflect the contrast between short-run and long-run dynamics. The ARDL model captures both short- and long-run relationships, showing that all variables significantly influence agricultural production—implying a strong interaction among climatic, economic, and agricultural input factors. However, in the DOLS and FMOLS models—which emphasize long-run equilibrium and structural relationships—the significance of rainfall disappears, indicating that the long-term role of climate has been offset by adaptation mechanisms such as irrigation development and agricultural technology adoption. In other words, the DOLS and FMOLS estimations suggest that in the long run, global agricultural systems depend less on climatic conditions per se and more on economic and technological capacities to adapt to them.

These findings carry important implications for cross-country agricultural development policy. First, macroeconomic factors such as GDP growth must be optimized to strengthen investment in climate-resilient agriculture. Second, improving fertilizer-use efficiency and enhancing irrigation systems should be prioritized as core strategies for maintaining and increasing sustainable agricultural productivity. Third, the insignificance of rainfall in long-run models underscores the urgency of policies for climate-change mitigation and adaptation to reduce dependence on weather variability through the adoption of climate-smart agricultural technologies. Overall, the results for the *All Countries* group (33 countries) indicate that global agricultural productivity is increasingly determined by the interaction between economic, technological, and adaptive policy factors—rather than by natural climatic conditions alone.

The aggregated evidence suggests that there is no single pathway toward building agricultural resilience to climate change. Instead, an integrated approach is required—combining economic strength, technological adoption, community participation, and ecological management (Sarkodie et al. 2019). Governments play a critical role in institutional coordination, climate-resilient infrastructure development, and expanding access to agricultural technologies (Mursyid et al. 2021).

Meanwhile, farmers remain at the core of adaptation processes. Studies have shown that farmers with stronger climate awareness are more likely to invest in climate-resilient strategies (Saptutyningsih et al. 2020). Therefore, modern agricultural extension services leveraging information and communication technologies (ICT) are essential to promote the widespread adoption of adaptive practices (Hasibuan et al. 2020).

Climate change continues to pose a major challenge to global agriculture. (Khan et al. 2022) report a decline in agricultural development across 101 countries due to rising global temperatures, while (Kalkuhl and Wenz 2020) estimate that a 3.5°C increase in global surface temperature could reduce global agricultural output by 7–14% by 2100, with tropical and low-income regions being the most affected. (Dewi 2009) also identifies tropical regions as the most vulnerable areas to climate change impacts.

Although previous studies have employed different climate indicators—ranging from temperature, drought, and rainfall variability to sea-level rise—the inclusion of rainfall and CO_2 emissions in this study reflects both their empirical relevance and theoretical significance. Rainfall represents the variability of the climatic system, while CO_2 emissions capture the anthropogenic drivers of climate change. Without decisive action, climate change will exacerbate global poverty (Carattini et al. 2020), hinder economic transformation (Chandy 2023), reduce labor productivity, and raise operational costs (Wade and Jennings 2016). As a sector positioned at the intersection of food security and climate change, agriculture must remain a top priority in both adaptation and mitigation strategies.

Short-Run Analysis (ECM Regression). Based on the calculation results, Table 6 presents the short-run ARDL estimation for the model classified by countries' income levels. ECM indicate speed of adjustment to long-run equilibrium. The table is presented as follows.

Table 6. Short-run panel ARDL estimation results

Country Groups	Variables	Coefficient	t-Statistics
High income	D(LNGDPII(-1))	0.01* (0.00)	2.72
	D(FRTZQ)	-0.20** (0.08)	-2.53
	D(FRTZQ(-2))	0.14** (0.07)	2.16
	CointEq(-1)	-0.19** (0.10)	-1.96

Country Groups	Variables	Coefficient	t-Statistics
Lower middle income	D(RAINI)	0.06* (0.02)	3.23
	D(RAINI(-1))	0.05*** (0.03)	1.87
	D(LBORQ(-2))	-0.83*** (0.47)	-1.79
	CointEq(-1)	-0.13** (0.10)	-1.27
Upper middle income	D(AGPVI(-1))	-0.39* (0.06)	-6.21
	D(AGPVI(-2))	-0.18* (0.06)	-2.97
	D(FRTZQ)	0.05*** (0.03)	1.72
	D(FRTZQ(-1))	0.06** (0.03)	2.00
	CointEq(-1)	-0.03** (0.02)	-1.91
All countries	D(AGPVI(-1))	-0.19* (0.03)	-5.47
	D(GDPII)	0.18* (0.07)	2.68
	CointEq(-1)	-0.12* (0.03)	-3.83

Note: The symbols *, **, and *** signify statistical significance at the 1%, 5%, and 10% levels, respectively. Standard errors are reported in parentheses.

The short-run estimation results from the Panel ARDL model reveal varying dynamics across country groups, reflecting differences in income levels and economic structures. Overall, economic and agricultural input variables exert significant short-run effects on changes in agricultural production (AGPVI), while the ECM is negative and statistically significant across all groups. This confirms the presence of stable correction mechanisms that guide short-run disequilibria toward long-run equilibrium in each agricultural system.

For high-income countries, the first lag of GDP growth (D(LNGDPII(-1))) shows a positive and significant effect on agricultural production, indicating that economic expansion continues to stimulate agricultural activity, even though the sector's contribution to overall GDP is relatively modest. Meanwhile, changes in fertilizer consumption (D(FRTZQ)) exert a negative and significant contemporaneous effect but turn positive and significant after two periods (D(FRTZQ(-2))). This pattern suggests that excessive fertilizer use may initially reduce productivity due to nutrient imbalances or overapplication, but yields improve in subsequent periods once soil absorption and plant uptake reach optimal levels. The negative and significant ECM value (-0.19) indicates that approximately 19% of short-run disequilibrium is corrected each period, reflecting a relatively rapid and efficient adjustment mechanism in advanced agricultural systems facing economic or input shocks.

In upper-middle-income countries, the results indicate strong internal adjustment effects within agricultural production itself, as reflected by two negative and significant lags of AGPVI (D(AGPVI(-1)) = -0.39 and D(AGPVI(-2)) = -0.18). This implies a short-run diminishing returns effect, where increased production in one period leads to slower growth in subsequent periods due to land and input constraints. Conversely, changes in fertilizer consumption (D(FRTZQ)) and its lag exhibit positive and significant impacts, indicating that modern input intensification immediately and sustainably enhances productivity. The negative and significant ECM (-0.03) suggests a very slow adjustment speed of about 3% per period, implying that while agricultural modernization has progressed, structural rigidities and institutional constraints continue to hinder rapid re-equilibration toward the long-run path.

In contrast, the lower-middle-income countries group exhibits short-run dynamics predominantly driven by climatic factors. Rainfall (D(RAINI)) exerts a positive and significant effect both contemporaneously (0.06) and with one lag (0.05), indicating that increased and sustained precipitation enhances agricultural productivity. This underscores the continued dependence of agriculture in these economies on natural climatic conditions, with limited protection from irrigation or adaptive technologies. Conversely, agricultural labor (D(LBORQ(-2))) shows a negative and significant effect at two lags, suggesting the presence of labor redundancy and low marginal productivity within the agricultural workforce. The negative and significant ECM (-0.13) indicates that approximately 13% of disequilibrium is corrected per period, implying a slow but stable adjustment process typical of economies still transitioning toward agricultural modernization.

For the aggregated sample of all countries (33 countries), short-run estimates show that GDP growth (D(GDPII)) exerts a positive and significant effect on agricultural production, while the first lag of production (D(AGPVI(-1))) is negative and significant. The positive GDP effect suggests that economic expansion stimulates agricultural investment and demand, while the negative production lag reflects a natural post-expansion adjustment following previous output surges. The ECM (-0.12), significant at the 1% level, indicates that approximately 12% of short-run disequilibrium is corrected toward long-run equilibrium each period, reflecting a moderate yet efficient global adjustment mechanism.

Taken together, the short-run ARDL results demonstrate that the determinants of agricultural production vary systematically with countries' income levels. High-income economies exhibit rapid and efficient adjustment mechanisms supported by strong technological and institutional capacity. Upper-middle-income countries show transitional behavior, with slower adjustment reflecting structural and institutional rigidities. Lower-middle-income countries remain highly dependent on climatic conditions and constrained by infrastructural and efficiency limitations. The consistently negative and significant ECM across all groups confirms that, despite varying adjustment speeds, agricultural systems tend to converge toward long-run equilibrium following short-run shocks.

In essence, the short-run dynamics underscore that the global agricultural sector's long-run stability depends critically on efficient adjustment mechanisms, technological availability, and adaptive capacity to both climatic variability and economic fluctuations.

CONCLUSION

This study provides a comprehensive examination of the relationship between economic, climatic, and agricultural input factors on agricultural production (AGPVI) across income-based country classifications. The combined evidence from the long-run and short-run analyses demonstrates that while the direction and magnitude of these relationships differ across groups, a consistent pattern emerges: modern agricultural inputs (such as fertilizer use) and macroeconomic factors (such as GDP) play dominant roles in shaping global agricultural productivity, whereas the influence of climatic variables (particularly rainfall) diminishes as countries advance economically and enhance their technological adaptive capacity.

In the long run, the results of the ARDL, DOLS, and FMOLS estimations indicate that high-income countries have reached the stage of *post-productivist agriculture*, where agricultural performance no longer depends on economic growth or climatic conditions, but rather on technological efficiency and the optimized use of modern inputs. In contrast, upper-middle-income countries exhibit a transitional pattern—from macroeconomic dependence toward a more modern, input-efficient agricultural system. Lower-middle-income countries, however, remain strongly influenced by climatic conditions and physical input intensification (e.g., fertilizer and labor), rendering their productivity more vulnerable to rainfall fluctuations and climate variability. At the aggregate level (33 countries), the long-run findings confirm that economic growth, fertilizer use, and irrigation infrastructure constitute the primary drivers of agricultural productivity, while the significance of climatic variables weakens as adaptation capacity and mitigation policies are increasingly internalized within national agricultural systems.

In the short run, the fluctuations in agricultural production are mainly driven by changes in economic and input-related factors. GDP growth generally exerts a positive effect—particularly in upper-middle-income and developing economies—by stimulating agricultural investment and demand. However, fertilizer use exhibits delayed effects: in some cases (e.g., high-income countries), its short-run impact is negative but turns positive in subsequent periods, suggesting a lag in soil and crop responsiveness to nutrient application. Climatic variables, such as rainfall, remain significant in the short run—especially in lower-middle-income countries—but lose significance in the long-run estimations. The negative and significant ECM across all country groups confirm that global agricultural systems possess stable adjustment mechanisms, whereby short-run shocks are gradually corrected toward long-run equilibrium.

Conceptually, these findings reinforce the structural transformation theory advanced by (Kuznets 1955) and Timmer (1988)—which posits that as income levels rise, economic structures shift from agriculture toward industry and services, while agriculture evolves from a growth engine to a stabilizing sector that ensures food security and social resilience. Nevertheless, the results of this study reveal that agriculture continues to play an essential role in sustaining macroeconomic balance and supporting long-term development—primarily through technological innovation and resource-use efficiency.

From a policy perspective, the findings generate several important implications: (1) For high-income countries, agricultural policy should prioritize technological innovation, energy efficiency, and the adoption of low-emission sustainable farming systems to maintain a balance between productivity and environmental integrity. (2) For upper-middle-income countries, policies should focus on improving input-use efficiency, strengthening agricultural research and technology adoption, and advancing institutional reforms to accelerate the structural transition from input intensification to innovation-driven agriculture. (3) For lower-middle-income countries, policy priorities should emphasize building adaptive capacity to climate change, expanding irrigation and water management infrastructure, and enhancing farmers' access to agricultural inputs and finance—thereby improving both resilience and productivity.

Overall, this study underscores that the success of sustainable agricultural development does not depend solely on economic growth or climatic conditions, but rather on a country's ability to integrate economic, technological, and environmental policies in a coherent and balanced manner. With adaptive, evidence-based approaches—such as those employed through the ARDL, DOLS, and

FMOLS models—agriculture can play a pivotal role in global sustainable development strategies: not merely as a provider of food, but as a cornerstone of economic stability, social resilience, and ecological sustainability in the decades ahead.

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KEY DETERMINANTS OF YOUNG SMART FARMER SUCCESS IN NORTHEASTERN THAILAND FOR AGRICULTURAL DEVELOPMENT AND FARMER EMPOWERMENT

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ABSTRACT

This paper examines the socioeconomic factors influencing the success of the young smart farmers in the northeastern part of Thailand. This research provides empirical evidence on key socioeconomic and technological factors influencing young farmers' success, contributing to policies that promote youth participation in modern farming. Data were obtained from 375 farming households across eight provinces of northeastern Thailand from May 2022 to May 2023 using multistage sampling. The Logit model was used to identify the main factors of the farm success, achieving an 89.5% prediction accuracy. Statistically significant positive predictors included education level, technology adoption, farm area, farm record keeping, and participation in the Young Smart Farmer program. Technology adoption was the most influential positive predictor of success (48.82%), while credit accessibility and farming experience showed positive effects ($P<0.01$). Education increased the likelihood of success by 6.33%, credit access by 0.44%, farming experience by 1.05% and record keeping by 0.16%. The results imply that even less-educated young farmers can achieve productivity and sustainability by using improved technology, targeted education, and organized programmes. Consequently, sustaining the Young Smart Farmer initiative through continuous training, affordable credit, and land allocation is essential to strengthen Thailand's agricultural competitiveness and ensure long-term rural livelihoods.

Key words: aging farmer, farm income, technology adoption

INTRODUCTION

The transformation of Thailand's agricultural sector has increasingly involved the participation of youth from diverse backgrounds, like agriculture graduates, farm successors, and career shifters from non-agricultural fields. These young entrants are drawn to agriculture by greater access to knowledge, information technology, modern production systems, and expanding markets. Despite having higher education levels, many youths choose smallholder farming as a sustainable livelihood. This trend mirrors global patterns where youth are viewed as the next generation of agro-entrepreneurs visionary, efficient, and competitive (Balezentis et al. 2020). Young farmers actively participate in production, processing, and marketing, and tend to invest more in farm development than older counterparts, contributing to rural economic progress (Milone and Ventura 2019). Their adaptability to social and technological changes allows them to introduce innovations that promote regional development. Many pursue strategies such as expanding land holdings, obtaining GAP or organic certifications, and adopting modern technologies that enhance sustainability and climate resilience (Läpple et al. 2011; Lastra-Bravo et al. 2015). Thailand's 12th National Economic and Social Development Plan (2017–2021) and the 20-Year National Strategy (2018–2037) emphasize strengthening agriculture by empowering young farmers to lead agribusiness transformation. Programs like the Young Smart Farmer (YSF) that was launched in 2014 by the Department of Agricultural Extension, Ministry of Agriculture and Cooperatives of Thailand initiative have enhanced the skills and technological capacity of young farmers aged 18-45 years. The program offers comprehensive training on modern means of production, digital agriculture, farm management and marketing. This orientation toward the digital is consistent with evidence that YSF members in Central Thailand have a strong need for increased knowledge of digital agricultural technologies (Klayson and Jirakajohnkool 2023). In addition, as the program provides continued mentoring and networking support. Media and communication have also been significant means of disseminating the YSF activities, with young farmers requesting more extension media program (Purintrapibal and Kruekum 2023). Each year, participants are recruited through provincial agricultural offices, and the program operates on an ongoing basis with regular monitoring, evaluation, and follow-up activities to ensure sustainable skill development. Recent study also indicates a significant increase in farm income among the YSF and increased yield and productivity as a result of greater access to training and networks (Poungchompu and Phuttachat 2023). Between 2014 and 2022, YSF participants demonstrated notable improvements in technology adoption and farm management. Despite such efforts, many young farmers still face obstacles in accessing land, credit, and modern technologies (Adekunle et al. 2009). The same conclusion was reached by Jansuwan and Zander (2021), who evaluated Thailand's YSF scheme, which further emphasized the ongoing issue with access to resources, and the long-term viability of programmes. Limited financial access constrains their ability to invest in productivity-enhancing tools, while high collateral requirements, lending risks, and bureaucratic hurdles further restrict capital access. In addition, gaps in business management skills such as planning, budgeting, and marketing limit their ability to respond to volatile market demands. Beyond economic and technical capabilities, social networks and peer collaboration play a vital role. These networks promote knowledge sharing and innovation, as well as improve access to markets and collective action opportunities (Koutsou et al. 2014; Lastra-Bravo et al. 2015). Such dynamics are essential for resilience and long-term sustainability. However, while existing literature addresses youth involvement in agriculture, there remains a gap in region-specific research that identifies the nuanced drivers of young farmers' success in Northeastern Thailand. Tikum and Ahmad (2024) also explored the social and institutional constraints of YSF participants, where they state that policy support for YSF is ineffective without addressing the local context. Although many previous studies have examined access to agricultural resources and government support, few have explored how these factors influence young farmers' success within the socioeconomic and institutional context.

To address this gap, the study aims to analyze key socioeconomic factors influencing the success of young smart farmers in Northeastern Thailand based on measurable indicators such as farm income, productivity, and credit accessibility, which collectively represent the socioeconomic performance of young farmer. Unlike traditional research that emphasizes capital or marketing alone, this study applies a comprehensive framework incorporating variables such as farm size, type, labor availability, off-farm income, digital technology usage, education, and access to extension services (Beck and Demirguc-Kunt 2006; Gabre-Madhin and Haggblade 2004). Previous research also tends to rely on self-assessed financial performance, yet recent findings suggest that many farmers prioritize income stability and work-life balance over profit maximization (Hayden et al. 2022). This study focuses particularly on access to finance as a key factor differentiating successful and struggling farm enterprises (Bakshy et al. 2012). It explored both the socioeconomic and technological dimensions of success by comparing successful and less successful young farmer cases. Findings from this research will offer practical insights for policymakers to design targeted development strategies that support young farmers, promote inclusive agribusiness, and align with Thailand's long-term goals of strengthening the agricultural sector and preparing future-ready farmers.

RESEARCH METHODOLOGY

Study area and sampling procedure. This research was performed in Northeastern Thailand which is centrally located in the Mekong Sub-region (latitude 14°7′–18°27′ N, longitude 100°54′–105°37′ E), and covers 8.38 million hectares, representing 16.3% of the country's total land area. Land use is dominated by rice fields (64.6%) followed by field crops (21.0%) and para rubber (8.7%); average landholding size is about 3.008 ha. (National Statistical Office 2018). The YSF Programme which is in pursuit of livelihood since 2014, in this region, is undertaken by the Department of Agricultural Extension. The study participants were young farmers aged 18–45 years and actively involved in farming. The multistage random sampling method was used. Km), which purposively selected eight provinces (Khon Kaen, Chaiyaphum, Kalasin, Maha Sarakham, Roi Et, Loei, Nong Khai, and Nakhon Ratchasima) according to their agricultural productivity and income results. A district was drawn from each province in collaboration with the Office of Agricultural Extension and Development No 4, totaling eight districts. The overall number of young farmers was believed to be 5,900. A sample size of 375 farm households was calculated using Yamane's formula (95% confidence level). An equal number of participants (46–47) were selected at random from each district using a simple random sampling procedure.

The list of registered Young Smart Farmers was obtained from the Provincial Agricultural Extension offices, and random numbers were generated to select the respondents. In districts where the list was incomplete, enumerators worked with local agricultural officers to verify eligible participants and applied systematic random selection within the village. The household ratio was not adjusted. Data collection was done from May 2022 to May 2023 using structured questionnaires administered through guided interviews. The guided interview technique was applied to ensure that respondents clearly understood each question and to maintain consistency in data collection across all districts. Data included socio-economic characteristics and agricultural practices for the 2022–2023 cropping season. All data were processed with SPSS (Version 17). A portion of the sampling framework was derived from Poungchompu and Phuttachat (2023), who studied Young Smart Farmer Programme (YSF) program participants and non-participants in 5 provinces in Northeastern Thailand. For the present study, the dataset was expanded and updated between May 2022 and May 2023 by collecting new observations from the same provinces (Khon Kaen, Chaiyaphum, Kalasin, Maha Sarakham, and Nakhon Ratchasima province) and by adding three provinces was Loei, Nong Khai, and Roi Et province. The entire sample included 375 YSF participants who were newly recruited from all eight provinces. Each original provinces collected an additional 4–5 samples, and the new provinces each produced 47 respondents, all of whom were active YSF members. Contrasting the previous research which has investigated the income effect of YSF participation, this study stresses the socioeconomic and technological antecedents behind success among YSF participants to provide a broader understanding of regional empowerment and agricultural production results.

Economic model. Success in this research is described as making a profit on the farm, which is aligned with the Department of Agricultural Extension (DOAE)'s standard and characterized as young farmers as those earning annual net farm income exceeding 5,168.70 USD (1 USD = 28.72 THB). Although net farm income more accurately reflects profitability, net farm income was adopted in this study to maintain consistency with the DOAE's official evaluation criteria and to ensure comparability with national statistics on young farmer performance. A number of socio-economic variables were hypothesized to influence farm success, including gender, education, area under cultivation, experience in farming, membership in an organization, access to credit, access to market, record keeping, support from government, training, and participation in the YSF programme. The relationships between these variables and farm success were tested using a Binary Logistic Regression Model, which estimated the likelihood of success (1=successful, 0=otherwise) as a function of these explanatory factors. Previous studies have highlighted the significance of high adoption of technology and income (Ruiz et al. 2019), access to credit, education (Balana and Oyeyemi 2022; Consentino et al. 2023), market (Bakshy 2012; Changsheng et al. 2020), training (Adeyanju et al. 2021; Lekhanya and Mason 2014), and record keeping (Hayden et al. 2022). Logistic regression analysis was performed where the binary response (success=1, non-success=0) as the dependent variables. Based on Walker and Duncan (1967), the log odds of success is estimated by the model considering that this is a linear function in 12 independent variables, including categorical and continuous predictors. The model used is summarized below:

$$\ln\left(\frac{P_i}{1-P_i}\right) = \mathrm{Y_i} = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 X_4 + \beta_5 X_5 + \beta_6 X_6 + \beta_7 X_7 + \beta_8 X_8 + \beta_9 X_9 + \beta_{10} X_{10} + \beta_{11} X_{11} + \beta_{12} X_{12} + \varepsilon \quad (1)$$

Where P_i is the probability of young farmers' success, P_i = 0 indicates no success, and = 1 indicates success

Y_i	=	The probability of success for a Young Smart Farmer; (0 if an unsuccessful young farmer 1 if a successful young farmer)
β_0	=	The Intercept
β_1- β_{12}	=	The regression coefficients of the dependent variables
X_1	=	Gender of Farmer (1 if Male 0 if Female)
X_2	=	Farmer's Education (years)
X_3	=	Membership of Group Farmer (1 if being a member of a farming group, 0 if otherwise)
X_4	=	Farming Experience (years)
X_5	=	Cultivated area (ha)
X_6	=	Technology Adoption (1 if adoption 0, if non-adoption)
X_7	=	Government Support (1 if yes, 0 if no)
X_8	=	Credit Access (1 if yes, 0 if no)
X_9	=	Recordkeeping (1 if yes, 0 if no)
X_{10}	=	Market Access (1 if yes, 0 if no)
X_{11}	=	Training (1 if yes, 0 if no)
X_{12}	=	Being a Young Smart Farmer (1 if yes, 0 if otherwise)
ε	=	the disturbance term

RESULTS AND DISCUSSIONS

Characteristics of farmers. Of the 375 surveyed youth-operated farm households, 50.7% were labelled as successful while 49.3% were unsuccessful as presented in Table 1. In this study, a successful farmer refers to a respondent whose net farm income exceeded the sample mean, indicating better management efficiency and profitability after accounting for production expenses. The successful farmers were equally divided with respect to their gender, with 50% being male and 50% female. This distribution occurred by chance through random sampling, as no gender quota or stratification was imposed during the selection process. Education was another significant discriminator: 90.5% of successful farmers had at least a bachelor's level compared to 53.5% of less successful farmers. Both successful and unsuccessful farmers had almost similar participation rates in farmer organizations (52.1 and 49.9%, respectively), suggesting efforts on collaborative learning and entrepreneurship networks.

Technology use was also strikingly different between the two groups. Modern technologies were used in cultivation by 93.2% of successful and only 27% of unsuccessful farmers. Such a result highlights the importance of developing new technology, especially technology that is both productive and sustainable. The successful and non-successful young farmers had an average farming experience of 8.8 years and 11.7 years, respectively, indicating that younger entrants with training and access to technology achieved a higher success rate, highlighting the positive effect of targeted support programs such as YSF, rather than implying differences in government support across age group. Farm size was not statistically different among groups, averaging 3 hectares (Table 2). But, the YSF program beneficiaries were associated with a higher probability of success. More proportion of the successful farmers are involved in YSF activities and supported by the government (55.8%) than the unsuccessful farmers (49.7%). These findings are consistent with those in Chokpigunthong and Chantaranamchoo (2023), who explore the success factors of smart farmers in Nakhon Pathom, showing similar institutional patterns.

Loan was also found to be a significant determinant: 77.4% successful had access to a loan, whereas only 31.9% unsuccessful had access to loan. This shows how financial inclusion allows investment in inputs, infrastructure, and innovation. It was observed that records were more frequently kept among successful (87.9%) than unsuccessful (70.3%), indicating that the successful group demonstrated stronger business management practices. Market access was also higher among successful farmers (74.2%) than the unsuccessful group (53.5%).

Gender, membership, cultivated land, and general government support were found to be insignificant while education, technology adoption, credit access, market access and training and YSF participation were found to have a significant relation with the success ($P<0.05$). Although the t-statistics for these variables are negative, this does not imply an inverse relationship. The negative sign arises from the group-coding order used in SPSS, where the unsuccessful group was coded first. In fact, the proportions presented in Tables 1 and 2 indicate that successful farmers had higher levels of education, technology adoption, record-keeping, credit access, market access, and participation in YSF program, findings that are consistent with the positive effects reported in the logistic regression results.

Moreover, farming systems also varied such that the majority of the young farmers were practicing integrated farming, including field crops (such as rice, sugarcane) with horticultural crops (e.g., vegetables) with or without livestock. This method provides year-round revenue and is sustainable. However, there also some young farmers who concentrate on either single-crop rice cultivation or vegetable farming. Jasmine 105, Glutinous RD6, and Riceberry were the most frequently planted rice varieties, and the types of vegetables grown depended on market demand (lettuce, morning glory, eggplant, tomatoes, onions, and garlic). These choices range from integrated, resilient agricultural practices to market-driven, specialized farming.

Table 1. Socioeconomic characteristics of success and non-success.

Variable	Successful (N= 190)	Less Successful (N= 185)	t-Statistics
	%	%	
Gender of farmer			
0= Female	50.0	50.3	-0.052^{NS}
1= Male	50.0	49.7	
Farmer's education			
0 = under bachelor's degree	9.5	46.5	-8.767***
1= bachelor's degree or above	90.5	53.5	
Membership			
0= No	47.9	54.1	1.192^{NS}
1= Yes	52.1	49.9	
Technology adoption			
0= No	6.8	73.0	-17.738***
1= Yes	93.2	27.0	

Variable	Successful (N= 190)	Less Successful (N= 185)	t-Statistics
	%	%	
Government support			
0= No	44.2	50.3	-1.174 ^{NS}
1= Yes	55.8	49.7	
Credit access			
0= No	22.6	31.9	-2.020***
1= Yes	77.4	68.1	
Farming record			
0= No	12.1	29.7	
1= Yes	87.9	70.3	-4.295***
Market access			
0= No	25.8	46.5	-4.264***
1= Yes	74.2	53.5	
Training			
0= No	26.3	37.8	-2.403***
1= Yes	73.7	62.2	
Being a young smart farmer			
0= No	26.3	62.2	-7.799***
1= Yes	73.4	37.8	

Note: ***, **, and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively. ns means not significant.

Table 2. Mean comparison of selected variables

Variable	Successful (N=190) (Mean ± SD)	Less successful (N=185) (Mean ± SD)	t-Statistics
Farming experience (years)	8.6 ± 6.9	11.7 ± 9.7	-3.381***
Cultivated area (ha)	3.2 ± 3.1	3.1 ± 2.8	-0.123 ^{NS}

Factors affecting the success of Young Smart Farmers. The Logit regression analysis yielded a stable, well-fitted model, which achieved the overall classification accuracy of 89.5%, including 86.4% of successful and 82.7% of unsuccessful farming classified. A -2 Log Likelihood of 252.497 showed that the model fitted well and 68.0% of the variance in farm success was explained by the independent variables as indicated by the generalized R^2, which was 0.680. This R^2 level is high, especially for logistic regression models on a cross-sectional sample where acceptable values of R^2 tend to be between 0.2 and 0.5. Furthermore, the p-value of the Hosmer-Lemeshow test was 0.604, which is more than 0.05, indicating that the model had a good fit and was valid. Nine of the twelve variables were found to be significant statistically ($p < 0.05$ or $p < 0.01$), that is, formal education, hectares of land cultivated, technology adoption, keeping of farm records, participation in YSF programme, gender, farming experience, government support, and access to credit as presented in Table 3. Education ($p < 0.05$) had a strong association with the chances of being successful on the farm with each additional level increased the chances of farm success by 6.331 times. This further underscores the vital role of formal education in building the innovative capacity of young farmers to analyze, assimilate, and strategize their decision-making under dynamic agro-environmental conditions, in line with the earlier evidence that associated education with productivity and innovation (Mottaleb et al. 2017).

The effect of the main factor, cultivated area ($p < 0.05$) was also noteworthy with each one unit increase increasing the odds of a success by 1.136%. This finding is in line with the hypothesis that larger landholdings can have the potential for greater economies of scale, as well as access to other infrastructures, such as irrigation, machinery and different crop diversification practices such as rotation as emphasized in Foster and Rosenzweig 2010; Pereira et al. (2012). Technology ($p < 0.05$) utilization presented as the most prominent predictor, implies that a unit rise in this variable contributed around 48.821 times increase in odds of being successful. This result is consistent with those of Khobkhet et al. (2024) who found that YSF participants taking up solar and digital technologies showed higher levels of innovative behavior and farm efficiency. The use of digital technology, such as sensors, precision farming tools and mobile applications, contributes to resource efficiency, environmental sustainability and resource management (Jones-Garcia and Krishna, 2021). Likewise, a 0.161 times gain in probability of success was generated by better record-keeping and establishment of better basis in financial tracking, loan eligibility, and decision-making in line with Morgan et al. (2010) and Hayden et al. (2022).

The YSF programme ($p < 0.05$) also demonstrated significant effects, accounting for 38.1% increase in success and observing positive learning outcomes in the form of skills, digital literacy and market readiness. These results confirm those of the previous studies by Sinyolo and Mudhara (2018), which emphasized the opportunities for domiciled training support and institutional support targeting youth. The male gender ($p < 0.01$) was significant, increasing the chances of success by 0.5%, possibly as a result of more access to training, credit and leadership positions. This is consistent with the previous findings of Lastra-Bravo et. al. (2015) and Läpple et al. (2011). Notably, farm training contributed a relatively limited 1.0% increase as evidenced by the fact that young farmers, while holding the experience constant can be more productive than their experienced counterparts when they receive training and are open to innovations, confirming assertions of Sinyolo and Mudhara (2018). Government support also incurred a 1.77% change, which confirms the supportive role of policy measures, subsidies, and extension services on farm performance. Similarly, having access to credit increased the success probability by 0.447 times. While credit can increase access to inputs that raise productivity, it can also lead to exposure risks if not adequately managed as pointed out in Balana and Oyeyemi (2022); Beck and Demirguc-Kunt (2006), and Stiglitz and Weiss (1981).

The other three variables, namely, market access, training and membership to organizations, did not reach conventional statistical levels of significance, though they provided useful qualitative information. For instance, market access was linked to improved price realization and increased linkages to supply chains. Initiatives such as Thailand's "Market-led Production" show that when production is moved towards consumer demand it makes farms more competitive and reduces post-harvest losses. Participation in its training programmes proved positive and it is a complement to the effect of the YSF programme through the consolidation of the acquisition of knowledge and the change in behaviour. The membership in associations can allow access to networks of peers, knowledge exchange, and bargaining power for collaboration which would increase the ability of resilience and market integration. Also, young farmers' farming system preferences also affect their performance. Over 60% of the sample performed integrated farming of field crops and horticulture as part of the agricultural practices, securing long-term income and building resilience. Diversified agriculture (integrated farming) was more robust in anomalous years than monoculture, for which prices and the anomaly-prone climate can be very volatile. These practices are also linked to sustainable farming objectives, such as enhancing soil health through the use of livestock manure and managing risk.

The success of young farmers in Northeast Thailand is clearly a manifestation of a mix of both socio-economic and technology factors. Some similar findings were found in Meechoovet (2022), where smart agriculture projects of Thailand provided a positive impact on farmers' adaptation and income. The results of the logistic regression analysis are summarized in Table 3. Education, land size, technology adoption and institutional support, with special reference to programs like YSF, were identified as the most significant determinants. These findings underscore the necessity of prioritizing youth capacity development, land access system overhauling and appreciation of digital agriculture infrastructure. For decision makers who want to scale successful interventions, while addressing structural issues behind credit and training, and supporting the shift to climate-smart and competitive farming systems. The role of smart farming in improving social and economic well-being has also been illustrated in Thailand's Pa-Laew Pak Dee Dee project (Suntornmeth et al. 2025). Not only will these approaches help to turn young farmers into empowered producers, they will also work to build success in rural development, food security, and environmental sustainability at large.

Table 3. Factors affecting the success of young farmers.

Variables	B	S.E.	Wald	Exp(B)
Gender	-0.664*	0.368	3.269	0.515
Education level	1.845***	0.480	14.766	6.331
Membership	0.489ns	0.361	1.839	1.631
Farming experience	0.049*	0.028	3.201	1.051
Cultivated area	0.128***	0.058	4.832	1.136
Technology adoption	3.888***	0.400	94.422	48.821
Government subsidy	0.573*	0.342	2.807	1.774
Credit access	0.805*	0.420	3.664	0.447
Record keeping	1.825***	0.688	7.030	0.161
Market Information access	0.169 ns	0.409	0.170	1.184
Training	0.201 ns	0.369	0.298	1.223
Becoming YSF	3.800***	0.898	17.892	44.709
Constant	-6.169***	0.927	44.293	0.002

-2Log likelihood = 252.497
LR chi2 = 267.297
Prob > $\chi 2$ = 0.0000
Nagelkerke R Square = 0.680

Note: ***, **, and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively. ns means not significant.

CONCLUSIONS

Five determinants significantly affected the success of young farmers, namely education, farm size, technology utilization, record-keeping, and the young smart farmer (YSF) participant. One of these being the adoption of technology, and in the case of smart farming, the technology can be used to optimize productivity, efficiency, and environmental sustainability. The YSF initiative is key in educating young farmers on how to use such technologies, informing decisions that make them more efficient in how they farm and therefore reduce costs and boost yields. In addition, educated farmers are better equipped to learn, judge, and accept new innovations and the related practices, thereby improving their managerial capacity to oversee contemporary farming. With agriculture moving towards technology-enabled and precision farming, bridging the divide between the next-generation farmers will be critical, in terms of upskilling, providing access to capital, and targeted interventions. Providing young farmers with essential resources, education, and accessibility will secure their success and further national objectives for innovation, competitiveness, and sustainability in agricultural production. Thus, the authorities need to scale up support for YSF projects and promote the greater use of modern agricultural technologies to promote sustainable rural development and long-term food security.

Farmer empowerment and agricultural development is important for the success of young farmers. Such programs offer important resources to young farmers and ranchers such as access to new technologies, government programs, and education and market opportunities. Since farmer empowerment is closely related to agricultural development and scores are effectively higher in the process of the production chain, well-coordinated movement between these two fronts eventually transforms into a great force for change in the agricultural sector.

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MODELLING SOIL ORGANIC CARBON IN MAJOR AGRICULTURAL AREAS OF JAVA ISLAND INDONESIA

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ABSTRACT

Agricultural practices that rely solely on inorganic inputs without amelioration with organic matter to the soil will rapidly decrease the soil organic carbon (SOC) content. This study sought to determine the status of SOC levels, to determine the correlations between SOC and several soil chemical properties, and to determine the equation model to estimate SOC levels in agricultural soils of Java Island. The soil sampling was conducted in 2012 followed by various laboratory analysis to reveal the soil chemical properties of agricultural soil in Java Island, Indonesia. The correlation analysis among soil chemical properties was conducted to see the relationship between SOC and the soil chemical properties. Models to relate the SOC content and the soil chemical properties were obtained using regression analyses. The results showed that the SOC content in Java varied from low, medium to high status. The SOC content had positive correlation ($p<0.01$) with total nitrogen (N); and oxides of aluminum (Al), iron (Fe) and silicon (Si) extracted by ammonium oxalate (Al_o, Fe_o and Si_o). SOC also had positive correlation ($p<0.01$) with elevation, Al extracted by dithionite citrate bicarbonate (Al_d), and $Al_o + \frac{1}{2} Fe_o$ (andic property). SOC did not have correlation with oxides of Fe and Si extracted by dithionite citrate bicarbonate (Fe_d and Si_d). The best equation model to estimate SOC by excluding total N was $SOC = 1.43 + 0.035\ Al_o + 0.016\ Fe_o + 0.109\ Al_d - 0.007\ Fe_d - 0.124\ Si_o - 0.063\ Si_d - 0.0001$ elevation (R^2=0.872). The model indicated that Al_o, Fe_o, and Al_d were very important to predict SOC accumulation in Java Island, Indonesia.

Key words: crystalline oxide, elevation, regression

INTRODUCTION

Soil that meets the requirements for optimal plant growth must certainly have sufficient nutrient content. One important component that can determine the level of soil fertility is soil organic carbon (SOC) content. SOC content in the soil reflects the soil organic matter (SOM) content which is an important benchmark for better future soil management. SOC is part of the soil organic fraction that has degraded and decomposed either partially or completely and has undergone chemical and biological resynthesis.

Soil organic matter (SOM) has many benefits including improving soil structure, increasing available nutrients from the mineralization process of easily decomposed parts of organic matter, and increasing the diversity of organisms that can live in the soil. Indonesia is one of the countries in the humid tropics that is challenged by marginal problematic mineral soils due to the high rate of organic matter decomposition and nutrient leaching. SOC is generally low (< 2.00%) and soil pH is acidic (Brown et al. 2024).

Soil organic carbon (SOC) fractions are very important for understanding soil organic matter decomposition and stabilization. These fractions, with varying turnover rates, help model carbon cycling and assess soil health. The main types are particulate organic carbon (POC), mineral-associated organic carbon (MAOC), and pyrogenic carbon (Pyc). POC is the most labile with a high turnover rate and is sensitive to land use changes like tillage and crop rotation that can affect its contribution significantly (Leifeld and Kögel-Knabner 2004; Liu et al. 2024). MAOC is more stable than POC and is associated with soil minerals phyllosilicate, iron (Fe) and aluminum (Al) hydrous oxides (Dobarco et al. 2023; Zhang et al. 2024).

Even though SOC fractions are important but in a developing country like Indonesia, soil fertility is assessed using the data of SOC content, which is obtained by NC autoanalyzer or Walkley and Black method (Walkley and Black 1934). SOC levels of agricultural soils in Java Island, in general, are reported very low to low due to intensive cultivation with the addition of high rates of inorganic fertilizers, while very little organic matter is returned back to the soils. Efforts that must be made to restore these degraded agricultural soils can be achieved by adding organic matter to the soils so that there will be a gradual increase in soil organic matter content. The resulting accumulation of soil organic matter, together with SOC conservation efforts, can improve the quality of degraded soils, which in turn can contribute to increasing the productivity of cultivated commodities.

Soil organic carbon (SOC) content is generally related to oxides of Al and iron Fe, which are extracted using ammonium oxalate at pH of 3.00 (Ashida et al. 2021; Lyu et al. 2024). It is possible to have other soil properties to relate to SOC content, such as hydrous oxides of Al, Fe, and silicon (Si) extracted by dithionite-citrate-bicarbonate.

Based on the above explanations, a better understanding of the relation between SOC accumulation with soil chemical properties, in particular the oxides of Al, Fe, and Si is needed. This is important in order to restore degraded tropical mineral soils due to lowering SOC content through organic matter amelioration. This study sought to determine the status of SOC content levels, to determine the correlation between SOC content and several soil chemical properties, and to determine the equation model to estimate SOC levels in agricultural soils of Java Island, Indonesia.

MATERIALS AND METHODS

The soil samples were collected in 2012 in a design to obtain varying SOC data from agricultural soils in Java. The location of soil samples collected is presented in Figure 1. The soil samples were collected from agricultural soil both upland soils and paddy field soils. Each soil sample was collected from 0-30 cm depth compositely from 10 points representing the intended area (Tan 2005).

Although the soil chemical properties were mostly analyzed in 2013, it is still relevant to be used for building mathematical equation models because the data were from the soil samples collected in the same year so the equation obtained is valid and could be used to estimate soil organic carbon for different locations. The number of soil samples collected were 48 samples from 48 locations. The number of location was assumed to represent the various agricultural soils in West Java, Central Java and East Java.

Soil samples were air-dried for one week. After that, soil samples were crushed and sieved using 2mm-sieve to have proper size for soil analyses. Before soil analyses, the water content of the air-dried weight was determined to calculate the oven-dried weight (105 ºC) of the soil samples collected.

P = Paddy field, U = Upland

Figure 1. Location of soil sample collection
Source: (Yanai et al. 2014, with modification)

The data were used in this research were elevation, SOC content, total N, extracted Al, Fe, and Si using dithionite-citrate-bicarbonate (DCB method), and extracted Al, Fe, and Si using ammonium oxalate pH 3.00 (oxalate method). The DCB method extracts free and crystalline Al, Fe, and Si oxides, while oxalate method extracts the non-crystalline and poorly crystalline (hydrous oxide) forms of Al, Fe, and Si in soils. The data of SOC content, total N, extracted Al, and Fe, using dithionite-citrate-bicarbonate (DCB method), and extracted Al, Fe, and Si using ammonium oxalate pH 3.00 (oxalate method) referred to Yanai et al. (2014) and Hartono et al. (2015).

Elevation was determined using GPS, SOC and total N were determined using a NC autoanalyzer. Dithionite-citrate-bicarbonate Al and Fe hydrous oxides were extracted using dithionite-citrate-bicarbonate by the method of Mehra and Jackson (1960) hereafter referred to as Al_d, Fe_d, and Si_d. Oxalate-extractable Al, Fe and Si oxides were extracted using ammonium oxalate pH 3.00 for 4 hours in a dark room by the method of McKeague and Day (1966) hereafter referred to as Al_o, Fe_o, and Si_o. The extracted Al, Fe and Si by these two methods were determined using Inductively Coupled Plasma (ICP). All analyses were conducted at the Soil Science Laboratory, Kyoto University, Japan.

Analysis of variance (ANOVA) was used to determine the effect of location on SOC content in paddy fields and upland soils. The locations were West Java, Central Java and East Java. The mean difference test was conducted using the Tukey test at an alpha level < 0.05. Systat 13 (SPSS Inc. 1998) was used for the analysis.

A simple correlation analysis was conducted to see the relationship between SOC content and the selected soil chemical properties. The Pearson correlation test was used to have the significance of the correlation. Models to relate the SOC content and the selected soil chemical properties were obtained using regression analyses. Systat 13 (SPSS Inc. 1998) was used for the analysis.

RESULTS AND DISCUSSION

Selected soil chemical properties and status of soil organic carbon (SOC) content in Java Island
The site name, longitude, latitude, soil order and elevation of paddy fields were presented in Table 1, as well as the Al_o, Fe_o, Al_o+1/2Fe_o, Si_o, Al_d, Fe_d, Si_d, total C and total N content of paddy fields. Overall, the SOC content of paddy field in Java Island ranged from very low to low SOC, but some locations had medium status distributed in West Java, Central Java, and East Java (Soepraptohardjo et al. 1983). This low SOC content in paddy field of Java Island was reported by Hartono et al. (2015). Low SOC levels in paddy fields could be caused by the removal of harvested straw from the field and also due to rotation from paddy field to other crops in the dry season (Chen et al. 2016).

The site name, longitude, latitude, soil order and elevation of upland soil samples were presented in Table 2. The SOC content in upland soil of West Java ranged from 9.65 to 79.4 g kg^{-1}. In Central Java the SOC content of upland soil ranged from 7.55 to 21.6 g kg^{-1} while in East Java the SOC content of upland soil ranged from 9.12 to 49.8 g kg^{-1}.

For upland agricultural soil, carbon loss occurs through increased decomposition of organic matter in the tillage layer due to tillage and erosion. The decrease in SOC levels in upland soil through tillage can occur through mechanisms such as mixing between organic matter-rich upper horizons and relatively organic matter-poor lower layers, accelerated mineralization due to increased tillage intensity, erosion, and low C inputs (Jakab et al. 2023). The range of soil organic content is highly variable and influenced by a combination of soil type, management practices, and environmental conditions (Lim et al. 2022; Matus et al. 2024). Andosols order exhibited much higher SOC content especially the Andosols which occupy the high upland which is about 1600 m above sea level as shown in West Java in Sagalaherang and Lembang and as shown in East Java in Brawijaya University farm, Batu (Table 2).

Soil samples that do not belong to Andosols order exhibited a SOC content of very low to low status (Soepraptohardjo et al. 1983). Andosols order showed very high status of SOC content. Andosols had high amounts of ammonium oxalate pH 3.00-extractable Al, Fe and Si oxides known also as short-range order clay minerals. Short-range order clay minerals have a high capacity to bind SOC. The strong bonding between short-range order clay minerals with SOC protects the SOC from decomposition by soil organisms. This aligns with Lenhardt et al. (2022), stating that carboxyl groups in organic matter strongly bind to structural Al on the surface of allophane spheres (inner sphere complexation). Stabilization of organic matter in soil through interaction with structural Al is important for maintaining soil quality and slowing decomposition of soil organic matter. Some degradation products of non-humified materials are bound by clay containing short-range order clay minerals, making this organic matter difficult for microorganisms to decompose. Higher Al_o + ½Fe_o levels in Andosols indicate high levels of allophane and imogolite in the soil. Soils containing allophane and imogolite will interact with soil organic matter to form stable allophane-organic or imogolite-organic complexes, protecting the organic fraction from degradation (Matus et al. 2014).

Andosols develop from volcanic ash and are characterized by high soil organic matter content, good physical properties, and comparable anion and cation exchange capacities (Manuel et al. 2022). The mineral clay of Andosol consists of allophane, imogolite, and short-range order Fe and Al hydrous oxides (Candra et al. 2021). Allophane is a group of clay minerals composed of Si, Al, and water in chemical combination (Margenot et al. 2017). High stability of soil organic matter in Andosols is related to the presence of "active Al," a term referring to Al residing in Al-humus complexes and allophanic clay (Takahashi and Dahlgren 2016). High Al_o levels lead to stable soil aggregates offering physical protection to SOC. Short-range order clay materials are crucial for stabilizing and aggregating SOC in allophanic Andosols (Asano and Wagai 2014).

Table 1. Location of collected samples in paddy fields and their selected soil properties

Site Name	Longitude S	Latitude E	Soil order according to FAO	Elevation (m)	Al_o (g kg^{-1})	Fe_o (g kg^{-1})	Al_o+1/2Fe_o (g kg^{-1})	Si_o (g kg^{-1})	Al_d (g kg^{-1})	Fe_d (g kg^{-1})	Si_d (g kg^{-1})	Total C (g kg^{-1})	Total N (g kg^{-1})
West Java													
Palimanan	06°40' 52.3"	108°25' 32.6"	Fluvisols	28	1.11	4.61	3.42	0.75	0.70	6.25	2.31	8.06	0.78
Indramayu	06°24' 57.7"	108°16' 33.2"	Fluvisols	23	1.81	7.09	5.35	0.61	1.37	10.5	1.36	17.2	1.97
Jatisari	06°21' 26.4"	107°32' 36.9"	Fluvisols	45	1.49	12.7	7.86	0.25	1.01	15.7	1.40	21.6	2.19
Karawang	06°16' 25.0"	107°17' 08.7"	Fluvisols	31	1.47	14.8	8.86	0.42	1.06	15.5	1.59	23.2	2.29
Cikarawang	06°33' 05.1"	106°44' 22.4"	Acrisols	195	8.86	27.5	22.6	1.02	4.83	54.1	1.49	23.6	2.35
Pamanukan	06°16' 43.4"	107°50' 39.2"	Fluvisols	22	1.63	9.3	6.29	0.41	1.27	12.1	1.89	27.0	2.52
Cicalengka	07°06' 07.3"	108°06' 09.6"	Andosols	785	6.60	28.5	20.9	0.66	5.11	40.7	1.75	28.9	2.90
Central Java													
Jogjakarta	07°49' 49.3"	110°27' 21.4"	Luvisols	103	3.94	14.0	10.9	0.47	1.54	5.56	1.59	8.97	1.00
Brebes	06°52' 32.5"	109°03' 46.6"	Fluvisols	19	1.74	8.03	5.76	0.89	1.03	9.65	1.81	13.1	1.37
Jekulo	06°48' 07.8"	110°56' 02.7"	Nitosols	29	1.74	10.2	6.8	1.02	1.90	12.7	1.91	14.6	1.42
Borobudur	07°34' 39.0"	110°15' 01.8"	Luvisols	318	6.17	11.5	11.9	0.82	1.90	5.49	1.88	14.7	1.51
Demak	06°55' 46.7"	110°32' 38.7"	Fluvisols	16	1.75	6.39	4.94	0.83	1.26	9.33	1.29	15.9	1.59
Suradadi	06°52' 24.2"	109°15' 02.0"	Nitosols	23	1.73	8.12	5.79	0.79	1.22	11.5	1.35	16.0	1.73
Kutoarjo	07°43' 26.4"	109°52' 20.5"	Acrisols	23	7.31	26.4	20.5	0.95	2.78	19.9	2.91	18.6	1.83
Karanganyar	07°37' 36.1"	109°33' 55.4"	Acrisols	22	7.00	32.1	23.0	0.67	2.71	22.1	3.00	19.8	1.91
Kendal	06°56' 29.5"	110°14' 36.1"	Luvisols	19	1.74	11.5	7.50	0.76	1.10	14.6	1.87	24.0	2.32
Buntu	07°35' 24.2"	109°15' 07.3"	Fluvisols	18	9.90	40.8	30.3	1.28	3.64	22.4	2.31	27.0	2.65
Batang	06°58' 39.3"	109°53' 39.1"	Nitosols	178	2.22	10.4	7.42	0.76	2.47	20.0	2.11	29.9	2.95
East Java													
Jombang	07°31' 48.1"	112°15' 24.8"	Luvisols	39	3.32	2.87	4.76	0.56	1.05	2.45	1.87	9.78	0.97
Tambak Rejo	07°15' 54.7"	111°35' 10.9"	Vertisols	79	1.39	1.86	2.32	0.76	0.86	3.00	1.02	10.8	0.86
Nganjuk	07°33' 56.7"	111°50' 34.3"	Fluvisols	74	5.37	1.21	5.97	0.89	1.01	3.65	2.06	14.9	1.36
Bojonegoro	07°08' 14.3"	111°48' 47.9"	Fluvisols	40	2.32	6.75	5.69	0.63	1.83	8.55	1.05	18.2	1.59
Ponorogo	07°51' 53.2"	111°27' 17.3"	Fluvisols	112	6.36	8.26	10.49	1.16	1.98	5.34	2.00	23.8	2.16

o = extracted using ammonium oxalate pH 3.00
d = extracted using dithionite-citrate-bicarbonate
Source: (Yanai et al. 2014; Hartono et al. 2015)

Table 2. Location of collected samples in upland and their selected soil properties

Site Name	Longitude S	Latitude E	Soi order according to FAO	Elevation (m)	Al_o (g kg^{-1})	Fe_o (g kg^{-1})	Al_o+1/2Fe_o (g kg^{-1})	Si_o (g kg^{-1})	Al_d (g kg^{-1})	Fe_d (g kg^{-1})	Si_d (g kg^{-1})	Total C (g kg^{-1})	Total N (g kg^{-1})
West java													
Ciamis	07°18' 44.2"	108°17' 01.9"	Luvisols	326	6.84	14.5	14.1	1.48	3.77	27.6	1.02	9.65	1.03
Malangbong	07°07' 00.3"	108°07' 18.9"	Andosols	662	7.15	16.1	15.2	1.10	7.67	66.9	1.17	19.3	1.92
Bantar Kambing	06°30' 52.6"	106°41' 50.0"	Acrisols	140	11.4	34.2	28.5	0.81	7.00	66.4	0.96	20.9	2.10
Darangdan	06°40' 22.4"	107°25' 31.7"	Andosols	502	14.2	14.7	21.5	0.92	12.8	81.6	0.94	21.7	2.23
Cikabayan, Darmaga	06°33' 08.7"	106°42' 58.4"	Acrisols	190	9.07	11.4	14.8	0.39	10.3	67.9	1.13	23.7	2.47
Cikabayan, Darmaga	06°33' 08.7"	106°42' 58.4"	Acrisols	190	9.02	11.6	14.8	0.45	9.83	67.4	1.12	24.0	2.91
Cikabayan, Darmaga	06°33' 08.7"	106°42' 58.4"	Acrisols	190	9.52	12.5	15.8	0.51	9.69	67.3	0.97	25.0	2.66
Cikabayan, Darmaga	06°33' 08.7"	106°42' 58.4"	Acrisols	190	10.7	11.3	16.3	0.48	9.50	67.3	0.96	25.6	2.58
Sagalaherang	06°40' 34.2"	107°40' 39.2"	Andosols	577	88.1	41.5	109	12.5	23.3	47.5	2.96	56.0	4.82
Lembang	06°48' 11.5"	107°38' 53.5"	Andosols	1239	176	59.2	205	30.9	22.8	32.8	2.38	70.2	6.79
Lembang	06°48' 20.0"	107°39' 22.4"	Andosols	1214	212	92.5	258	36.2	25.6	41.2	1.99	79.4	4.90
Central Java													
Borobudur	07°34' 48.5"	110°14' 52.2"	Luvisols	301	6.70	15.2	14.3	0.86	1.84	6.36	1.35	7.55	0.76
Wonogiri	07°49' 48.3"	111°05' 14.8"	Luvisols	351	5.67	19.3	15.3	1.63	4.10	41.9	2.64	12.5	1.21
Kudus	06°43' 17.5"	110°52' 36.7"	Nitosols	213	3.61	7.23	7.23	0.83	3.83	15.4	1.43	13.4	1.27
Wonosari	07°55' 32.9"	110°33' 50.2"	Vertisols	217	5.45	31.3	21.1	2.35	3.28	40.3	3.46	13.8	1.23
Batang	06°56' 51.2"	109°47' 11.7"	Nitosols	91.0	1.86	7.78	5.75	0.80	2.56	18.9	1.94	17.3	1.80
Lumbir	07°28' 25.9"	108°58' 58.5"	Acrisols	67.0	9.62	17.2	18.2	0.83	5.19	35.3	1.43	21.6	2.15
East Java													
Bancar	06°46' 24.6"	111°44' 08.1"	Luvisols	19.0	0.82	1.11	1.38	0.47	1.01	4.43	2.89	9.12	0.82
Batu, Malang	07°52'58.84"	112°32'23.5"	Andosols	835	8.64	23.4	20.4	1.30	3.10	13.6	3.28	11.5	1.21
Tambak Rejo	07°15' 54.7"	111°35' 10.9"	Vertisols	79.0	1.76	1.40	2.46	0.91	0.94	2.74	0.96	11.8	0.95
Tuban	06°54' 24.4"	112°12' 14.0"	Luvisols	40.0	2.23	3.88	4.17	0.85	4.61	59.7	1.93	13.2	1.50
Tulungagung	08°06' 27.2"	112°02' 17.4"	Fluvisols	131	10.5	10.5	15.7	6.47	3.08	4.17	1.92	13.6	1.18
Paciran	06°52' 39.7"	112°24' 47.7"	Luvisols	28.0	2.51	5.26	5.14	1.29	4.38	55.3	1.92	14.9	1.85
Ngantang	07°53' 18.8"	112°21' 41.0"	Andosols	693	15.2	20.9	25.7	3.07	3.31	9.77	1.90	15.5	1.65
Brawijaya University Farm, Batu	07°44' 24.7"	112°32' 15.0"	Andosols	1664	67.7	34.7	85.0	10.4	14.2	15.3	2.17	49.8	4.70

o = extracted using ammonium oxalate pH 3.00
d = extracted using dithionite-citrate-bicarbonate
Source: (Yanai et al. 2014; Hartono et al. 2015)

The SOC levels of paddy fields in Java Island were not statistically different (Table 3). As for upland soils, the SOC levels of upland soils in Java Island were not different either (Table 4). West Java and East Java upland soils had higher SOC content than Central Java (Table 4). Some samples from West Java and East Java were Andosols.

Table 3. The effect of location to the SOC content in paddy field soil.

Province	**Number of sample**	**SOC (g kg^{-1})**
West Java	7	18.7a
Central Java	11	18.4a
East Java	5	15.5a

Means followed by the same letter within a column are not significantly different (Tukey's test, $p<0.05$)

Table 4. The effect of location to the SOC content in upland soil

Province	**Number of samples**	**SOC (g kg^{-1})**
West Java	11	34.1a
Central Java	6	14.4a
East Java	8	17.4a

Means followed by the same letter within a column are not significantly different (Tukey's test, $p<0.05$)

Correlation between SOC and selected soil properties. The correlation was established using all soil properties data from paddy field soils and upland soils. Based on Pearson correlation, SOC content of agricultural soils in Java Island had a very significant correlation ($p < 0.01$**) with total N, Al_o, $Al_o + ½Fe_o$, Al_d, Fe_o, Si_o, and elevation (Table 5). This indicates a strong relationship between SOC content and total N. Higher SOC content correlates with higher total N content. Furthermore, higher Alo + ½Feo, Alo, Ald, Feo, Sio, and elevation also correlate with higher SOC content.

Table 5. Correlation among selected soil properties

	Total N	**Al_o + ½Fe_o**	**Al_o**	**Al_d**	**Si_o**	**Fe_o**	**Elevation**	**Fe_d**	**Si_d**
SOC	0.956**	0.911**	0.906**	0.874**	0.868**	0.818**	0.679**	0.276	0.146
Total N		0.806**	0.803**	0.845**	0.756**	0.719**	0.656**	0.349*	0.111
Al_o + ½Fe_o			0.996**	0.861**	0.982**	0.893**	0.721**	0.181	0.221
Al_o				0.860**	0.989**	0.847**	0.713**	0.159	0.194

	Total N	Al_o + ½Fe_o	Al_o	Al_d	Si_o	Fe_o	Elevation	Fe_d	Si_d
Al_d					0.805**	0.754**	0.709**	0.550**	0.059
Si_o						0.821**	0.687**	0.091	0.217
Fe_o							0.667**	0.267	0.324*
Elevation								0.188	0.187
Fe-d									-0.233

** Very significant (p<0.01)
* Significant (p<0.05)

SOC content had significant correlations with total N, Al_o, Al_o + ½Fe_o, Al_d, Fe_o, Si_o, and elevation (Table 4), suggesting that a model to relate SOC in Java agricultural areas is feasible. SOC content also significantly correlated with elevation. High elevation areas have low temperature that slows organic matter decomposition. High elevation causes low air and soil temperatures (Serrano et al. 2020). Climatic factors like temperature affect SOC content (Jiang et al. 2023), where higher elevation leads to lower temperatures, increasing total SOC content (Tan et al. 2020).

Organic matter provides nutrients such as N, P, and S through microbial mineralization processes. Higher organic matter levels result in higher total N content. Positive correlations of SOC content with total N and Al_o + ½Fe_o levels indicate the influence of volcanic materials on organic matter accumulation in Java's agricultural soils (Yanai et al. 2014) . Volcanic eruptions produce pyroclastic materials, forming Andosol soil order. Weathering of volcanic ash produces allophane and imogolite, increasing alongside rising levels of Al_o + ½Fe_o (ammonium oxalate extraction). Al and Si contents, extracted with ammonium oxalate (Al_o, Si_o), estimate the presence of allophane and imogolite. Positive correlations between Al_o + ½Fe_o and Al_o, Fe_o, and Si_o reflect the relationship between short-range order clay minerals and Al, Fe, and Si extracted by ammonium oxalate. Soil fractions of Fe, Al, and Si can be crystalline clay minerals, short-range order clay minerals, or humus complexes. Chemical separation for those forms of Al, Fe hydrous oxides and Si amorphous and crystalline uses dithionite-citrate, ammonium oxalate, and sodium pyrophosphate solutions (Boland et al. 2012).

Model to predict soil organic carbon (SOC) accumulation. Significant correlations between SOC content and selected soil properties (Al_o, Al_o + ½Fe_o, Al_d, Fe_o, Si_o, and elevation) enable the formulation of empirical models to relate SOC content with these selected soil properties. In this model, total N was excluded in the models because SOC and total N are very correlated each other. This model, in turn, can be used to predict the causes of SOC accumulation. Model to predict SOC content using soil data from paddy field and upland field existing in the soil as a result of soil development including the effect of soil management such as returning rice straw to the field.

Multiple linear regression equations derived from this soil samples data were shown in Table 6. High R^2 values indicated model suitability. Smith (2015) emphasized selecting regression equations based on statistical criteria, particularly the coefficient of determination R^2 and practical considerations.

Table 6. Model to predict SOC in paddy field and upland soils

Model	Equation	R^2
1	SOC = 1.43 + 0.035 Al_o + 0.016 Fe_o + 0.109 Al_d - 0.007 Fe_d - 0.124 Si_o - 0.063 Si_d- 0.0001 elevation	0.872
2	SOC = 1.43 + 0.036 Al_o + 0.015 Fe_o - 0.127 Si_o + 0.099 Al_d - 0.006 Fe_d - 0.062 Si_d	0.871
3	SOC = 1.33 + 0.039 Al_o + 0.013 Fe_o - 0.136 Si_o + 0.095 Al_d - 0.005 Fe_d	0.871
4	SOC = 1.218 + 0.011 Al_o + 0.016 Fe_o + 0.130 Al_d - 0.007 Fe_d	0.865
5	SOC = 1.20 + 0.017 Al_o + 0.013 Fe_o + 0.086 Al_d	0.862
6	SOC = 1.43 + 0.027 Al_o + 0.015 Fe_o	0.829
7	SOC = 1.61 + 0.032 Al_o	0.820
8	SOC = 1.45 + 0.027 Al_o + ½ Fe_o	0.829

The ideal model was SOC = 1.43 + 0.035 Al_o + 0.016 Fe_o + 0.109 Al_d - 0.007 Fe_d - 0.124 Si_o - 0.063 Si_d - 0.0001 elevation (R^2=0.872). Figure 2 compares predicted SOC by model 1and actual SOC values. Even though in correlation, Si_o had positive constant with SOC content, but in equation models, Si_o had a negative constant for predicting SOC accumulation.

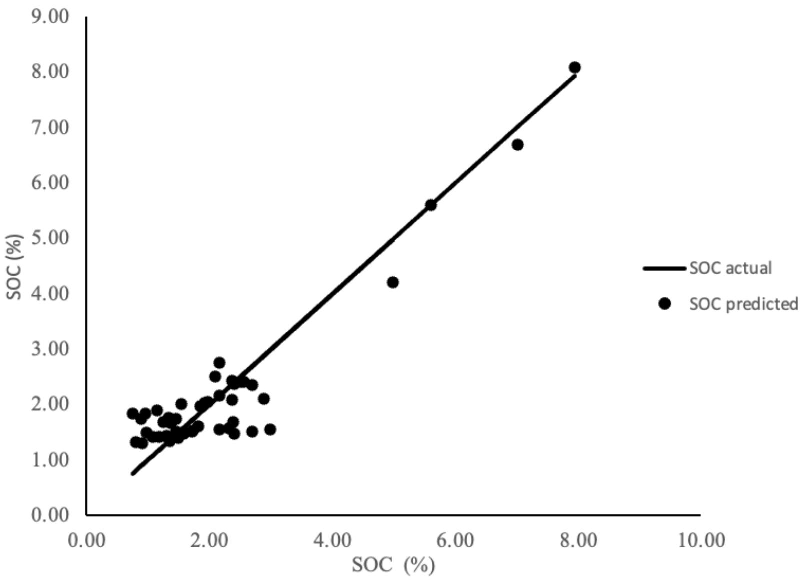

Figure 2. Plotting actual SOC and predicted by model 1

Another suitable model, SOC = 1.43 + 0.036 Al_o + 0.015 Fe_o - 0.127 Si_o + 0.099 Al_d - 0.006 Fe_d - 0.062 Si_d (R^2=0.871), lacks elevation data yet remains effective. Figure 3 compares the SOC accumulation predicted using model 2 with the actual SOC values. Although Si_o positively correlates with SOC content, its negative constant in prediction models indicates that Al_o, Al_o + ½Fe_o, Al_d, and Fe_o are better predictors.

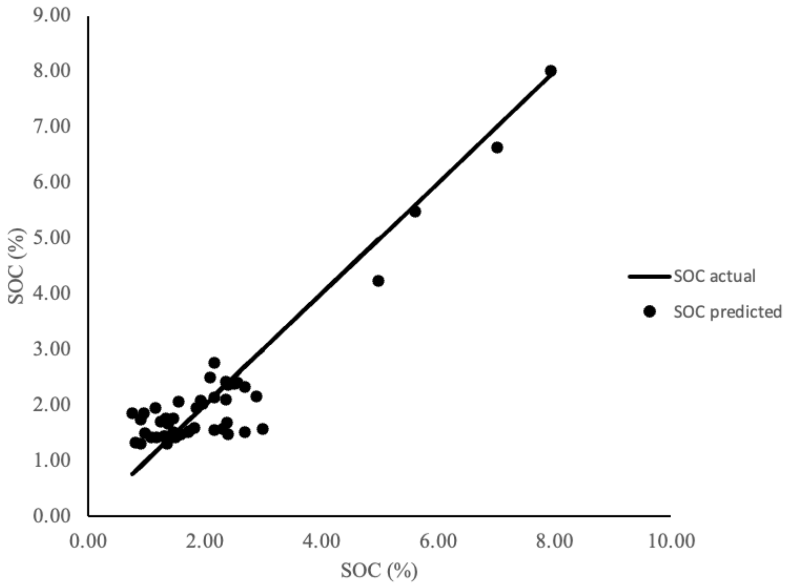

Figure 3. Plotting actual SOC and predicted by Model 2

Figure 4 compares the SOC accumulation predicted by model 8 with actual values. Al, Fe extracted by ammonium oxalate (Al_o, Fe_o, and Al_o + ½Fe_o) positively contribute to SOC prediction, indicating increased SOC stability due to binding by short-range order clay minerals.

The best model to predict SOC accumulation was SOC = 1.43 + 0.035 Al_o + 0.016 Fe_o + 0.109 Al_d - 0.007 Fe_d - 0.124 Si_o - 0.063 Si_d - 0.0001 elevation (R^2=0.872). Model 2 (SOC = 1.43 + 0.036 Al_o + 0.015 Fe_o - 0.127 Si_o + 0.099 Al_d - 0.006 Fe_d - 0.062 Si_d (R^2=0.871) was also effective, though inclusion of elevation data improves prediction accuracy.

Those models are very important in identifying the soil properties that control the SOC accumulation. The models show that Al_o and Fe_o or the non-crystalline and poorly crystalline (hydrous oxide) of Al and Fe, or amorphous Al and Fe, are the main components in controlling SOC accumulation. In addition, Al_d, the more crystalline of Al oxide, also controls SOC accumulation. The high amount of Al_o, Fe_o and Al_d increases the amount of SOC content in the soils. Ligand exchange between carboxyl and hydroxyl groups of organic compounds and mineral surfaces is a key adsorption mechanism (Gu et al. 1994). As a result, carboxylic acids like oxalic acid show high adsorption affinity to clay minerals, especially iron oxides (Jagadamma et al. 2012; Jagadamma et al. 2014; Yeasmin et al. 2014).

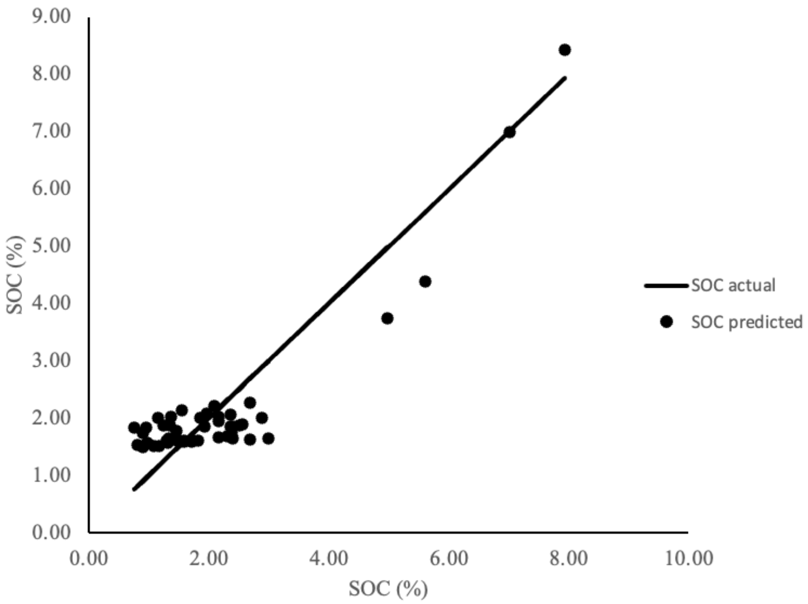

Figure 4. Plotting actual SOC and predicted by Model 8

The models obtained in this research are very location-specific. Different places have different models for predicting SOC accumulation. In China, in coastal wetlands, multiple linear regressions and random forest model showed that soil pH was the most important variable impacting SOC, followed by Cl and silt content (Zhang et al. 2017). In Calabar, Cross River State, Nigeria, the Ca to Mg ratio, effective CEC, base saturation, and K to Ca ratio had a significant influence on SOC distribution in that area (John et al. 2020). Therefore, the models obtained in this study indicate that Al_o, Fe_o, and Al_d are very important to predict SOC accumulation in soils of Java Island, Indonesia.

CONCLUSION

Soil organic carbon (SOC) in Java Island's agricultural soils ranges from low to high, influenced by short-range order clay minerals. SOC is significantly correlated with total nitrogen, Alo, Feo, Ald, Sio, and elevation. Higher values of these factors correspond to higher SOC levels. The most effective model to predict SOC accumulation, according to the coefficient of determination (R^2), was SOC = 1.43 + 0.035 Al_o + 0.016 Fe_o + 0.109 Al_d - 0.007 Fe_d - 0.124 Si_o - 0.063 Si_d - 0.0001 elevation (R^2=0.872). The equations could be valid and relevant to estimate SOC of different years due to high R^2 values, which are close to 1.00 although the soil data were collected in 2012.

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