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Article

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Suggested Citation: AR, Nuhfil Hanani et al. (2024) : Does the climate change adaptation affect technical efficiency? Empirical evidence from potato farmers in East Java, Indonesia, Cogent Economics & Finance, ISSN 2332-2039, Taylor & Francis, Abingdon, Vol. 12, Iss. 1, pp. 1-16, https://doi.org/10.1080/23322039.2024.2426528

This Version is available at:
https://hdl.handle.net/10419/321659

Cogent Economics & Finance

ISSN: 2332-2039 (Online) Journal homepage: www.tandfonline.com/journals/oaef20

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To cite this article: Nuhfil Hanani AR, Moh Shadiqur Rahman, Fahriyah Fahriyah, Dodyk Pranowo, Hery Toiba, Rosihan Asmara, Sujarwo Sujarwo, Mohammad Ilyas Shaleh, Mohammad Wahyu Firdaus, Mahfudlotul 'Ula & Dwi Retnoningsih (2024) Does the climate change adaptation affect technical efficiency? Empirical evidence from potato farmers in East Java, Indonesia, Cogent Economics & Finance, 12:1, 2426528, DOI: 10.1080/23322039.2024.2426528

To link to this article: https://doi.org/10.1080/23322039.2024.2426528

COGENT ECONOMICS & FINANCE
2024, VOL. 12, NO. 1, 2426528
https://doi.org/10.1080/23322039.2024.2426528

ECONOMETRICS & DATA ANALYTICS | RESEARCH ARTICLE
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Does the climate change adaptation affect technical efficiency? Empirical evidence from potato farmers in East Java, Indonesia

Nuhfil Hanani AR[a], Moh Shadiqur Rahman[a], Fahriyah Fahriyah[a], Dodyk Pranowo[b], Hery Toiba[a], Rosihan Asmara[a], Sujarwo Sujarwo[a], Mohammad Ilyas Shaleh[a], Mohammad Wahyu Firdaus[a], Mahfudlotul 'Ula[a] and Dwi Retnoningsih[c]

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ABSTRACT
Under climate change, maintaining technical efficiency in farming is crucial for smallholder farmers to enhance their yield and productivity; therefore, it is essential to implement climate change adaptation strategies to sustain this technical efficiency. This study investigates the impact of diversifying climate change adaptation strategies on the technical efficiency of 217 potato farmers in East Java, Indonesia. Stochastic frontier analysis (SFA) was employed to measure farming technical efficiency, while a two-stage residual inclusion approach (2SRIA) was used to estimate the impact of climate change adaptation on this efficiency. This research identifies six common adaptation strategies: adjusting planting dates, cultivating drought-tolerant varieties, intercropping, altering input usage, conserving land, and improving irrigation systems. The empirical findings reveal a significant positive correlation between diversifying climate change adaptation strategies and enhanced technical efficiency among potato farmers. This suggests that employing more adaptation strategies will significantly improve farmers' technical efficiency. Analyzing each adaptation strategy, the research highlights the positive impact of adjusting planting dates, adopting drought-tolerant varieties, implementing land conservation, and improving irrigation systems on technical efficiency. By contrast, intercropping and altering input usage adversely affect technical efficiency. This finding implies the need to promote climate change adaptation based on farmers' specific characteristics.

IMPACT STATEMENT
This study reveals that diversifying climate adaptation strategies—such as adjusting planting dates and enhancing irrigation—boosts technical efficiency in potato farming. Key factors like education and experience further influence adaptation. These insights offer guidance for tailored adaptation policies, fostering resilience and productivity among smallholder farmers facing climate change challenges.

ARTICLE HISTORY
Received 29 April 2024
Revised 31 July 2024
Accepted 3 November 2024

KEYWORDS
Climate change adaptation; potato farming; technical efficiency; two-stage residual inclusion approach; adaptation strategies

SUBJECTS
Economics and Development; Sustainable Development; Economics

1. Introduction

Climate change is an environmental issue that has been a pressing concern worldwide, including in developing countries. This phenomenon results from global warming, leading to a continuous increase in global temperatures over the years (Chen et al., 2023; Wang et al., 2017). The Intergovernmental Panel on Climate Change (IPCC) stated in 2001 that global air temperatures have risen by 0.6 degrees Celsius since 1861 (Houghton et al., 2001). The primary cause of this global warming is human activities that generate greenhouse gases. Climate change significantly impacts social, economic, and political conditions, as well as communities' livelihoods (Ahmed et al., 2023), particularly those reliant on natural

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resources for their sustenance, such as farmers (Bozzola & Smale, 2020; Shaffril et al., 2017). Agriculture is one of the sectors most vulnerable to this phenomenon, as agricultural productivity is heavily influenced by climatic conditions (Somboonsuke et al., 2018), such as temperature fluctuations, precipitation changes, and drought. Climate change is predicted to cause a decline in agricultural production, especially in developing countries such as Thailand (Marks, 2011), Vietnam (Trinh et al., 2021), and Indonesia (Sekaranom et al., 2021). This is because rising average temperatures or insufficient water supply can disrupt plant growth and reduce crop yields (Bandara and Cai, 2014). Moreover, extreme events, especially floods and droughts, can lead to harvest failures, which lower crop yields. Abid et al. (2016) highlighted that lower yields reduce farmers' agricultural income. Such adverse impacts on the agricultural sector necessitate appropriate adaptation strategies.

According to Smit et al. (1999) and Smith and Lenhart, adaptation is a suitable response to mitigate the impacts of climate change, enabling farmers to sustain and enhance agricultural productivity. Adaptation involves adjustments to rectify damages in response to environmental changes (FAO 2011). Previous studies have recommended and applied various adaptation strategies to climate change, such as land and water conservation, to mitigate climate-related erosion (Amare & Simane, 2017). In developing countries, farmers diversify their adaptation strategies, including adopting drought-tolerant crop varieties, diversifying crops, improving irrigation systems, and altering planting patterns. More specifically, developing drought-tolerant crop varieties can enhance productivity during dry seasons (Lebel et al., 2011). In sum, diversification in adaptation strategies has proven beneficial, but there remain challenges in the implementation and efficacy.

Previous studies, such as by Akpa et al. (2024), have examined the impact of climate change adaptation on farmers' productivity, measured by the technical efficiency level. According to Battese and Coelli (1988) technical efficiency refers to the ability of a firm or production unit to maximize output from a given set of inputs. In other words, it measures how well inputs are used to produce outputs. The study revealed that adaptation strategies improve technical efficiency by 1.28%. Studies have proven that climate change adaptation contributes positively to productivity (Akpa et al., 2024; Finger et al., 2011; Mendelsohn et al., 2000), but the practices are not systematic. The wide range of adaptation strategies suggested in past studies makes it difficult for stakeholders to determine which ones are the most suitable for which situations. Therefore, understanding adaptation strategies to enhance farmers' efficiency is crucial in order to maximize agricultural productivity (Ankrah Twumasi & Jiang, 2021).

Farmers' productivity and technical efficiency are vital indicators for economic development in developing countries (Ma et al., 2018). However, determining input use is a common challenge among farmers, especially in the adoption of relatively new strategies like climate change adaptation. For instance, research by Li et al. (2022) in China indicated that the greatest intensity of agricultural technology adoption by farmers does not necessarily lead to improved technical efficiency. Similarly, Amankwah and Gwatidzo (2024) highlighted that different adoption practices can impact the economic outcomes of farmers differently. Therefore, in line with these findings, various adaptation practices adopted by farmers could affect technical efficiency in different ways. Using household-scale data, this study aims to address these challenges.

The importance of technical efficiency in climate change adaptation practices has attracted researchers' attention. For example, Ho and Shimada (2019) analyzed the impact of climate change adaptation on farm efficiency in Vietnam. The results showed that farmers implementing adaptation measures tended to have higher technical efficiency levels than those who did not. Similar research was conducted by Khanal et al. (2018), examining the contribution of climate change adaptation to farmers' technical efficiency. The findings indicate that climate change adaptation significantly improves farmers' technical efficiency. Empirical evidence also demonstrates that climate change adaptation enhances technical efficiency in other sectors, such as fisheries (Nguyen et al., 2018) and livestock farming (Ankrah Twumasi & Jiang, 2021). All these studies suggest the importance of examining the relationship between climate change adaptation and technical efficiency for agricultural development.

Although previous studies have explored climate change adaptation and technical efficiency (Ho & Shimada, 2019; Khanal et al., 2018), some gaps warrant further investigation. First, prior research treated adaptation variables dichotomously (i.e., 1 for adaptation, 0 otherwise) (Ho & Shimada, 2019; Khanal et al., 2018). However, agricultural adaptation practices are diverse, so treating it as a binary dummy variable may not adequately capture farmers' nuanced adaptive capacity (Ho & Shimada, 2019; Khanal et al., 2018; Syafrial Toiba et al., 2021). To address this limitation, this study proposes measuring adaptation diversity by quantifying the number of adaptation practices adopted by farmers. This approach has been employed in recent research by Rahman et al. (2022) and Mabe and Asase (2020). By incorporating adaptation diversity, this study seeks to provide a more comprehensive picture of farmers' adaptive capacities in response to environmental challenges. Secondly, previous studies assumed homogeneity among farmers, especially concerning income levels, ignoring the pervasive heterogeneity in developing countries like Indonesia (Rahman, Huang et al., 2023a; Rahman, Toiba, et al., 2023b). Considering this, adaptation's impact on technical efficiency among farmers with varying income levels may differ (Ma & Zheng, 2022). To address these gaps, this study analyzes the effects of climate change adaptation strategies on farmers' technical efficiency while disaggregating the analyses to investigate how adaptation impacts technical efficiency based on farmers' household income groups.

This study contributes three significant aspects to the literature on climate change adaptation and technical efficiency in agriculture. First, it proposes measuring adaptation diversity by quantifying farmers' practices, departing from the dichotomy observed in previous studies. These studies generally classify adaptation in a binary manner (applying adaptation or not) without estimating the impact of each adaptation practice on technical efficiency (Ho & Shimada, 2019; Khanal et al., 2018). Second, it recognizes farmer heterogeneity, especially in income, by disaggregating the analyses to explore the impact of adaptation on efficiency across socioeconomic strata (Ma et al., 2020). Lastly, this study aligns with Sustainable Development Goal No. 13, "Climate Action," by supporting initiatives to address climate change challenges.

The remaining sections of this article are organized as follows: Section 2 outlines the research methodology, Section 3 presents the results and corresponding discussion, and Section 4 concludes the study and offers the policy implications.

2. Methodology

2.1. Research data

This study used a quantitative approach with cross-sectional data to estimate the impact of climate change adaptation on farmers' technical efficiency. The determination of the research locations was carried out through a multistage sampling process. The first step was selecting the province from which two districts were chosen. These two districts, namely Probolinggo district and the city of Batu, East Java, Indonesia, were purposively selected because they are significant horticulture producers in East Java and have experienced climate change-related issues. Climate change in East Java poses a significant threat to farmers' technical efficiency in the region (Hakim et al., 2021). Farmers face numerous challenges in optimizing their agricultural practices with changing weather patterns, including alterations in rainfall distribution and temperature fluctuations (Purwanti et al., 2022; Rahman et al., 2023a). These changes can disrupt traditional farming schedules, reducing crop yields and increasing vulnerability to pests and diseases (Mabe & Asase, 2020). Yet, these two locations produce the most potatoes in the country, with all-year-round production. Secondly, the selection of sub-districts for sampling was done randomly based on information from relevant institutions (the Department of Agriculture, Agricultural Extension Services, and farmer groups) and data from Statistics Indonesia (*Badan Pusat Statistik*/BPS). One sub-district was chosen from each district. Thirdly, after selecting the sub-districts, one village was purposively chosen from each sub-district, following recommendations from the district department. These recommendations were based on the highest number of potato farmers with all-year-round production. The respondents for this research were potato farmers. The selection of respondents was determined using a simple random sampling method. First, a list of potato farmers in each targeted research location was created using information from local agricultural organizations, specifically farmers' groups, forming the sampling framework. Farmers were sampled using the Slovin method from this list, resulting in a minimum sample of 103 farmers in each location. Then, in each village, an oversampling of 105–100 farmers was conducted, and the final selection was made randomly. In total, 217 potato farmers were selected in the two chosen districts. the ethical concern of this study was approved by Faculty of Agriculture, Brawijaya University.

This study employs a structured questionnaire designed for face-to-face interviews, consisting of six sections. The first section of the questionnaire inquires about household characteristics, including the number of family members, age, education, and farming experience. The second section covers asset ownership, both agricultural and non-agricultural. The household characteristics and asset ownership were used to model the factors affecting farmers' adaptation diversity and technical efficiency.

The third section focuses on farming activities, including agricultural land, input, and agricultural production. This information was used to measure the farmers' technical efficiency. The fifth section explores farmers' understanding and perception of climate change, this section will explore farmers' adaptation to climate change and subsequently analyze the impact of these adaptations on farmers' technical efficiency. the question starting with a basic question, "Have you ever heard of climate change?" Enumerators confirm the responses; if a farmer answers "do not know" or incorrectly, the enumerator explains what climate change is. Following this, the questions deal with farmers' perceptions of climate change and its impact on the agricultural sector. Finally, the sixth section asks about the adaptation strategies the farmers had implemented to deal with climate change, specifically, "Have you applied adaptation strategies to mitigate the impacts of climate change?" This question is complemented with a list of strategies to select from to indicate the ones they have applied. These options were developed based on literature reviews and group discussions with agricultural-related stakeholders. The adaptation options consist of adapting planting timing, using drought-resistant varieties, intercropping, adjusting input usage, conserving land, and irrigation. Before conducting the survey, the questionnaire was validated through a pilot test involving five farmers from each village.

2.2. Measurement of key variables

2.2.1. Adaptation strategies

The treatment variable in this study is the adaptation to climate change, which is measured in two ways: adaptation decision and diversification. The adaptation decision refers to farmers' decisions. However, since the climate change adaptation implemented by farmers is diverse—such as changing planting timing, adopting drought-tolerant varieties, intercropping, adjusting input usage, and conserving land—we also use adaptation diversification to capture farmers' adaptation capacity. The adaptation diversity is measured by the total number of adaptation practices applied by the farmers.

Following the approach of Mabe and Asase (2020) and Rahman et al. (2022), this study measures the diversification level using the number of adaptation strategies farmers have applied, ranging from 0 to 6 (treated as an ordinal variable). The adaptation strategies include changing planting timing, adopting drought-tolerant varieties, intercropping, adjusting input usage, and conserving land. Each adaptation strategy is measured by a dummy variable (1 if the farmer adopts the strategy and 0 otherwise).

2.2.2. Technical efficiency

Two approaches have been widely used to measure technical efficiency: the Stochastic Production Frontier (SPF) model and the data envelopment analysis (DEA) (Bibi et al., 2021). These approaches differ significantly. The SPF model distinguishes inefficiency from stochastic variation, whereas the DEA model cannot separate inefficiency from random noise. SPF is a parametric method that considers the effects of production inputs on crop output, but the non-parametric DEA model does not have this capability. Given our interest in understanding how input use impacts the output in potato farming, we opt for the parametric, specifically a Cobb-Douglas stochastic production frontier model (SPF). This model not only estimates technical efficiency but also accounts for random shocks such as temperature, rainfall, and climate conditions.

Based on Ma et al. (2018), the Cobb-Douglas SPF model can be written as follows:

$$Prod = f(X_i) + e_i \text{ with } \quad e_i = v_i - u_i \tag{1}$$

where *Prod* is potato production measured in kg per ha, X_i is the production factor or inputs in potato farming activities. e is error term included the random noise with (v_i) with $v_i^{\sim}$ $N(0.\partial_v^2)$ and half normal non-negative technical inefficiency term (u_i) with $u_i^{\sim}$ $N^+(0, \partial_u^2)$.

After executing Eq. (1) using SPF, the technical efficiency score is predicted to create the technical efficiency variable to be included in estimating the impact of climate change adaptation on the technical efficiency level. According to Zheng et al. (2021), the technical efficiency score can be calculated by Eq. (2)

$$EFF_i = \frac{Prod_i}{Prod_i^*} = e^{-u_i} \tag{2}$$

where EFF_i^j is the technical efficiency score of the potato farmers *i*, C_i refers to farmers' adaptation strategies, *Prod* is potato production measured in kg per ha, and $Prod_i^*$ describes the most efficient potato production, considering that all available inputs (X_i) have been utilized to their maximum potential. e^{-u_i} is the exponential expression with a negative inefficiency term ($-u_i$). Equation (3) suggests that farmers utilizing adaptation techniques to enhance potato production ($Prod_i$) with existing inputs (X_i) might achieve greater total efficiency (*EFF*) in potato production compared to those who do not.

2.3. Estimation strategy

In estimating the effect of the diversification of climate change adaptation strategies on farming technical efficiency, we assumed that the potato farmers' technical efficiency is the faction of the diversification level and farmers' technical efficiency. Therefore, the technical efficiency model can be written in Eq. (3).

$$EFF_i = \partial_i C_i + \beta_i M_i + u_i \tag{3}$$

where EFF_i and C_i are variables that have been explained earlier, M_i represents farmers characteristics, such as age, education, family size, and asset ownership. ∂_i and β_i are the parameters to be calculated, and u_i is the error term for Eq. (3). Equation (3) can be executed using a simple Tobit regression since the dependent variable EFF_i is censored, ranging from 0 to 1. However, the variable the adaptation diversification variable (C_i) is potentially endogenous as farmers' decisions to apply the adaptation strategy are influenced by the observable factors M_i and the unobservable factors, such as motivation (Rahman et al., 2022; Rahman, Huang et al., 2023a). Therefore, using a simple Tobit model in executing Eq. (3) could produce a biased estimation.

Several approaches have been proposed to address the endogeneity issue in estimating the effect, such as the endogenous switching regression (ESR) (Ma & Abdulai, 2016; Toiba et al., 2020), two-stage predictor substitution approach (2SPSA) (Rahman et al., 2022), and two-stage residual inclusion approach (2SRIA) (Rahman et al., 2022; Rahman, Toiba, et al., 2023b). Among them, the ESR model required a dummy treatment variable (Ma & Abdulai, 2016), and 2SPS and 2SRIA are more flexible for the treatment variable. The treatment variable of this study is climate change adaptation with an ordinal measurement from 0-6, measured by the number of adaptation strategies (Mabe & Asase, 2020). Therefore, 2SPS and 2SRIA are appropriate. However, 2SRIA provides more consistent results compared to 2SPS (Zhu et al., 2022), so this study used the 2SRIA approach in the estimation.

Following Zhu et al. (2022), and Rahman et al. (2022), the 2SRIA approach consists of two steps. In the first stage, we model climate change, assuming that climate change adaptation is influenced by farmers' characteristics, such as education, age, family size, and asset ownership. Yet, to address the endogeneity issue, at least one instrumental variable must be included. Following Rahman, Toiba, et al. (2023b), we use climate information and agricultural mechanization as instruments. Therefore, the first stage of the 2SRIA can be written as follows:

$$C_i^* = \delta_i M_i + \rho_i iv_i + \varepsilon_i \ \ with \ \ C_i = \{0 - 6 \tag{4}$$

where C_i^* is the diversification of climate change adaptation strategies measured by ordinal value, M_i is the farmers' characteristics as defined earlier, and iv_i is the instrumental variable. δ_i, ρ_i, are parameters to be estimated. Finally, ε_i is the error term for Eq. (4). Since the dependent variable is treated as a count, Eq. (4) can be executed using Poisson regression. After executing the ordered Poisson model, the residual from Eq. (4) is included for further estimation.

At the second stage of 2SRIA, Eq. (3) is rewritten by including the residual variable that has been predicted from Eq. (4). Therefore, it can be formulated as follows:

$$EFF_i = \tau_i C_i + \alpha_i M_i + \varphi_i RL_i + \epsilon_i \tag{5}$$

where EFF_i, C_i and *are* variables that have been mentioned earlier, RL_i is the residual that predicted from Eq. (4), τ_i, α_i, and φ_i are parameters to be estimated, and ϵ_i is a random error term for Eq. (5).

3. Results and discussion

3.1. Descriptive statistics

Table 1 presents the descriptive statistics of the variables examined in this study. First, the input-output variables utilized in the SPF model are introduced. The data reveals that, on average, potato production in our sample amounts to approximately 31,994.980 kg per hectare in a single season. The average inputs include 2092.18 kg of seeds per hectare, 2257.12 kg of chemical fertilizer per hectare (including NPK, urea, and potash), 2910.65 kg of organic fertilizer per hectare, 1.20 liters of pesticides per hectare, and 126.95 labor hours per hectare. Second, employing the SPF approach, our sample demonstrates an average technical efficiency score of about 0.791.

Third, the variable under consideration in this study is climate change adaptation practices. The data indicates that the most widely adopted adaptation strategy among farmers is the utilization of drought-tolerant varieties (65.9% of respondents). Following closely are changes in planting dates (64.5% of respondents), adjustments in input usage (63.1% of respondents), improvements in irrigation (44.7% of respondents), The improvement of the irrigation system implemented by farmers includes building wells on their land, intercropping (43.3% of respondents), intercropping practiced by farmers involves planting potatoes alongside green onions. The least adopted strategy is land conservation through minimum tillage (34.6% of respondents). The diversification in the adaptation was measured by the number of

Table 1. Descriptive statistics.

Variables	Measurement	Mean	Std. Dev
Input-output variables			
Production	Potato production kg pe ha	31994.980	36310.600
Seed	Seed kg per ha	2092.184	1806.989
Chemical fertilizer	Chemical fertilizer kg per ha	2257.120	4242.615
Organic fertilizer	Organic Fertilizer kg per ha	2910.654	3279.159
Pesticide	Pesticide litter per ha	1.195	1.018
Labor	Labor days per ha	126.945	230.127
Outcome variable			
Technical	Technical efficiency score	0.791	0.053
Treatment variables			
Planting date	Dummy, 1 if the farmer adjusts the planting timing; 0 otherwise	0.645	0.480
Drought tolerance variety	Dummy, 1 if the farmer adopts drought tolerance variety; 0 otherwise	0.659	0.475
Intercropping	Dummy, 1 if the farmer applies intercropping, 0 otherwise	0.433	0.497
Adjusting input usage	Dummy, 1 if the farmer adjusts input usage	0.631	0.484
land conservation	Dummy, 1 the farmer conserve land	0.346	0.477
Irrigation	Dummy, 1 the farmer improves the irrigation system	0.447	0.498
Adaptation diversification	Number of adaptation strategies applied by the farmer (0–6)	3.161	1.638
Control variables			
Age	Age of farmer in year	46.000	11.396
Education	Education of the farmer in year	8.235	2.998
Family members	Number of family members	3.590	0.997
Extension activity	Dummy, 1 if the farmer participated in extension activity	0.295	0.496
Experience	Farming experience in year	21.770	11.706
Off-farm	Dummy, 1 if the farmer has an off-farm job	0.488	0.501
Transport	Dummy, 1 the farmer has a private vehicle for agricultural activities	0.180	0.385
Mechanization	Dummy 1, if the farmer has agricultural mechanization	0.350	0.478
Climate Information	Dummy, 1 if the farmer has access to climate information	0.862	0.346
Obs.		217	

strategies employed by farmers. The average value was 3.161, indicating that farmers typically employed 3 to 4 adaptation strategies for climate change.

Fourth, the control variables are farmers' characteristics. The results show that the average age was 46 years, and the average education level was 8.235 years, which equals the elementary school level. The average number of family members per household was three to four, with an average of one dependent member. The average experience in farming was approximately 21.77 years, with 29.5% of farmers participating in extension activities and 44.80% having off-farm jobs. In terms of transportation, 18% of farmers owned private vehicles used in farming activities. Also, 35% of farmers owned agricultural mechanization, such as tractors and irrigation machinery. Finally, 86.2% of farmers had access to climate information.

3.2. The determinant of potato production: the SPF approach

Table 2 presents the results of the Cobb-Douglas stochastic production frontier model, with a single output and five inputs represented in natural logarithms. This estimation strategy was employed to predict the technical efficiency level of farmers using Eq. (1). The predictions will be used to further estimate the impact of adaptation on technical efficiency and highlight the factors that influence farmers' production. In general, the finding shows that potato production was positively and significantly influenced by three production factors: seeds, organic fertilizers, and labor.

The seed variable significantly enhances potato output, emphasizing its crucial role in agricultural productivity and yield improvement, aligned with previous studies by Andaregie and Astatkie (2020) and Wassihun et al. (2019) which highlighted that seed significantly improves farming production. Interestingly, chemical fertilizers negatively and significantly impact potato production, suggesting that excessive use of chemical fertilizers significantly reduces potato output. In contrast, organic fertilizers significantly improve potato production. Organic fertilizers provide a range of nutrients and contribute to soil health by improving soil structure, enhancing microbial activity, and maintaining a balanced nutrient supply. This promotes better plant growth and, ultimately, higher potato production. As for labor, its enhancement significantly improves potato production. Potato production is a labor-intensive profession, and increasing the workforce allows farmers to adopt technologies that enhance the yield of potato as recommended by agricultural practices. This, in turn, boosts the efficiency of agricultural input investments, leading to an increase in farmers' production. This aligns with a previous study highlighting the positive effect of labor on potato output (Mengui et al., 2019).

3.3. The determinant of the climate change adaptation diversification: the first stage of 2SRIA

The first stage of the 2SRIA approach estimates the determinant of farmers' adaptation diversification. This section presents the results of the first-stage model of 2SRIA, aiming to predict the residuals of the

Table 2. Stochastic frontier estimation.

Production	Coef. (Std. Err)
Seed	0.249 (0.041)***
Chemical fertilizer	−0.073 (0.037)**
Organic fertilizer	0.147 (0.024)***
Pesticide	0.023 (0.039)
Labor	0.263 (0.036)***
_cons	6.786 (0.502)***
/lnsig2v	−1.510 (0.343)***
/lnsig2u	−2.303 (2.032)
sigma_v	0.470 (0.081)
sigma_u	0.316 (0.321)
sigma2	0.321 (0.134)
Lambda	0.673 (0.398)
Log likelihood	−160.532
Wald chi2	185.990
Prob > chi2	0.000
Number of obs	217.000

Note. ***=sig 1%; **=sig 5%; *=sig 10%.

Table 3. Estimation results from two stage residual inclusion.

Variables	Adaptation diversification (poisson regression) Coef. (Std. Err.)	Technical efficiency (tobit regression) Coef. (Std. Err.)
Adaptation diversification		0.015 (0.002)***
Age	−0.011 (0.005)**	−0.001 (0.001)*
Education	0.051 (0.016)***	0.003 (0.002)
Family members	0.069 (0.056)	−0.010 (0.005)*
Dependence ratio	−0.029 (0.061)	0.008 (0.005)
Extension activity	0.014 (0.091)	0.009 (0.008)
Experience	0.007 (0.005)	0.001 (0.000)
Off-farm	−0.179 (0.090)**	0.015 (0.009)*
Transport	−0.113 (0.105)	−0.004 (0.009)
Mechanization	0.326 (0.092)***	−0.002 (0.012)
Climate Information	0.446 (0.147)***	
Residual		−0.022 (0.011)**
Constant	0.414 (0.316)	0.797 (0.024)***
Log likelihood	−380.656	361.919
LR chi2	75.620	60.610
Prob > chi^2	0.000	0.000
Pseudo R^2	0.090	0.091
Number of obs.	217	217

Note. ***=sig 1%; **=sig 5%; *=sig 10%.

adaptation model using Eq. (4). The predictions were subsequently incorporated into the second stage of 2SRIA. The results are presented in Table 3, specifically in the second column. The ordered probit regression shows that the diversification of adaptation strategies is positively and significantly affected by education, mechanization, and climate information and is negatively affected by age and off-farm work.

The age variable demonstrates a negative and significant coefficient, indicating that older farmers diversify less, possibly due to their beliefs in traditional practices and resistance to change. A previous study by Maguza-Tembo et al. (2017) also shows that low adoption of new technology adoption among older farmers is due to limited exposure or entrenched mindsets. Conversely, education exhibits a positive and statistically significant coefficient at 1%, suggesting a direct relationship between higher education levels and diversified adaptation strategies. Education plays a vital role in farmers' adoption of innovations, such as adaptive practices (Rahman et al., 2021)—the higher the education, the more likely to adapt. the number of family members significantly enhances strategy diversification—the more members the more likely farmers diversify. This positive correlation between family size and adaptation strategies aligns with a study by Ali and Erenstein (2017) in Pakistan, which highlighted that family size significantly improves climate change adaptation strategies.

Farming experience also positively impacts strategy diversification—the more experience, the more strategies are adopted. This relationship between expertise and adaptive strategies aligns with a study by Ojo and Baiyegunhi (2020) in Nigeria, which found a positive relationship between farming experience and climate change adaptation strategies. By contrast, off-farm employment has a negative impact on strategy diversification in agricultural communities. Farmers engaged in off-farm work diversify their adaptive strategies less, indicating challenges in coping with the impact of climate change, in line with a previous study by Mulwa and Visser (2020). Meanwhile, agricultural mechanization significantly enhances strategy diversification. Farmers with machinery like tractors and irrigation tools implement more adaptive strategies effectively, allowing them to overcome climate challenges in their farming practices. Likewise, the availability of climate information significantly improves strategy diversification. Early warnings enable farmers to prepare effectively and adapt to climate change challenges. This finding aligns with Rahman et al. (2022) in Indonesia, highlighting the importance of timely climate information in enhancing strategy diversification.

3.4. The impact of strategy diversification on farming technical efficiency

The second stage of the 2SRIA approach is presented in Table 3, specifically column three. The appropriateness of the 2SRIA approach can be seen in the residual variables. The results show that the residual variable is statistically significant, suggesting an endogeneity issue. In this case, the 2SRIA approach is appropriate to estimate the impact of climate change adaptation on potato farming technical efficiency (Wooldridge, 2015). Returning to the research question, the findings show that climate change adaptation has a positive and statistically significant effect on improving the technical efficiency of potato farming. Diversified climate change adaptation strategies increase technical efficiency significantly. The positive and significant impact of climate change adaptation on potato farming's technical efficiency can be attributed to various factors. First, adaptation strategies, such as adjusting planting timing, cultivating drought-tolerant varieties, intercropping, changing input usage, land conservation through minimum tillage, and improving irrigation systems, enhance the resilience of potato farming systems against adverse weather conditions. This resilience ensures stable potato farming activities amid climatic challenges. Second, awareness and implementation of climate change adaptation strategies lead to optimized resource utilization, waste reduction, and higher productivity. Additionally, adaptation measures frequently involve the use of innovative technologies and knowledge, which also boosts efficiency in potato farming. This finding aligns with previous studies by Ho and Shimada (2019) and Khanal et al. (2018), which highlighted that adaptation strategies significantly improve technical efficiency. However, previous studies used a dummy variable to indicate whether the farmer was applying adaptation strategies or not. This study improves the measurement of adaptation by using a count value, representing the total number of adaptation practices applied by the farmers. Likewise, a previous study also shows that climate change adaptation improves economic outcomes, such as income (Rahman et al., 2021), food security (Di Falco et al., 2011), and well-being (Rahman, Huang et al., 2023a).

The next objective of this research is to investigate the impact of each adaptation strategy (i.e., adjusting planting timing, cultivating drought-tolerant varieties, intercropping, changing input usage, conserving land, and improving irrigation systems) on potato farming technical efficiency. The results are presented in Table 4. In general, the results show that four strategies have a positive and significant coefficient: adjusting planting timing, cultivating drought-tolerant varieties, conserving land, and improving irrigation systems. However, intercropping and adjusting input usage shows the opposite. The statistical results of this study confirm that the most significant adaptation strategy that improves farming technical efficiency is the adoption of drought-tolerant varieties, followed by improving irrigation systems (building wells on their cultivated land), changing planting timing, and conserving land through minimum tillage. However, intercropping potato with green onions and modifying input usage negatively and significantly impact technical efficiency.

The enhancement of potato farming technical efficiency hinges on strategic adaptation practices. Adopting drought-tolerant potato varieties turns out to be the most impactful. These varieties are specifically engineered to withstand water scarcity, a common challenge exacerbated by climate change. Farmers can maintain their yields even during drought seasons by cultivating these resilient varieties, ensuring consistent potato harvests regardless of the challenges posed by extreme weather conditions. The next most significant is the improvement of irrigation systems (building wells on their cultivated land). Efficient water management is paramount in agriculture, particularly in regions susceptible to water scarcity. Modernizing irrigation techniques, precision watering, can minimize input wastage in the watering of potato crops. Aside from sustaining plant growth, proper irrigation systems also conserve water resources, making farming processes more sustainable (Chartzoulakis & Bertaki, 2015). Next, changing planting timing also proves instrumental in adapting to climate change. This adaptation strategy

Table 4. The impact of each adaptation strategy on farmers' technical efficiency.

TE	Coef. (Std. Err.)
Planting timing	0.025 (0.008)***
Drought-tolerant variety	0.026 (0.008)***
Intercropping	−0.040 (0.008)***
Adjusting input usage	−0.016 (0.007)**
Land conservation	0.018 (0.007)***
Irrigation	0.025 (0.007)***
Control	Yes
Log likelihood	393.95826
LR chi^2	124.690
Prob $> chi^2$	0.000
Pseudo R^2	0.188

Note. ***=sig 1%; **=sig 5%; *=sig 10%.

Table 5. Disaggregate analysis.

TE	Household income Tertile 1 Coef. (Std. Err.)	Household income Tertile 2 Coef. (Std. Err.)	Household income Tertile 3 Coef. (Std. Err.)
Planting timing	0.037 (0.014)***	0.018 (0.017)	0.020 (0.012)
Drought-tolerant variety	0.030 (0.015)*	0.042 (0.015)***	0.009 (0.009)
Intercropping	−0.046 (0.015)***	−0.022 (0.013)	−0.042 (0.011)***
Adjusting input usage	−0.018 (0.011)	−0.002 (0.014)	−0.005 (0.010)
Land conservation	0.004 (0.011)	0.024 (0.012)*	0.029 (0.009)***
Irrigation	0.038 (0.014)**	0.023 (0.011)**	0.018 (0.011)*
Control	Yes	Yes	Yes
Log likelihood	140.250	131.252	145.999
LR $chi^2(16)$	60.110	44.400	49.880
Prob > chi^2	0.000	0.000	0.000
Pseudo R^2	0.273	0.204	0.206

Note. ***=sig 1%; **=sig 5%; *=sig 10%.

capitalizes on favorable temperature and moisture levels to optimize potato growth and yield. By adjusting planting timing, farmers can align their cultivation with optimal weather conditions, maximizing the chances of successful harvests. Lastly, land conservation through minimum tillage also plays a vital role. Erosion and degradation are often exacerbated by climate-related factors, which can significantly impact agricultural productivity. Therefore, conserving land will improve technical efficiency.

However, not all adaptation practices yield positive results. Intercropping, while beneficial in some contexts, can negatively affect potato farming technical efficiency. Competition for resources between different crops can reduce yields and overall efficiency. Similarly, modifying input usage without a careful balance can adversely impact both productivity and sustainability.

Furthermore, Table 3 also presents the determinant of technical efficiency, specifically in the third column. The results indicated that off-farm work positively and significantly affects the technical efficiency of potato farmers, whereas age and the number of family members show different outcomes. Age has a negative and significant coefficient, revealing that older farmers are less technically efficient than younger farmers. Older farmers often rely on traditional knowledge or information passed on by relatives regarding the usage of farming inputs. In contrast, younger farmers are more open to new ideas and willing to experiment with innovative approaches. They are also better educated and more aware of the latest developments in agriculture (Šūmane et al., 2018). The number of family members negatively influences farmers' technical efficiency—the more family members, the lower the technical efficiency. Finally, off-farm work shows a positive and significant effect on farming technical efficiency—the more engaged a farmer is in off-farm employment, the higher the technical efficiency. This is because off-farm employment can provide a stable source of income, reducing financial stress on farming households. This financial stability enables farmers to invest in better farming practices, high-quality inputs, and technology, ultimately improving their technical efficiency. This finding is in line with a previous study by Ma et al. (2023), which highlights the positive association between off-farm work and farming technical efficiency.

3.5. Disaggregate analysis

Farmers may face a barrier related to financial resources when adopting climate change adaptation strategies (Antwi-Agyei et al., 2015; Shackleton et al., 2015). This financial constraint can affect their ability to adapt. Therefore, this study examines the impact of specific adaptation strategies on the technical efficiency of potato farming based on farmers' household incomes. The results are presented in Table 5. For households with the lowest income (Tertile 1), adjusting planting timing and improving irrigation systems significantly enhance their farming practices. In households with middle income (Tertile 2), technical efficiency significantly increases along with the cultivation of drought-tolerant varieties and improvements in irrigation systems. Lastly, households with the highest income (Tertile 3) benefit significantly from enhancing their irrigation systems. Notably, improving irrigation systems proves significant across all income levels since a consistent water supply to crops reduces the risk of crop failure triggered by water scarcity.

4. Conclusion and policy implication

This study explores the link between climate change adaptation diversification and the technical efficiency of potato farmers. Data were collected from 217 potato farmers in East Java, Indonesia, and a two-stage residual inclusion approach (2SRIA) was employed to address endogeneity issues in the analysis. The study identified six adaptation strategies implemented by potato farmers in Indonesia: adjusting planting dates, cultivating drought-tolerant varieties, intercropping, changing input usage, conserving land, and improving irrigation systems. The empirical results show that greater diversifying adaptation strategies can significantly improve the technical efficiency of potato farmers. Specifically, when farmers employ more adaptation strategies, their technical efficiency increases. Regarding which adaptation strategies work best, this study found that adjusting planting timing, adopting drought-tolerant varieties, conserving land, and improving irrigation systems significantly enhance technical efficiency. However, intercropping and altering input usage negatively and significantly impact technical efficiency. Meanwhile, disaggregated estimations based on farmers' household income levels reveal that adjusting planting dates and improving irrigation systems significantly enhance technical efficiency for farmers with the lowest income. Those with middle-income levels benefit from adopting drought-tolerant varieties and improving irrigation systems. Finally, households with the highest income primarily benefit from improving irrigation systems.

The findings of this study suggest that policymakers in the agricultural sector focus on promoting and supporting climate change adaptation diversification among potato farmers in East Java, Indonesia. Specifically, initiatives should be implemented to encourage the adoption of effective adaptation strategies, such as adjusting planting dates, cultivating drought-tolerant varieties, and conserving land. Additionally, efforts should be made to enhance the technical efficiency of potato farmers by improving irrigation systems. Policymakers should consider providing targeted support based on farmers' income levels and tailoring interventions to address the specific needs of different groups.

One limitation of this study is the utilization of cross-sectional data, which provides a snapshot of the relationship between climate change adaptation diversification and the technical efficiency of potato farmers at a specific point in time. Cross-sectional data may not capture the dynamics of agricultural practices and the evolving impact of adaptation strategies over time. To address this limitation and provide a more comprehensive understanding, future research could consider employing longitudinal data to examine changes and trends in adaptation strategies and technical efficiency over an extended period.

Authors' contributions

Nuhfil Hanani AR: developing ideas of research, coordinating research activities, analysis, writing; Moh Shadiqur Rahman: developing ideas of research, coordinating research activities, analysis, writing; Fahriyah Fahriyah: developing ideas, supervising data collection, analysis, writing; Dodyk Pranowo: developing ideas, supervising data collection, analysis, writing; Hery Toba: developing ideas, supervising data collection, analysis, writing; Rosihan Asmara: developing ideas, supervising data collection, analysis, writing; Sujarwo Sujarwo: developing ideas, supervising data collection, analysis, writing; Mohammad Ilyas Shaleh: collecting data, analysis, writing, editing and translating. Mohammad Wahyu Firdaus: collecting data, writing, reviewing, editing and translating. Mahfudlotul Ula: collecting data, analysis, editing and translating. Dwi Retnoningsih: collecting data, analysis, writing, editing and translating.

Disclosure statement

The authors declare no conflict of interest.

Informed consent statement

Written informed consent was obtained prior to administering the questionnaire.

Ethical approval statement

The ethical concern of this study was approved by Faculty of Agriculture, Brawijaya University, No. 3784/UN10.F04.01/TU/2023.

Funding

Brawijaya University supports research funding for all of these research activities with grant numbers 612.63/UN10.C20/2023.

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Data availability statement

The data presented in this study are available on request from Moh Shadiqur Rahman. The data are not publicly available due to ethical reasons.

References

Abid, M., Schilling, J., Scheffran, J., & Zulfiqar, F. (2016). Climate change vulnerability, adaptation and risk perceptions at farm level in Punjab, Pakistan. *The Science of the Total Environment*, *547*, 447–460. 10.1016/j.scitotenv.2015.11.12526836405

Ahmed, N., Padda, I. U. H., Khan, A., Otil, M. D., Cismas, L. M., Miculescu, A., & Rehman, A. (2023). Climate change adaption strategies in urban communities: New evidence from Islamabad, Pakistan. *Environmental Science and Pollution Research International*, *30*(14), 42108–42121. https://doi.org/10.1007/s11356-023-25316-x

Akpa, A. F., Amegnaglo, C. J., & Chabossou, A. F. (2024). Climate change adaptation strategies and technical efficiency of maize producers in Benin, West Africa. *International Journal of Productivity and Performance Management*, *73*(4), 1071–1087. https://doi.org/10.1108/IJPPM-06-2022-0284

Ali, A., & Erenstein, O. (2017). Assessing farmer use of climate change adaptation practices and impacts on food security and poverty in Pakistan. *Climate Risk Management*, *16*, 183–194. https://doi.org/10.1016/j.crm.2016.12.001

Amankwah, A., & Gwatidzo, T. (2024). Food security and poverty reduction effects of agricultural technologies adoption – a multinomial endogenous switching regression application in rural Zimbabwe. *Food Policy*, *125*, 102629. https://doi.org/10.1016/j.foodpol.2024.102629

Amare, A., & Simane, B. (2017). Determinants of smallholder farmers' decision to adopt adaptation options to climate change and variability in the Muger Sub basin of the Upper Blue Nile basin of Ethiopia. *Agriculture & Food Security*, *6*(1), 1–20. https://doi.org/10.1186/s40066-017-0144-2

Andaregie, A., & Astatkie, T. (2020). Determinants of technical efficiency of potato farmers and effects of constraints on potato production in Northern Ethiopia. *Experimental Agriculture*, *56*(5), 699–709. https://doi.org/10.1017/S0014479720000253

Ankrah Twumasi, M., & Jiang, Y. (2021). The impact of climate change coping and adaptation strategies on livestock farmers' technical efficiency: the case of rural Ghana. *Environmental Science and Pollution Research International*, *28*(12), 14386–14400. https://doi.org/10.1007/s11356-020-11525-1

Antwi-Agyei, P., Dougill, A. J., & Stringer, L. C. (2015). Barriers to climate change adaptation: Evidence from northeast Ghana in the context of a systematic literature review. *Climate and Development*, *7*(4), 297–309. https://doi.org/10.1080/17565529.2014.951013

Bandara, J. S., & Cai, Y. (2014). The impact of climate change on food crop productivity, food prices and food security in South Asia. *Economic Analysis and Policy*, *44*(4), 451–465. 10.1016/j.eap.2014.09.005

Battese, G. E., & Coelli, T. J. (1988). Prediction of firm-level technical efficiencies with a generalized frontier production function and panel data. *Journal of Econometrics*, *38*(3), 387–399. https://doi.org/10.1016/0304-4076(88)90053-X

Bibi, S., Ali, N., Nazneen, S., Rehman, S., Yousaf, R., & Khan, S. (2021). Climate change impacts on the cropping pattern in the foothills of the Himalayas, Pakistan. Arabian Journal of Geosciences, 14(24), 2732. https://doi.org/10.1007/s12517-021-08999-9

Bozzola, M., & Smale, M. (2020). The welfare effects of crop biodiversity as an adaptation to climate shocks in Kenya. *World Development*, *135*, 105065. https://doi.org/10.1016/j.worlddev.2020.105065

Chartzoulakis, K., & Bertaki, M. (2015). Sustainable water management in agriculture under climate change. *Agriculture and Agricultural Science Procedia*, *4*, 88–98. https://doi.org/10.1016/j.aaspro.2015.03.011

Chen, J., Shi, X., Gu, L., Wu, G., Su, T., Wang, H.-M., Kim, J.-S., Zhang, L., & Xiong, L. (2023). Impacts of climate warming on global floods and their implication to current flood defense standards. *Journal of Hydrology*, *618*, 129236. https://doi.org/10.1016/j.jhydrol.2023.129236

Di Falco, S., Veronesi, M., & Yesuf, M. (2011). Does adaptation to climate change provide food security? A micro-perspective from Ethiopia. *American Journal of Agricultural Economics*, *93*(3), 829–846. https://doi.org/10.1093/ajae/aar006

Finger, R., Hediger, W., & Schmid, S. (2011). Irrigation as adaptation strategy to climate change—a biophysical and economic appraisal for Swiss maize production. *Climatic Change*, *105*, 509–528. 310.1007/s10584-010-9931-5

Hakim, R., Haryanto, T., & Sari, D. W. (2021). Technical efficiency among agricultural households and determinants of food security in East Java, Indonesia. *Scientific Reports*, *11*(1), 4141. https://doi.org/10.1038/s41598-021-83670-7

Ho, T. T., & Shimada, K. (2019). The effects of climate smart agriculture and climate change adaptation on the technical efficiency of rice farming—an empirical study in the Mekong Delta of Vietnam. *Agriculture*, *9*(5), 99. https://doi.org/10.3390/agriculture9050099

Houghton, J. T., Ding, Y., Griggs, D. J., Noguer, M., van der Linden, P. J., Dai, X., Maskell, K., & Johnson, C. A. (2001). *Climate change 2001: The scientific basis* (Vol. 881). Cambridge University Press.

Khanal, U., Wilson, C., Lee, B., & Hoang, V.-N. (2018). Do climate change adaptation practices improve technical efficiency of smallholder farmers? Evidence from Nepal. *Climatic Change*, *147*(3–4), 507–521. https://doi.org/10.1007/s10584-018-2168-4

Lebel, L., Manuta, J. B., & Garden, P. (2011). Institutional traps and vulnerability to changes in climate and flood regimes in Thailand. *Regional Environmental Change*, *11*, 45–58. 10.1007/s10113-010-0118-4

Li, Y., Hua, Y., Liao, B., Yuan, X., & Zhou, Z. (2022). Adoption intensity of a standardized technical system: The higher the better?—Evidence from China. *Frontiers in Environmental Science*, *10*, 937287. https://doi.org/10.3389/fenvs.2022.937287

Ma, W., & Abdulai, A. (2016). Does cooperative membership improve household welfare? Evidence from apple farmers in China. *Food Policy*, *58*, 94–102. https://doi.org/10.1016/j.foodpol.2015.12.002

Mabe, F. N., & Asase, A. (2020). Climate change adaptation strategies and fish catchability: The case of inland artisanal fishers along the Volta Basin in Ghana. *Fisheries Research*, *230*, 105675. https://doi.org/10.1016/j.fishres.2020.105675

Ma, W., Grafton, R. Q., & Renwick, A. (2020). Smartphone use and income growth in rural China: Empirical results and policy implications. *Electronic Commerce Research*, *20*(4), 713–736. https://doi.org/10.1007/s10660-018-9323-x

Maguza-Tembo, F., Mangison, J., Edris, A. K., & Kenamu, E. (2017). Determinants of adoption of multiple climate change adaptation strategies in Southern Malawi: An ordered probit analysis. *Journal of Development and Agricultural Economics*, *9*(1), 1–7.

Ma, W., Renwick, A., Yuan, P., & Ratna, N. (2018). Agricultural cooperative membership and technical efficiency of apple farmers in China: An analysis accounting for selectivity bias. *Food Policy*, *81*, 122–132. https://doi.org/10.1016/j.foodpol.2018.10.009

Marks, D. (2011). Climate change and Thailand: Impact and response. *Contemporary Southeast Asia*, *33*(2), 229–258. https://doi.org/10.1355/cs33-2d

Mendelsohn, R., Morrison, W., Schlesinger, M. E., & Andronova, N. G. (2000). Country-specific market impacts of climate change. *Climatic Change*, *45*(3), 553–569. 10.1023/A:1005598717174

Ma, W., & Zheng, H. (2022). Heterogeneous impacts of information technology adoption on pesticide and fertiliser expenditures: Evidence from wheat farmers in China. *Australian Journal of Agricultural and Resource Economics*, *66*(1), 72–92. https://doi.org/10.1111/1467-8489.12446

Ma, W., Zheng, H., Donkor, E., & Owusu, V. (2023). Off-farm work and technical efficiency of wheat production: An analysis accounting for multiple dimensions of off-farm work. *International Journal of Sustainable Development & World Ecology*, *30*(3), 278–294. https://doi.org/10.1080/13504509.2022.2142316

Mengui, K. C., Oh, S., & Lee, S. H. (2019). The technical efficiency of smallholder Irish potato producers in Santa subdivision, Cameroon. *Agriculture*, *9*(12), 259. https://doi.org/10.3390/agriculture9120259

Mulwa, C. K., & Visser, M. (2020). Farm diversification as an adaptation strategy to climatic shocks and implications for food security in northern Namibia. *World Development*, *129*, 104906. https://doi.org/10.1016/j.worlddev.2020.104906

Nguyen, L. A., Pham, T. B., Bosma, R., Verreth, J., Leemans, R., De Silva, S., & Lansink, A. O. (2018). Impact of climate change on the technical efficiency of striped catfish, Pangasianodon hypophthalmus, farming in the Mekong Delta, Vietnam. *Journal of the World Aquaculture Society*, *49*(3), 570–581. https://doi.org/10.1111/jwas.12488

Ojo, T., & Baiyegunhi, L. (2020). Determinants of credit constraints and its impact on the adoption of climate change adaptation strategies among rice farmers in South-West Nigeria. *Journal of Economic Structures*, *9*(1), 1–15. https://doi.org/10.1186/s40008-020-00204-6

Purwanti, T. S., Syafrial, S., Huang, W.-C., & Saeri, M. (2022). What drives climate change adaptation practices in smallholder farmers? Evidence from potato farmers in Indonesia. *Atmosphere*, *13*(1), 113. https://doi.org/10.3390/atmos13010113

Rahman, M. S., Toiba, H., & Huang, W.-C. (2021). The impact of climate change adaptation strategies on income and food security: Empirical evidence from small-scale fishers in Indonesia. *Sustainability*, *13*(14), 7905. https://doi.org/10.3390/su13147905

Rahman, M. S., Huang, W.-C., Toiba, H., & Efani, A. (2022). Does adaptation to climate change promote household food security? Insights from Indonesian fishermen. *International Journal of Sustainable Development & World Ecology*, *29*(7), 611–624. https://doi.org/10.1080/13504509.2022.2063433

Rahman, M. S., Huang, W.-C., Toiba, H., Putritamara, J. A., Nugroho, T. W., & Saeri, M. (2023a). Climate change adaptation and fishers' subjective well-being in Indonesia: Is there a link? *Regional Studies in Marine Science*, *63*, 103030. https://doi.org/10.1016/j.rsma.2023.103030

Rahman, M. S., Toiba, H., Nugroho, T. W., Hartono, R., Shaleh, M. I., Sugiono, S., & Saeri, M. (2023b). Does internet use make farmers happier? Evidence from Indonesia. *Cogent Social Sciences*, *9*(2), 2243716. https://doi.org/10.1080/23311886.2023.2243716

Sekaranom, A. B., Nurjani, E., & Nucifera, F. (2021). Agricultural climate change adaptation in Kebumen, central Java, Indonesia. *Sustainability*, *13*(13), 7069. https://doi.org/10.3390/su13137069

Shackleton, S., Ziervogel, G., Sallu, S., Gill, T., & Tschakert, P. (2015). Why is socially-just climate change adaptation in sub-Saharan Africa so challenging? A review of barriers identified from empirical cases. *WIREs Climate Change*, *6*(3), 321–344. https://doi.org/10.1002/wcc.335

Shaffril, H. A. M., Samah, A. A., & D'Silva, J. L. (2017). Adapting towards climate change impacts: Strategies for small-scale fishermen in Malaysia. *Marine Policy*, *81*, 196–201. https://doi.org/10.1016/j.marpol.2017.03.032

Smit, B., Burton, I., Klein, R. J., & Street, R. (1999). The science of adaptation: a framework for assessment. Mitigation and Adaptation Strategies for Global Change, 4, 199–213. https://doi.org/10.1023/A:1009652531101

Somboonsuke, B., Phitthayaphinant, P., Sdoodee, S., & Kongmanee, C. (2018). Farmers' perceptions of impacts of climate variability on agriculture and adaptation strategies in Songkhla Lake basin. *Kasetsart Journal of Social Sciences*, *39*(2), 277–283. https://doi.org/10.1016/j.kjss.2018.05.006

Šūmane, S., Kunda, I., Knickel, K., Strauss, A., Tisenkopfs, T., Des los Rios, I., Rivera, M., Chebach, T., & Ashkenazy, A. (2018). Local and farmers' knowledge matters! How integrating informal and formal knowledge enhances sustainable and resilient agriculture. *Journal of Rural Studies*, *59*, 232–241. https://doi.org/10.1016/j.jrurstud.2017.01.020

Syafrial Toiba, H., Rahman, M. S., & Retnoningsih, D. (2021). The effects of improved cassava variety adoption on farmers' technical efficiency in Indonesia. *Asian Journal of Agriculture and Rural Development*, *11*(4), 269–278. https://doi.org/10.18488/journal.ajard.2021.114.269.278

Toiba, H., Nugroho, T. W., Retnoningsih, D., & Rahman, M. S. (2020). Food system transformation and its impact on smallholder farmers' income and food security in Indonesia. *Cogent Economics & Finance*, *8*(1), 1854412. https://doi.org/10.1080/23322039.2020.1854412

Toiba, H., Rahman, M. S., Nugroho, T. W., Priyanto, M. W., Noor, A. Y. M., & Shaleh, M. I. (2024). Understanding the link between climate change adaptation and household food security among shrimp farmers in Indonesia. *Marine Policy*, *165*, 106206. https://doi.org/10.1016/j.marpol.2024.106206

Trinh, T.-A., Feeny, S., & Posso, A. (2021). The impact of natural disasters and climate change on agriculture: Findings from Vietnam. In *Economic effects of natural disasters* (pp. 261–280). Elsevier.

Wang, X., Jiang, D., & Lang, X. (2017). Future extreme climate changes linked to global warming intensity. *Science Bulletin*, *62*(24), 1673–1680. https://doi.org/10.1016/j.scib.2017.11.004

Wassihun, A. N., Koye, T. D., & Koye, A. D. (2019). Analysis of technical efficiency of potato (Solanum tuberosum L.) Production in Chilga District, Amhara national regional state, Ethiopia. *Journal of Economic Structures*, *8*(1), 1–18. https://doi.org/10.1186/s40008-019-0166-y

Wooldridge, J. M. (2015). Control function methods in applied econometrics. *Journal of Human Resources*, *50*(2), 420–445. https://doi.org/10.3368/jhr.50.2.420

Zheng, H., Ma, W., & Li, G. (2021). Adoption of organic soil amendments and its impact on farm performance: Evidence from wheat farmers in China. Australian Journal of Agricultural and Resource Economics, 65(2), 367–390. https://doi.org/10.1111/1467-8489.12406

Zhu, Z., Ma, W., & Leng, C. (2022). ICT adoption, individual income and psychological health of rural farmers in China. *Applied Research in Quality of Life*, *17*(1), 71–91. https://doi.org/10.1007/s11482-020-09879-2