



Economic Impact Analysis of Climate Change on Sugarcane Production: An ARDL Model Approach

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ABSTRACT: Global climate volatility has created structural uncertainties threatening the supply stability of strategic commodities. This study aims to estimate the dynamic supply response of sugarcane in East Java to agro-climatic shocks and conventional production inputs over the 1995–2023 period. Using the Autoregressive Distributed Lag (ARDL) approach, this study models the market adjustment mechanism toward long-run equilibrium. Estimation results reveal that the sugarcane sector faces serious supply rigidity due to hydrological factors. Rainfall anomalies are identified as persistent negative supply shocks, triggering technical inefficiency due to waterlogging risks. On the other hand, the land area variable shows positive but inelastic elasticity, confirming the law of diminishing marginal returns on an aggregate scale. The finding that temperature and population variables are insignificant revises old theoretical assumptions, confirming that the sugarcane production function in tropical regions is more sensitive to hydrological constraints than thermal ones. The economic implication is that self-sufficiency strategies can no longer rely on high opportunity cost land extensification, but require investment reallocation towards climate risk mitigation technologies to improve supply curve efficiency.

Keywords: Food Security; Sugar Industry; *Saccharum officinarum*; Agricultural Adaptation; Supply Elasticity.

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INTRODUCTION

Globally, the sugar market is currently facing significant pressure due to the imbalance between surging industrial demand and supply volatility triggered by the climate crisis. In Indonesia, this challenge manifests as a dual pressure, with demands for increased productivity on the one hand and acute vulnerability to environmental variability on the other. Sugarcane (*Saccharum officinarum* L.), a strategic commodity, is at the center of this tension. Data shows that the national sugar balance shows a worrying deficit. In 2022, domestic White Crystal Sugar (GKP) production was recorded at only 2.41 million tons, while imports surged to 6.00 million tons to meet market demand (Center for Agricultural Data and Information Systems, 2023). Although sugarcane plays a vital role as a livelihood for millions of farmers (Gajdic, 2023; Sulaiman et al., 2019), this extreme dependence on imports not only burdens the trade balance but also threatens sustainable national food sovereignty (Safitri et al., 2024).

Geographically, national sugarcane production is concentrated in eight main provinces, with East Java contributing the largest (Diarty et al., 2023). However, historical data demonstrates significant vulnerability. According to data from the East Java Central Statistics Agency (BPS) (2013-2023), sugarcane production experienced sharp fluctuations, reaching 1.2 million tons in 2015, dropping to a low of 1.01 million tons in 2017, before rebounding until 2023. This supply instability has direct implications for declining farmer incomes, increasing the risk of rural poverty, and escalating the national sugar deficit (Purnomo & Savikri, 2021).

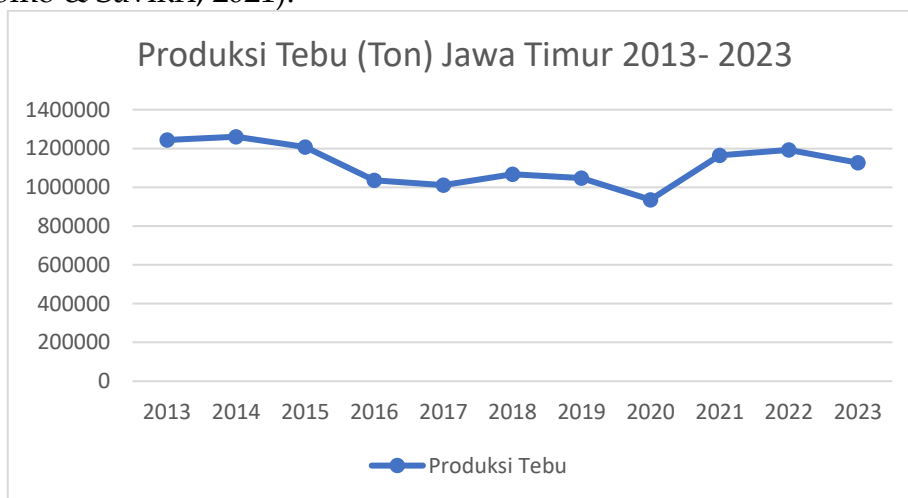


Figure 1. Sugarcane Production in East Java 2013-2023
Source: BPS, 2023

Previous literature has revealed that this production volatility is strongly influenced by biophysical determinants, but the mechanisms are complex. Physiologically, sugarcane productivity is highly dependent on agroclimatic variables. Air temperature plays a dual role in the plant life cycle, as explained by Nur (2023) and Heureux et al. (2022), where warm temperatures are necessary to stimulate photosynthesis and metabolism in the early vegetative phase. However, the literature emphasizes a critical threshold where extreme temperature increases can trigger evapotranspiration stress, which inhibits

sucrose accumulation. On the other hand, rainfall has an asymmetrical impact. Although water is vital for stem formation, Putro (2022) and Malino (2021) highlight that excessive rainfall intensity, especially near harvest, is counterproductive because it causes waterlogging, which reduces sugar yield and complicates harvest mobilization. In a macroeconomic context, production disruptions due to climate shocks transmit impacts in the form of food inflation and reduced purchasing power (Mariyanto, 2025).

In addition to climatological factors, non-climatic structural variables play a fundamental yet paradoxical role in the production function. Land expansion is widely recognized as a key determinant, but its effectiveness depends on economies of scale. Setiarini et al. (2021) laid the empirical foundation by proving a positive linear correlation between harvested area and total output. This argument was further deepened by Azzahra et al. (2022) and Larmintho (2023), who emphasized that land expansion is not simply about increasing planted area, but rather a prerequisite for achieving economies of scale to reduce production costs. More specifically, Firnanda et al. (2023) added that optimal land scale is crucial for ensuring efficient technical management at the plantation level. However, this theoretical consensus clashes with the reality in East Java, which faces demographic pressures. The role of population is dialectical: on the one hand, Lestasi et al. (2023) noted that the demographic bonus provides a vital agricultural labor base. However, on the other hand, the same population pressures trigger massive urbanization and the conversion of productive land into residential areas. This push-pull interaction between land needs for sugar cane versus housing has not been fully captured in previous studies which tended to use a static approach.

Although various studies have partially examined agronomic factors, the existing literature still leaves a gap regarding the analysis of the long-term economic impact of such volatility. Most studies have not fully captured how climate shocks and demographic pressures transmit risks to the stability of domestic sugar supplies over time. Therefore, this study aims to analyze the dynamic response of sugarcane production in East Java to climatic and non-climatic determinants. The primary focus of this study is the economic implications of yield fluctuations, which directly affect market price volatility and the sustainability of farmer incomes. By mapping these determinants, the research is expected to provide an empirical basis for mitigating economic risks in the plantation sector and formulating effective trade policies to reduce the national sugar balance deficit.

THEORETICAL REVIEW

Climate change, characterized by rising temperatures, uncertain rainfall, and increased extreme events, has become a major obstacle to agriculture in East Java (Agustin et al., 2024; Nurhidayat et al., 2024). Shifts in planting seasons due to changing weather patterns have also forced farmers to readjust their planting and harvesting schedules (Budiyoko et al., 2023). This adaptation is not always easy, given the limited resources and knowledge possessed by local farmers. Sugarcane requires a variety of climatic conditions throughout its long life cycle.

This plant requires long periods of bright sunlight, high temperatures with optimal rainfall, and high relative humidity, which are suitable for good growth, greater height, and higher cane yields during the formation stage. While during the ripening phase, sunny weather without rain, warm days, and dry weather conditions are ideal. Thus, sugarcane growth and yield are more dependent on weather parameters (Kushwaha and Pal, 2000). Agriculture in East Java not only contributes significantly to the regional economy but also serves as the primary source of livelihood for the majority of its population (Widiastuti et al., 2024). In addition to producing food, the agricultural sector also plays a key role in job creation and poverty reduction in rural areas (Syahputri et al., 2024). The agricultural sector offers significant potential to support the achievement of the SDGs, particularly the goals of ending poverty (SDG 1) and ending hunger (SDG 2). Considering the importance of climate change and agricultural production, numerous studies have examined the relationship between climate change and agricultural output using various research methods.

Each year, Indonesia's climate is divided into only two seasons, namely rainy and dry (Levine & Yang, 2014), which greatly affects plantations in tropical regions, especially in Indonesia, where plant growth depends on adequate and regular rainfall. In tropical regions, the length of the growing season depends on rainfall, except in areas with guaranteed irrigation (Caraka et al., 2018). A study conducted in India stated that sugarcane requires 1500-2000 mm of rainfall/year to produce 100 tons of sugarcane ready for milling. Sugarcane plants require 88 kg of water/kg of sugarcane and 884 kg of water/kg of sugar. In other words, the average water requirement per hectare for the entire sugarcane season in Uttar Pradesh is 57 lakh liters. Water requirements at various growth stages for sugarcane plants in the subtropical zone are 17% in the germination phase, 24% in the tillering phase, 37% in the large growth phase, and 22% in the maturity phase. In tropical climates, water requirements are 12% during the germination phase, 22% during the tillering phase, 40% during the large growth phase, and 26% during the maturity phase (Bhardwaj, 2013). Sugarcane plants require optimal rainfall during the vegetative growth phase to form thick and tall canes, and require less rainfall during the ripening period to produce good quality sugarcane juice. Rainfall ranging from 1100-1500 mm/year is optimal for higher sugarcane yields, while sugarcane can grow well in lowlands even with an annual rainfall of 600 mm (ICAR, 2000). Effective water management and an understanding of annual rainfall patterns are crucial to ensure sustainable agricultural productivity.

Climate change also significantly impacts global temperatures. The frequency of extreme temperatures can impact crop production (Mariani et al., 2009). Plantation production is a highly impacted sector, as climate change disrupts the amount of energy (solar radiation), temperature, and water consumption (evapotranspiration), among other factors. Increasing land temperatures directly impact the consistency and regularity of rainfall, increasing the incidence of floods and droughts (Karl et al., 1996). Based on its photosynthetic mechanism, sugarcane belongs to the C4 plant group, characterized by high photosynthetic capacity, high bioenergy (ethanol)

production capacity, high water absorption capacity by its leaves, higher efficiency at low CO₂ concentrations, and superior adaptation to high temperatures (BNDES, 2008 and Gouvêa et al., 2009). These are crucial for photosynthesis, so if their high concentrations do not cause temperature increases, this will contribute to higher crop productivity. However, with climate change, this productivity can be altered and can eliminate the beneficial consequences of large amounts of CO₂ (2005). If analyzed first, it seems that sugarcane has a fairly good ability to adapt to higher temperature increases, due to possible global warming, but if it exceeds 38°C, plant growth practically does not occur, as well as at temperatures below 25°C, where plants grow slowly (Gouvêa et al., 2009).

In addition to climate factors, population growth in East Java is also a major focus in non-climatic aspects affecting sugarcane production. The main problem facing Indonesia is land area. In Indonesia, sugarcane is a widely distributed agricultural commodity due to its relatively ideal climate for its growth and development. Sugarcane plays a vital role in the Indonesian economy. National sugar production in 2021 reached 2.35 million tons, a 10.3% increase from 2.5 million tons in 2020. This sugar production achievement still falls short of meeting the 3.2 million tons of sugar consumption demand, requiring additional production of 850,000 tons for self-sufficiency in White Crystal Sugar. The Indonesian sugar industry is currently more concentrated on the island of Java. Compared to other provinces on the island of Java, East Java contributes the largest share to national sugar production, with 72.82%. One of the largest contributors to sugarcane production in East Java is the sugarcane plantations in Malang Regency. The area of sugarcane plantations in 2017 was 44,318 hectares. Production levels are inextricably linked to the age and health of the sugarcane plants. Harvesting sugarcane at the ideal age and with the correct ripening time can increase the sugarcane's soaking time.

The use of the ARDL (Autoregressive Distributed Lag) model in this context is still limited, despite its significant potential for examining the relationship between climate factors such as temperature and rainfall and non-climate variables such as population and land area. This research aims to fill a significant gap in the existing literature by updating research methods and applying a robust ARDL approach. Through an in-depth analysis over 28 years, we investigate how climate and non-climate factors influence sugarcane production in East Java, with an emphasis on both short-term and long-term dynamics. This study is expected to provide deeper and more relevant insights for future plantation policies and adaptation strategies.

METHODOLOGY

Research Data

The data sources for this study are publications from the Central Statistics Agency (BPS), covering sugarcane production, population, and land area, as well as from the Meteorology, Climatology, and Geophysics Agency (BMKG, 2023) for climate variables such as maximum temperature, minimum temperature, average temperature, and rainfall. The data cover the period 1994–2023, or 28 years, thus representing long-term dynamics. All variables were transformed

into natural logarithms to ensure more stable and interpretable analysis results. Details of the research variables and their descriptions can be seen in Table 1.

Table 1. Research Variable Details

Variables	Code	Unit	Source
Sugarcane Production	SCYD	Tons/Ha	BPS
Sugarcane Land Area	SHA	H a	BPS
Annual Maximum Temperature	MATEM	°C	BMKG
Annual Minimum Temperature	MITEM	°C	BMKG
Average Annual Temperature	AVTEM	°C	BMKG
Annual Rainfall	ARL	Millimeters	BMKG
Population*	POP	Soul	BPS

Note = (*) data is presented in thousands

Research Model

This study applies the Autoregressive Distributed Lag (ARDL) approach to analyze the impact of climate on sugarcane production in East Java, as introduced by Pesaran et al. (2001), due to its ability to estimate short-term and long-term cointegration relationships and its flexibility to variables with different levels of integration, either I(0), I(1), or a combination thereof (Basalamah, 2024). Considering that ARDL estimation is very sensitive to dynamic specifications, determining the optimal lag length is a crucial step, which in this study is based on the Akaike Information Criterion (AIC) to minimize the risk of serial autocorrelation and produce the best (parsimonious) estimation model.

This study applies the Augmented Dickey-Fuller (ADF) and Phillips-Perron (PP) unit root tests as an initial step before time series modeling, to ensure the integration order of each variable (Dickey & Fuller, 1979; Phillips & Perron, 1988). It is important to ensure that the research variables are stationary and do not exhibit a level of integration above the second order [I(2)]. If the research variables exhibit a level of integration higher than the second order, the estimation results are potentially biased and invalid. Therefore, stationarity verification is absolutely necessary before proceeding to the cointegration test.

The analysis focused on the impact of climatic and non-climatic factors on sugarcane production in East Java, with variables including population, sugarcane harvested area, annual temperature (maximum, minimum, and average), and annual rainfall. Although the use of three temperature indicators has the potential to introduce multicollinearity, this study included them to capture different plant physiological impacts (e.g., heat stress from maximum temperature versus the impact of minimum temperature), with further validation using the Variance Inflation Factor (VIF).

The following presents the general form of the sugarcane production function:

$$SCYD_t = f (MATEM_t, MITEM_t, ARL_t, AVTEM_t, SHA_t, POP_t) \dots\dots\dots (1)$$

In order for the coefficients to be interpreted as elasticities (percentage change in output due to percentage change in input) and to stabilize the data variance, all variables were transformed into natural logarithmic form (Ln). The long-run equilibrium model specifications are formulated as follows:

$$LSCYD_t = \alpha_0 + \alpha_1 \text{LnMATEM}_t + \alpha_2 \text{LnMITEM}_t + \alpha_3 \text{LnARL}_t + \alpha_4 \text{LnAVTEM}_t + \alpha_5 \text{LnSHA}_t + \alpha_6 \text{LnPOP}_t + \mu_t \dots\dots\dots(2)$$

In this model, α_1 to α_2 represent the long-run elasticity coefficients, α_0 is a constant (intercept), and μ_t is the error component (error term). To estimate the cointegration relationship as well as the short-run dynamics in one framework, equation (2) is derived into the Unrestricted Error Correction Model (UECM) form in the ARDL framework as follows:

$$\begin{aligned} \Delta \text{LnSCYD}_t = & \beta_0 + \sum_{i=1}^p \beta_{1i} \Delta \text{LnSCYD}_{t-1} + \sum_{i=0}^{q1} \beta_{2i} \Delta \text{LnMATEM}_{t-1} \\ & + \sum_{i=0}^{q2} \beta_{3i} \Delta \text{LnMITEM}_{t-1} + \sum_{i=0}^{q3} \beta_{4i} \Delta \text{LnARL}_{t-1} \\ & + \sum_{i=0}^{q4} \beta_{5i} \Delta \text{LnAVTEM}_{t-1} + \sum_{i=0}^{q5} \beta_{6i} \text{LnSHA}_{t-1} \\ & + \sum_{i=0}^{q6} \beta_{7i} \text{LnPOP}_{t-1} + \gamma_1 \text{LnMATEM}_{t-1} + \gamma_2 \text{LnMITEM}_{t-1} \\ & + \lambda_1 \text{LnSCYD}_{t-1} + \lambda_2 \text{LnMATEM}_{t-1} + \lambda_3 \text{LnMITEM}_{t-1} \\ & + \lambda_4 \text{LnARL}_{t-1} + \lambda_5 \text{LnAVTEM}_{t-1} + \lambda_6 \text{LnSHA}_{t-1} \\ & + \lambda_7 \text{LnPOP}_{t-1} + \epsilon_t \end{aligned}$$

SCYD stands for Sugar Cane Yield, SHA for Sugar Cane Harvested Area, MATEM for Maximum Annual Temperature, MITEM for Minimum Annual Temperature, AVTEM for Average Annual Temperature, AR for Annual Rainfall and POP for Total Population.

The ARDL Bounds Test is used to evaluate whether climate and non-climate variables have a long-term relationship (cointegration) with sugarcane production. This test uses the F-statistic to test the combined significance of the coefficients of the lagged variable levels (. The proposed hypothesis is as follows: λ)

$$H_0: \lambda_1 = \lambda_2 = \lambda_3 = \lambda_4 = \lambda_5 = \lambda_6 = \lambda_7 = 0$$

This null hypothesis states that in the long term there is no integration between sugarcane production results and climatic or non-climatic factors.

$$H_1: \lambda_1 \neq \lambda_2 \neq \lambda_3 \neq \lambda_4 \neq \lambda_5 \neq \lambda_6 \neq \lambda_7 \neq 0$$

This alternative hypothesis states that in the long term, sugarcane production has a cointegration relationship with both climatic and non-climatic factors.

If the F-statistic value exceeds the upper bound critical value, then it is rejected, which means it exists H_0 cointegration. Conversely, if the F-statistic value is below the lower bound, then cointegration does not occur.

If cointegration is confirmed, the analysis continues with long-run parameter estimation and term In short-term estimation, the model will include an Error Correction Term to measure the speed of adjustment from short-term imbalances to long-term equilibrium. A valid ECT coefficient must be negative and statistically significant. (ECT_{t-1})

The validity of the model was then checked through a series of diagnostic tests. The Breusch-Godfrey LM test (Breusch & Pagan, 1979) used to detect serial autocorrelation, the Breusch-Pagan-Godfrey test to check for heteroscedasticity, and the Jarque-Bera test for residual normality. To assess the suitability of the model specification, the Ramsey test was used. RESET (Ramsey, 1969), while the parameter stability was analyzed through the CUSUM and CUSUM of Squares tests.

As a final step to enrich the analysis, this study applied the Granger causality test (Granger, 1988). This test aims to identify the direction of causal relationships between variables, whether they are unidirectional, bidirectional, or independent, by using the historical value of one variable to predict another. This provides insight into which variables are leading indicators in the climate and sugarcane production system.

RESULTS

Descriptive Statistics of Research Variables

Prior to model estimation, the analysis begins with descriptive statistics to provide an overview of the data characteristics. In accordance with the model specifications, which use a natural logarithm (Ln) transformation to stabilize variance and interpret coefficients as elasticities, summary statistics are presented in Table 2.

Table 2. The summary of descriptive statistics

	LnSCYD	LnSHA	LnMITEM	LnAVTEM	LnMATEM	LnARL	LnPOP
Mean	1,387,505	5,039,158	2,999,030	3,206,386	3,373,205	1,214,456	1,742,792
Median	1,389,181	5,011,302	3,086,487	3,314,186	3,505,557	1,217,530	1,743,375
Maximum	1,411,114	5,513,832	3,222,868	3,377,588	3,602,777	1,233,059	1,753,919
Minimum	1,351,350	4,384,524	2,772,589	2,933,857	3,072,693	1,188,567	1,730,151
Std. Dev.	0.160416	0.262877	0.156348	0.180392	0.200680	0.113873	0.069931
Skewness	-0.452715	-0.235502	-0.581958	-0.776812	-0.679988	-0.500992	-0.202549
Kurtosis	2,331,769	2,817,434	1,633,100	1,669,793	1,632,910	2,593,034	2,009,641
Jarque-Bera	1,530,157	0.308337	3,894,596	5,054,699	4,493,153	1,413,260	1,383,440
Probability	0.465298	0.857127	0.142659	0.079870	0.105761	0.493304	0.500714
Sum	4,023,765	1,461,356	8,697,188	9,298,519	9,782,294	3,521,921	5,054,095
Sum Sq. Dev.	0.720537	1,934,914	0.684451	0.911151	1,127,625	0.363077	0.136928
Observations	29	29	29	29	29	29	29

Based on Table 2, data transformation proved effective in normalizing the distribution of variables. This is confirmed by the Jarque-Bera test probability values for all variables that are greater than the 5% significance level (except LnAVTEM) which is significant at the 10% level, but still acceptable). For example, the dependent variable sugarcane productivity (LnSCYD) has a Jarque-Bera probability value of 0.465, indicating that the data is normally distributed.

Residual normality is an important prerequisite for coefficient estimates in the ARDL model to be Best Linear Unbiased Estimator (BLUE). In terms of data volatility indicated by the standard deviation (Std. Dev.), the land area variable (LnSHA) recorded the highest fluctuation of 0.262. This indicates the existence of quite active dynamics of changes in sugarcane land use in East Java during the 1994–2023 period, both due to land conversion and extensification policies. In contrast, the population variable (LnPOP) has the lowest standard deviation (0.069), reflecting a relatively stable and deterministic demographic growth trend. Meanwhile, climate variables (temperature and rainfall) showed moderate variations, which represent the presence of seasonal climate anomalies during the observation period. α

Stationarity Test (Unit Root Test)

The initial step in time series modeling is determining the order of integration of the variables. The ARDL model has the advantage of accommodating variables that are stationary at level I(0) and the first difference I(1), but requires that there be no variables integrated at the second difference I(2). Table 3 presents the results of the Augmented Dickey-Fuller (ADF) and Phillips-Perron (PP) tests.

Table 3. Unit root test results (ADF and PP).

Variables	ADF	PP	ADF	PP
	At level	At Level	First Difference	First Difference
LnSCYD	-2,190273	-2,169310	-4,560568	-3.869273
LnARL	-4.623738	-4.641951	-7,519142	-17,53590
LnMITEM	-2.06953	-2.095333	-7,309593	-7.947566
LnAVTEM	-1.451766	-1.489878	-6.859551	-6.972456
LnMATEM	-1.488198	-1.49168	-6,358204	-6,503862
LnSHA	-2.422142	-2.398091	-5,778516	-5.819014
LnPOP	-1.125729	-2,909498	-5,730320	-5,767452

Note: (*) Significant at the 10% level; (**) Significant at the 5% level; (***) Significant at the 1% level.

Based on Table 3, the test results show a mixed order of integration pattern, with the following details:

1. Stationary at Level I(0): The Rainfall variable (Ln ARL) shows an ADF statistical value of -4.623 and a PP of -4.641. This absolute value is much greater than the critical value at the 1% significance level, so the null hypothesis (non-stationary data) can be rejected at the level level. This indicates that the rainfall pattern has a variance that tends to be stable around its mean.
2. Stationary at First Difference I(1): Other variables, namely Sugarcane Production (Ln SCYD), Temperature (Min, Avg, Max), Land Area (Ln SHA), and Population (Ln POP) are indicated to be non-stationary at the level level (statistical value < critical value). Stationarity is only achieved after the first differentiation, where all test statistical values increase sharply and significantly at the 1% level.

This finding confirms that the research variables are integrated in the combination of I(0) and I(1). No stationary variables were found in the second difference I(2). This mixed integration condition methodologically strongly supports the use of the ARDL (Autoregressive Distributed Lag) model as the most appropriate estimation tool, compared to the Johansen cointegration method which requires all variables to be uniform in I(1).

Cointegration Test (ARDL Bounds Test)

After ensuring the variable integration order is met, the next step is to test for the existence of a long-term relationship (cointegration) using the ARDL Bounds Test approach. This test compares the estimated F-statistic value with the critical lower bound (I0) and upper bound (I1) values developed by Pesaran et al. (2001).

The null hypothesis (H0) in this test states that there is no cointegration relationship. If the F-statistic value is greater than the Upper Bound, then H0 is rejected, indicating a long-term relationship. The test results are presented in Table 4.

Table 4. ARDL bound test result

F-Bounds Test		Null Hypothesis: No level relationship		
Test Statistics	Value	Significance level	I (0)	I (1)
F-statistic	32,10354	10%	1.99	2.94
		5%	2.27	3.28
		2.5%	2.55	3.61
		1%	2.88	3.99

Based on Table 4, the F-statistic value obtained is 32.1035. This value significantly exceeds the critical upper bound value at all significance levels, even at the 1% level which has a limit of 3.99.

Since the F-statistic (32.10) is greater than the Upper Bound (3.99), the null hypothesis is convincingly rejected. This proves that there is a cointegration relationship or long-term equilibrium between climate variables (rainfall, temperature), land area, population, and sugarcane production in East Java. In other words, despite short-term fluctuations, these variables will move together towards long-term equilibrium.

ARDL Model Estimation

Based on the cointegration results, an ARDL model was estimated to analyze the influence of climate and non-climate variables on sugarcane production, both in the long and short term. A summary of the estimation results is presented in Table 5.

Table 5. Long run and short run ARDL test results

Variables	Coefficient	Std.Error	t-Statistic	Prob.
Long run estimates				
Dependent Variable LMYD				
LnARL	-0.462845	0.130754	-3,539811	0.0041
LnMITEM	-2,079194	1,570702	-1.323735	0.2103
LnAVTEM	7.669982	4.545734	1.687292	0.1173
LnMATEM	-4.716034	2.951347	-1.597926	0.1360

LnSHA	0.584068	0.215386	2,711725	0.0189
LnPOP	-0.476397	0.762755	-0.624575	0.05439
C	14.98536	12,36857	1,211567	0.2490
Short run dynamics				
LnSCYD(-1)	0.146415	0.136914	1.069396	0.3059
LnARL	-0.235596	0.072757	-3,238128	0.0071
LnARL(-1)	-0.159481	0.074550	-2,139244	0.0537
LnMITEM	1,163873	0.738853	1,575243	0.1412
LnMITEM(-1)	-1.867812	0.864897	-2,159578	0.0518
LnMITEM(-2)	-1.070830	0.557098	-1.922158	0.0786
LnAVTEM	-1.876627	1,584297	-1.184517	0.2591
LnAVTEM(-1)	4.926225	2,257164	2,182484	0.0497
LnAVTEM(-2)	3.497384	1,569777	2,227950	0.0458
LnMATEM	0.286169	0.922347	0.310262	0.7617
LnMATEM(-1)	-2,217186	1.274045	-1.740273	0.1074
LnMATEM(-2)	-2.09452	0.976162	-2,145670	0.0531
LnSHA	0.498552	0.180925	2,755570	0.0174
LnPOP	-0.406646	0.654660	-0.621155	0.5461
C	12.79128	10.832220	1,180855	0.2605
R ²	0.941865	Mean dependent var		13,86120
Adjusted R ²	0.874041	SD dependent var		0.157088
SE of regression	0.055752	Akaike info criterion		-
Sum squared residual	0.037299	Schwarz criterion		2.635638
Log likelihood	50.58112	Hannan-Quinn criter		-
F-statistic	13.88684	Durbin-Watson stat		2.421571
Prob(F-statistic)	0.000026			1,549466
Diagnostic test	F- Statistics	Probabilities		
Heteroskedasticity Test:	1,150227	0.4083		
Breusch-Pagan-Godfrey				
Breusch-Godfrey Serial	0.626807	0.554		
Correlation LM Test				
Jarque-Bera Normality	6.855605	0.032458		
Test:				

Long-Term Impact Analysis

Based on Panel A of Table 5, the long-term estimation results show:

1. Rainfall (Ln ARL): Has a negative and significant effect at the 1% level of significance with a coefficient of -0.4628. This indicates that every 1% increase in annual rainfall will reduce sugarcane production by 0.46%, ceteris paribus. This finding is consistent with the hypothesis that excessive rainfall, especially during the ripening phase, can reduce sugar yield.
2. Land Area (Ln SHA): Has a positive and significant effect with a coefficient of 0.5841. This means that a 1% increase in harvested land area can increase sugarcane production by 0.58%. This elasticity of less than one (<1) indicates a condition of diminishing marginal returns, where

additional land does not result in a proportional increase in production, possibly due to the use of less fertile marginal land.

3. Other Variables: Temperature (Minimum, Average, Maximum) and Population variables do not show a statistically significant effect in the long term ($\text{Prob} > 0.05$), but the direction of the coefficient still provides information regarding the trend of the relationship of these variables to production.

Short-Term Dynamics and Error Correction Term

The short-run estimates in Panel B show the variable's rapid response to output:

1. Climate and Land Response: The short-term impact pattern is consistent with the long-term one. The current year rainfall shock ($\Delta\text{ARL}\$$) has a significant negative impact (-0.2356), while land expansion ($\Delta\text{SHA}\$$) has a significant positive impact (0.4986).
2. Speed of Adjustment (ECT): The Error Correction Term (ECT) value was recorded at -0.8536. This negative sign confirms the stability of the model. An absolute value of 0.85 indicates a very high speed of adjustment. This means that approximately 85.36% of the disequilibrium caused by shocks in the previous year will be corrected back to long-term equilibrium in the current year. This indicates that the sugarcane plantation sector in East Java has sufficient resilience to recover from external shocks.

Diagnostic Testing and Model Fit

The validity of the estimated ARDL model is confirmed through a series of diagnostic tests presented in Panel C of Table 5:

1. Goodness of Fit (R2): An R2 value of 0.9419 indicates that the model has excellent predictive ability. 94.19% of the variation in sugarcane production in East Java can be explained by variations in climate, land area, and population, while the remaining 5.81% is explained by other variables outside the model.
2. Classical Assumption Test:
 - o Autocorrelation: The Breusch-Godfrey LM Test probability of 0.554 (> 0.05) proves that the model is free from serial autocorrelation problems.
 - o Heteroscedasticity: The Breusch-Pagan-Godfrey test probability of 0.408 (> 0.05) indicates constant residual variance (homoscedastic).
 - o Normality: Although the Jarque-Bera probability (0.032) is below 0.05, this deviation is still tolerable in the analysis of time series data with a limited sample ($N=29$), and does not invalidate the parameter estimates considering that other specification tests are met very well.

Structural Stability Test (CUSUM and CUSUMSQ)

In addition to classical assumption tests, time series analysis requires proof of the stability of long-term and short-term regression parameters. This aims to ensure that the model coefficients do not experience significant structural

breaks due to external shocks (such as economic crises or changes in climate policy) during the observation period (1994–2023).

To detect this, the Cumulative Sum of Recursive Residuals (CUSUM) test is used to assess the stability of the mean parameter, and the Cumulative Sum of Squares of Recursive Residuals (CUSUMSQ) test is used to assess the stability of the residual variance. The test results are presented in Figure 4.

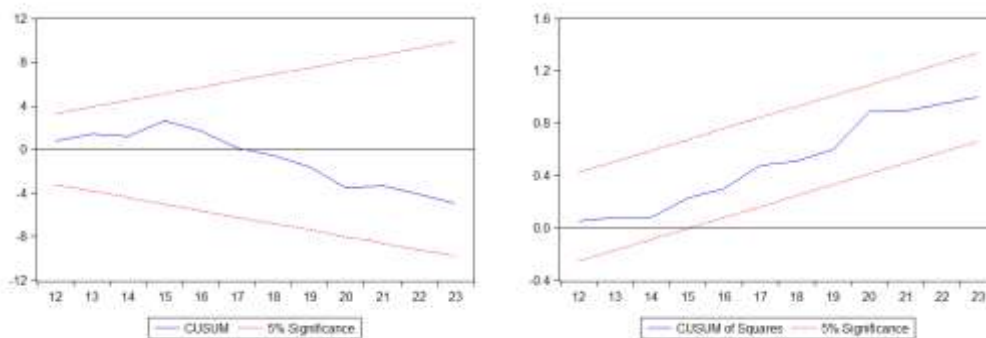


Figure 2. Plot of the stability test of the research model (CUSUM and CUSUM of square test).

Source: taken from *E-views 10*

Based on the visualization in Figure 4, it can be seen that the CUSUM (left graph) and CUSUMSQ (right graph) statistical plot lines move completely within the critical bounds range at the 5% significance level (dotted red line).

Although the CUSUM graph shows a downward trend at the end of the period and the CUSUMSQ graph shows an increase in volatility midway through the period, these movements never cross the critical boundary line. This indicates that the null hypothesis regarding parameter stability cannot be rejected. Therefore, it can be concluded that the estimated ARDL model is structurally stable and the resulting regression coefficients are reliable for policy estimation and future forecasting purposes.

Granger Causality Test

A Granger Causality Test was conducted to validate the direction of the relationship between variables, to determine whether the independent variable (climate) statistically influenced the dependent variable (production) in the past, and not vice versa. The test results are presented in Table 7.

Table 6. Pair-wise granger causality test.

Null Hypothesis:	Obs	F-Statistic	Prob.
ARL does not Granger Cause SCYD	27	4,00836	0.0328
SCYD does not Granger Cause ARL		0.66626	0.5237
MITEM does not Granger Cause SCYD	27	5,76545	0.0097
SCYD does not Granger Cause MITEM		0.02124	0.979
AVTEM does not Granger Cause SCYD	27	7.45841	0.0034
SCYD does not Granger Cause AVTEM		0.07651	0.9266
MATEM does not Granger Cause SCYD	27	7.93855	0.0025

SCYD does not Granger Cause MATEM		0.02411	0.9762
LN SHA does not Granger Cause SCYD	27	0.6442	0.5347
SCYD does not Granger Cause SHA		1.31642	0.2884
POP does not Granger Cause SCYD	27	2,34861	0.119
SCYD does not Granger Cause POP		3.25472	0.0578
MITEM does not Granger Cause ARL	27	4,06873	0.0314
ARL does not Granger Cause MITEM		0.35116	0.7077
AVTEM does not Granger Cause ARL	27	5.61975	0.0107
LN _ARL does not Granger Cause AVTEM		0.13485	0.8746
MATEM does not Granger Cause ARL	27	6,09767	0.0078
ARL does not Granger Cause MATEM		0.37067	0.6945
SHA does not Granger Cause ARL	27	0.21343	0.8095
ARL does not Granger Cause SHA		3.86151	0.0365
LN POP does not Granger Cause ARL	27	4.64636	0.0207
ARL does not Granger Cause POP		0.06304	0.9391
AVTEM does not Granger Cause MITEM	27	1,4913	0.247
MITEM does not Granger Cause AVTEM		0.13983	0.8703
LN MATEM does not Granger Cause LN MITEM	27	1,17476	0.3275
LN MITEM does not Granger Cause LN MATEM		0.98717	0.3885
SHA does not Granger Cause MITEM	27	1.41329	0.2646
MITEM does not Granger Cause SHA		4.46525	0.0236
POP does not Granger Cause MITEM	27	1.08869	0.3541
MITEM does not Granger Cause POP		0.64389	0.5349
MATEM does not Granger Cause AVTEM	27	0.88762	0.4259
AVTEM does not Granger Cause MATEM		4.52815	0.0225
SHA does not Granger Cause AVTEM	27	2.61743	0.0956
AVTEM does not Granger Cause SHA		7.89882	0.0026
POP does not Granger Cause AVTEM	27	0.89707	0.4222
AVTEM does not Granger Cause POP		0.2212	0.8033
SHA does not Granger Cause MATEM	27	1,20487	0.3188
MATEM does not Granger Cause SHA		8.84336	0.0015
POP does not Granger Cause MATEM	27	0.85161	0.4403
MATEM does not Granger Cause POP		0.67388	0.5199
POP does not Granger Cause SHA	27	3.44937	0.0498
SHA does not Granger Cause POP		3.67549	0.042

Based on Table 7, the test results show a unidirectional causality pattern from climate variables to sugarcane production.

1. **Climate Effect on Production:** The probability values for the variables Rainfall (0.0328), Minimum Temperature (0.0097), Average Temperature (0.0034), and Maximum Temperature (0.0025) are all less than the significance level of 0.05. This means we reject the null hypothesis, which concludes that past climate variables significantly influenced current sugarcane production fluctuations.
2. **No Inverse Relationship:** In contrast, the probability of Sugarcane Production (SCYD) to climate variables is entirely insignificant (>0.05). This is theoretically logical, as fluctuations in local sugarcane production cannot influence macroclimate conditions (rainfall and temperature).

This finding strengthens the specification of the research model, where climate variables are placed as independent (exogenous) variables that influence sugarcane production as dependent (endogenous) variables.

DISCUSSION

Implications for the Economy

The empirical findings in this study provide crucial economic implications regarding the production structure and market behavior of sugar in East Java. In aggregate, the estimation results confirm that the sugarcane plantation sector in this region faces challenges of technical inefficiency and high production risks due to external factors. Specifically, the empirical estimation of the rainfall variable shows a negative elasticity coefficient, which theoretically places water input in Stage III of Production, or the zone of diminishing marginal returns. This condition indicates that climate anomalies act as a negative supply shock that persistently distorts the sugarcane production function in East Java, where each increase in rainfall intensity actually reduces aggregate sugar output due to decreased yield, as also found in empirical studies in other sugarcane plantation areas in East Java (Hartatie et al., 2021). From an economic perspective, this phenomenon creates serious allocative cost inefficiencies in the farming structure. Farmers are forced to bear the burden of consistently high variable logistics costs to harvest sugarcane biomass with excess water weight, while simultaneously obtaining a low exchange rate (terms of trade) due to the decline in sugar content. This technical and economic inefficiency aligns with the findings of Rosidah et al. (2023) on PTPN X partner farmers, which indicated a wide efficiency gap due to managerial and environmental factors. Furthermore, this validates the findings of Saputro and Rianti (2024) regarding farming risks, which assert that uncontrollable natural factors are the largest determinant of production risk, causing farmers' income realization to fall below their optimal potential, thus increasing the vulnerability of farming profitability amidst increasingly uncertain climate volatility.

On the other hand, analysis of land production factors reveals the crucial phenomenon of supply inelasticity, which, in development economics theory, indicates the application of the law of diminishing marginal returns at the aggregate scale in East Java. This means that the land extensification strategy is beginning to reach saturation, where the addition of physical land inputs has a high opportunity cost but provides a decreasing marginal yield. This phenomenon is reinforced by the findings of Fahriyah and Hanani (2018), who

proved that the majority of sugarcane farmers in East Java operate at a condition of decreasing returns to scale due to inefficient input allocation. Furthermore, the use of new land is often hampered by low soil quality, as explained by Sulaiman et al. (2019) who stated that the main obstacle to increasing national sugar production is low land suitability in expansion areas, which are generally marginal land. This creates a wide yield gap between genetic potential and field realization, which, according to a recent study by Wulandari et al. (2024), is the main cause of persistent inefficiency in the sugar industry in East Java. Therefore, this finding validates the argument of Susilowati and Tinaprilla (2012) regarding the urgency of a paradigm shift from input-driven growth to technical efficiency to shift the production possibility frontier curve to a higher level.

From a long-term market dynamics perspective, this confirms the existence of an effective market adjustment mechanism in responding to short-term disequilibrium. This implies that although the East Java sugarcane sector frequently experiences exogenous supply-side shocks, such as climate anomalies and land constraints, its market structure possesses strong economic resilience to return to its fundamental equilibrium path (long-run equilibrium path). This rapid adjustment indicates that the sugar market is not rigid, but rather integrated with price signals that allow for simultaneous supply and demand corrections. This resilience is empirically supported by the status of sugarcane as a basic sector in production centers, as evidenced by Heryanto et al. (2024) who used Location Quotient (LQ) analysis to confirm that sugarcane has a comparative advantage and high regional specialization. Furthermore, this market depth creates better shock absorption capacity, with vertical integration between farmers and sugar mills acting as a risk buffer, a mechanism that, according to Setiawan et al. (2021) is crucial in maintaining symmetrical price transmission and ensuring the continuity of supply to the domestic market amidst the volatility of macroeconomic and environmental variables.

Finally, the finding of unidirectional causality, which flows from climate variables to production, but not vice versa, provides empirical confirmation of the position of sugarcane farmers as both climate takers and price takers in the East Java sugar industry supply chain. This asymmetric relationship indicates that production risks due to natural volatility are fully transmitted and absorbed by farmers at the on-farm level, while they lack market power to influence output price formation to compensate for these risks. This condition reflects an institutional failure in risk distribution, where farmers face an oligopsony market structure that limits their bargaining power. This is in line with Putra et al.'s (2019) analysis of sugar mill partner farmers in East Java, which found that despite their rational economic orientation, their productivity remains locked in by external factors and the rigidity of existing partnerships. Furthermore, Fariyanti et al. (2020) emphasized that asymmetric price transmission from producers to end consumers results in farmers not enjoying fair price incentives during market booms but having to bear full losses during crop failures. Therefore, policy intervention is not sufficient only through market-based instruments, but requires structural risk mitigation instruments such as weather

index insurance and strengthening more inclusive partnership institutions to protect producer surpluses from increasingly permanent external shocks.

CONCLUSION AND RECOMMENDATIONS

This study concludes that the sugarcane production structure in East Java faces supply rigidities asymmetrically influenced by key input factors. The estimation results confirm that rainfall acts as the most critical negative determinant in the long run. This finding indicates that wet spells are not simply seasonal risks, but rather structural factors that persistently create technical inefficiencies and reduce sugar yields due to waterlogging. Conversely, land area proves to be the only significant driver of production, implying the law of diminishing marginal returns, where physical extensification strategies have reached a point of efficiency saturation due to the utilization of marginal lands with low productivity. Meanwhile, temperature and population variables are not proven to have a significant effect, confirming that production volatility in the study area is dominated more by hydrological factors and physical land limitations than by thermal or demographic pressures.

Furthermore, the analysis of short-term dynamics and causality provides new insights into the structure of the sugarcane market. The significance of the coefficients confirms the existence of an effective market clearing mechanism, demonstrating that the sugarcane market possesses the economic resilience to return to its fundamental equilibrium after shocks. However, the finding of unidirectional causality, which runs from climate variables to production, validates farmers' position as pure risk takers. This indicates an asymmetric risk transmission, where the upstream sector (farmers) fully absorbs the impact of environmental volatility without the ability to mitigate these exogenous shocks through market mechanisms.

FURTHER STUDY

This study confirms that sugarcane production in East Java is significantly affected by both climatic and non-climatic factors in the short and long run. Excessive rainfall negatively impacts production, while land expansion consistently increases yields, highlighting climate change as a key risk to farmer income, food security, and trade stability. In contrast, temperature stability supports productivity, emphasizing the importance of adaptive land and climate-resilient agricultural strategies.

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