

# Asymmetric Impacts of Palm Oil Expansion and Industrial Downstreaming on Ecological Footprint: Evidence from Indonesia

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## ABSTRACT

**Purpose:** This study empirically investigates the asymmetric impacts of palm oil production, downstream industrialization, and trade openness on the ecological footprint. The primary objective is to determine whether environmental degradation responds differently to positive and negative macroeconomic shocks.

**Research Method:** The research employs a nonlinear autoregressive distributed lag framework to analyze annual time-series data spanning 30 years. The analytical procedure involves descriptive statistics, unit root tests to confirm stationarity, nonlinear bounds testing for long-run cointegration, and short-run Granger causality tests.

**Results and Discussion:** The empirical findings reveal a statistically significant asymmetric relationship. A positive shock in palm oil production exacerbates environmental degradation, while a negative shock is associated with measurable ecological recovery. Furthermore, downstream industrialization marginally reduces the ecological footprint in the long run, suggesting the potential for adopting circular economy practices. Conversely, trade openness slightly increases environmental pressures, indicating a global telecoupling effect in which international demand influences domestic industrialization and upstream expansion.

**Implications:** To mitigate imported environmental burdens, producing nations must implement robust integrated policies. Strategic interventions, such as enforcing strict forest moratoriums, facilitating land swaps to degraded mineral soils, and accelerating sustainable certification for smallholders, are critical for achieving long-term ecological resilience.

**Originality:** This research breaks new ground by employing a nonlinear framework to reveal asymmetric "ecological hysteresis," in which environmental recovery fails to keep pace with the degradation caused by palm oil expansion.

**Keywords:** asymmetric impact; circular economy; ecological footprint; palm oil production; trade openness.

## 1. Introduction

Agricultural commodities frequently exist at the intersection of economic development and environmental sustainability, with the global palm oil industry serving as a notable example. Driven by international demand for food, energy, and industrial materials, palm oil production has grown

substantially (Xin et al., 2022). For major producing nations such as Indonesia and Malaysia, this sector serves as a fundamental driver of macroeconomic stability and rural modernization (Edwards, 2026). However, this economic expansion is accompanied by significant ecological consequences, as the conversion of natural landscapes into plantations has contributed to deforestation, biodiversity loss, and considerable greenhouse gas emissions (Acobta et al., 2025). Consequently, the industry faces an ongoing challenge to balance financial returns with environmental conservation.

The environmental footprint of palm oil production exhibits structural asymmetries by plantation ownership scale (Zhao et al., 2025). Large-scale industrial corporations have historically accounted for a major share of forest clearance and carbon dioxide emissions through extensive land conversion (Gaveau et al., 2022). Conversely, independent smallholders, while crucial to the rural socioeconomic structure, frequently encounter constraints in capital, technical knowledge, and legal compliance that hinder their adoption of sustainable practices (Lamsali et al., 2025). This structural divergence creates a persistent policy challenge in balancing localized job creation with effective ecological mitigation (Edwards, 2026).

The complexities of the palm oil sector extend beyond upstream agricultural activities, particularly as producing nations pivot toward downstream industrialization to capture greater added value (Gandhi & Takashi, 2025). Although this structural transformation enhances gross domestic product and export competitiveness, it introduces new spatial and environmental challenges (Rifa'i, 2025). Intensive downstream processing generates considerable volumes of solid waste and effluents, while also potentially widening the economic disparity between rural crude palm oil-producing areas and urbanized refining zones (Rifa'i, 2025). In response to these socio-ecological pressures, producing countries have introduced various national certification schemes and explored spatial mitigation strategies, such as land swaps, to improve governance and reduce environmental degradation (Ariesca et al., 2023; Bok et al., 2022; Erdi et al., 2026; Shahimi et al., 2023).

While existing literature on palm oil sustainability is extensive, it frequently remains fragmented and focuses on isolated stages of the supply chain (Jayathilake et al., 2023). Many studies concentrate primarily on direct farm-level ecological impacts, often overlooking the socio-ecological trade-offs associated with downstream industrialization and macroeconomic variables (Yuslaini et al., 2026). Addressing these gaps requires a holistic analytical approach that integrates upstream cultivation, downstream processing, and international trade dynamics (Purnomo et al., 2025). Therefore, this study aims to comprehensively evaluate the asymmetric impacts of palm oil production, downstream industrialization, and trade openness on the ecological footprint. By employing a nonlinear framework, this research seeks to provide an objective analytical foundation for developing integrated, resilient, sustainable governance models.

The remainder of this paper is organized as follows. Section 2 provides a literature review and hypothesis development. Section 3 presents the research method and design. Section 4 provides a discussion. Section 5 Concluding Remarks and Recommendations

## 2. Literature Review and Hypothesis Development

### 2.1 The Asymmetric Impacts of Palm Oil Production

Driven by increasing global demand for food, renewable energy, and industrial commodities, palm oil plantations have expanded rapidly across tropical regions (Xin et al., 2022). This agricultural expansion

has resulted in significant ecological consequences, including deforestation, biodiversity loss, and substantial greenhouse gas emissions (Acobta et al., 2025). This trajectory aligns with the early developmental phase outlined in the Environmental Kuznets Curve (EKC) hypothesis, in which rapid economic and agricultural expansion inherently drives ecological degradation (Grossman & Krueger, 1991).

The environmental footprint of this sector exhibits distinct structural asymmetries across scales of plantation ownership (Zhao et al., 2025). Large-scale industrial plantations managed by private enterprises are the primary drivers of historical forest clearance, accounting for a major portion of total deforestation and carbon dioxide emissions. In contrast, while independent smallholder operations exhibit faster annual expansion rates, they contribute less to aggregate environmental degradation (Zhao et al., 2025). However, smallholders often face suboptimal environmental management due to financial and technical constraints (Lamsali et al., 2025). Although mandatory certification schemes such as the Malaysian and Indonesian Sustainable Palm Oil frameworks attempt to mitigate these impacts, structural barriers and low adoption rates among independent farmers remain persistent challenges (Bok et al., 2022; Erdi et al., 2026; Shahimi et al., 2023). Given the complex dynamics of agricultural expansion and natural ecosystem recovery, this study postulates the following hypothesis:

**H1:** *Palm oil production exhibits an asymmetric impact on the ecological footprint, where a positive shock increases environmental degradation, while a negative shock reduces it.*

## 2.2 Downstream Industrialization and Ecological Mitigation

The complex relationship between industrial expansion and environmental quality is conceptualized as a nonlinear trajectory in which initial economic growth exacerbates environmental degradation. However, eventual industrial maturation leads to ecological recovery (Grossman & Krueger, 1991). Complementing this macro perspective, industrial economies possess a self-correcting capacity wherein environmental burdens are mitigated through continuous technological innovation, resource efficiency, and the structural greening of industrial processes (Jänicke, 2008).

This theoretical framework is highly pertinent to the recent paradigm shift in palm oil governance, which increasingly promotes downstream industrialization (Gandhi & Takanashi, 2025). While commodity downstreaming is pivotal to enhancing national gross domestic product and export competitiveness, its early developmental stages inherently coincide with the ascent of environmental degradation. The spatial concentration of downstream facilities often exacerbates regional economic disparities and generates considerable volumes of industrial waste and effluents, necessitating advanced cross-sectoral waste management policies to prevent severe ecological degradation (Mukhlis et al., 2025; Rifa'i, 2025).

To balance industrial growth with environmental conservation, the sector is increasingly adopting operational mitigation strategies that reflect the core tenets of structural greening. The application of circular economy practices, such as using empty fruit bunches as organic fertilizer and biochar, is a practical manifestation of this industrial modernization (Yusuf et al., 2025). By transforming industrial waste into valuable inputs, these technologies significantly minimize reliance on synthetic chemicals and potentially offset the ecological footprint of processing facilities. Consequently, the transition toward advanced industrialization does not dictate a constant path of environmental destruction but rather yields dynamic, nonlinear environmental outcomes. Based on this theoretical rationale, the following hypothesis is formulated:

**H2:** *Downstream industrialization exhibits an asymmetric impact on the ecological footprint, where a positive shock reduces environmental degradation, while a negative shock increases it.*

### 2.3 Trade Openness and Global Telecoupling

The integration of producing nations into the global market through trade openness significantly influences domestic environmental realities. Operating under the paradigm of global telecoupling, distant socioeconomic forces and international market demands can substantially drive local land-use changes and industrial expansion. This dynamic is fundamentally anchored in the Ecologically Unequal Exchange theory (Hornborg, 1998; Jorgenson, 2006). This macro-structural theory posits that the global trade system inherently enables advanced economies to externalize their environmental costs by importing resource-intensive commodities, thereby shifting severe ecological degradation onto exporting nations. As a major export commodity, palm oil production dynamics are closely linked to international trade volumes. Increased trade openness may stimulate further agricultural expansion to meet foreign demand, thereby directly manifesting this unequal exchange by transferring the ecological burden to producing regions (Edwards, 2026; Purnomo et al., 2025). Therefore, trade openness is expected to impose distinct and potentially unequal pressures on the national ecological footprint depending on the direction of market shocks. This leads to the final hypothesis:

**H3:** *Trade openness has an asymmetric impact on the ecological footprint: a positive shock increases environmental degradation, whereas a negative shock reduces it.*

## 3. Research Method

### 3.1 Data

The dataset employed in this study comprises an annual time series covering the period 1991 to 2020, yielding 30 annual observations. This specific timeframe provides an adequate number of observations to generate robust econometric estimates. The endogenous variable, ecological footprint (lnEF), has been transformed into its natural logarithm. Rather than a simplistic measure of general pollution, it serves as a comprehensive biocapacity accounting metric that quantifies the biologically productive area required to support human consumption and absorb the corresponding waste. Specifically, it rigorously aggregates the ecological demands across six standardized categories: built-up land, carbon uptake land, cropland, grazing land, fishing grounds, and forest products, with data sourced from the Global Footprint Network database. The core exogenous variable, palm oil (lnPLO), measures the total national volume of crude palm oil production. This variable is similarly transformed into its natural logarithm and is directly retrieved from the Tree Crop Estate Statistics of Indonesia database. Furthermore, industrialization (IND) is defined as an index measuring the manufacturing sector's value added relative to gross domestic product, using data from the World Bank database. Finally, trade openness (TO) is measured as the percentage ratio of the total value of exports and imports to the gross domestic product, representing the degree of economic integration with the global market. The data for this trade variable has been compiled from the World Bank and the United Nations Commodity Trade Statistics Database.

3.2 Econometric Model and Methodology

This study examines the impact of PLO, IND, and TO on EF from 1991 to 2020. The fundamental functional form of this relationship is established in Equation (1):

$$EF_t = f(PLO_t, IND_t, TO_t) \tag{1}$$

This study employs a nonlinear model to examine the asymmetric effects of palm oil production, industrialization, and trade openness on Indonesia's ecological footprint. The impacts can manifest as positive or negative shocks, following the concept of hidden cointegration established by Granger and Yoon (2002). To examine these asymmetric effects, the study utilizes the Nonlinear Autoregressive Distributed Lag (NARDL) method introduced by Shin et al. (2014). The functional form of the nonlinear model, which separates positive and negative shocks, is defined in Equation (2):

$$EF_t = f(PLO_t^+, PLO_t^-, IND_t^+, IND_t^-, TO_t^+, TO_t^-) \tag{2}$$

In Equation (2), the subscript denotes the time period, while the superscripts and indicate the positive and negative shocks, respectively. To mitigate the risks of serial correlation, heteroscedasticity, and data volatility, the relevant variables are transformed to their natural logarithms. Equation (3) demonstrates the empirical transformation of the model:

$$\ln EF_t = \alpha_0 + \alpha_1 \ln PLO_t^+ + \alpha_2 \ln PLO_t^- + \alpha_3 \ln IND_t^+ + \alpha_4 \ln IND_t^- + \alpha_5 \ln TO_t^+ + \alpha_6 \ln TO_t^- + \mu_t \tag{3}$$

In this equation, ln represents the natural logarithm. The parameter  $\alpha_0$  acts as the constant intercept of the model. The parameters  $\alpha_1$  through  $\alpha_6$  denote the long-run elasticity coefficients for the specified exogenous variables. Finally, the term  $\mu_t$  captures the stochastic error or white noise at a given time period.

Prior to examining the cointegrating relationships among the regressors, it is imperative to establish their order of integration. This study employs the Augmented Dickey-Fuller (ADF) and Phillips-Perron (PP) unit root tests to evaluate the stationarity properties of the time series data. Utilizing both the ADF and PP methodologies ensures analytical robustness in determining the order of integration, thereby confirming that none of the variables are integrated of order higher than 1. Fulfilling this stationarity condition strictly satisfies the fundamental prerequisites required for the execution of the nonlinear autoregressive distributed lag bounds testing procedure.

Primarily, the NARDL bounds method assesses the variables for possible long-run relationships. Equation (4) formulates the estimation of cointegration as follows (Shin et al., 2014)

$$\begin{aligned} \Delta \ln EF_t = & \psi_0 + \psi_1 \ln EF_{t-1} + \psi_2 \ln PLO_{t-1}^+ + \psi_3 \ln PLO_{t-1}^- + \psi_4 \ln IND_{t-1}^+ + \psi_5 \ln IND_{t-1}^- + \\ & \psi_6 \ln TO_{t-1}^+ + \psi_7 \ln TO_{t-1}^- + \sum_{i=1}^k \phi_{1i} \Delta \ln EF_{t-i} + \sum_{i=0}^k \phi_{2i} \Delta \ln PLO_{t-i}^+ + \\ & \sum_{i=0}^k \phi_{3i} \Delta \ln PLO_{t-i}^- + \sum_{i=0}^k \phi_{4i} \Delta \ln IND_{t-i}^+ + \sum_{i=0}^k \phi_{5i} \Delta \ln IND_{t-i}^- + \sum_{i=0}^k \phi_{6i} \Delta \ln TO_{t-i}^+ + \\ & \sum_{i=0}^k \phi_{7i} \Delta \ln TO_{t-i}^- + \mu_t \end{aligned} \tag{4}$$

In Equation (4), the symbol  $\Delta$  represents the first difference operator. The parameter  $\psi_7$  is the constant intercept. The parameters  $\psi_1$  to  $\psi_7$  correspond to the long-run elasticity coefficients, whereas the parameters  $\phi_{1i}$  to  $\phi_{7i}$  represent the short-run dynamic coefficients. The symbol k denotes the optimal lag length determined by the applicable information criterion.

The NARDL bounds approach employs positive and negative shocks to specify cointegration in circumstances of nonlinearity. Cointegration among the indicators is established upon confirming the hypotheses using F-statistics and the critical values of the lower and upper bounds. The specific null and alternative hypotheses are formally defined below, where  $\beta^+$  and  $\beta^-$  represent the generic coefficients for positive and negative shocks (Shin et al., 2014)

- Null hypothesis ( $H_0$ ):  $\beta^+ = \beta^-$
- Alternative hypothesis ( $H_1$ ):  $\beta^+ \neq \beta^-$

Once cointegration is confirmed, further analysis proceeds to estimate the asymmetric impacts in the short and long run. The parameters for the positive and negative partial sums of the estimated variables are defined from Equation (5) to Equation (10):

$$\ln PLO_t^+ = \sum_{i=1}^t \Delta \ln PLO_i^+ = \sum_{i=1}^t \max(\Delta \ln PLO_i, 0) \tag{5}$$

$$\ln PLO_t^- = \sum_{i=1}^t \Delta \ln PLO_i^- = \sum_{i=1}^t \min(\Delta \ln PLO_i, 0) \tag{6}$$

$$IND_t^+ = \sum_{i=1}^t \Delta IND_i^+ = \sum_{i=1}^t \max(\Delta IND_i, 0) \tag{7}$$

$$IND_t^- = \sum_{i=1}^t \Delta IND_i^- = \sum_{i=1}^t \min(\Delta IND_i, 0) \tag{8}$$

$$TO_t^+ = \sum_{i=1}^t \Delta TO_i^+ = \sum_{i=1}^t \max(\Delta TO_i, 0) \tag{9}$$

$$TO_t^- = \sum_{i=1}^t \Delta TO_i^- = \sum_{i=1}^t \min(\Delta TO_i, 0) \tag{10}$$

Here, the index  $i$  denotes the specific observation in the time series up to period  $t$ , capturing the cumulative sums of positive (max) and negative (min) variations.

Nevertheless, it is essential to estimate the short-run impacts. This study expresses the short-run error correction equation in Equation (11):

$$\begin{aligned} \Delta \ln E F_t = & \varphi_0 + \sum_{i=1}^q \varphi_{1i} \Delta \ln E F_{t-i} + \sum_{i=1}^q \varphi_{2i} \Delta \ln PLO_{t-i}^+ + \sum_{i=1}^q \varphi_{3i} \Delta \ln PLO_{t-i}^- + \\ & \sum_{i=1}^q \varphi_{4i} \Delta IND_{t-i}^+ + \sum_{i=1}^q \varphi_{5i} \Delta IND_{t-i}^- + \sum_{i=1}^q \varphi_{6i} \Delta TO_{t-i}^+ + \sum_{i=1}^q \varphi_{7i} \Delta TO_{t-i}^- + \\ & \rho_1 \ln E F_{t-1} + \rho_2 \ln PLO_{t-1}^+ + \rho_3 \ln PLO_{t-1}^- + \rho_4 IND_{t-1}^+ + \rho_5 IND_{t-1}^- + \\ & \rho_6 TO_{t-1}^+ + \rho_7 TO_{t-1}^- + \mu_t \end{aligned} \tag{11}$$

In this error correction model,  $\varphi_0$  is the constant term. The parameters  $\varphi_1$  through  $\varphi_7$  denote the short-term dynamic coefficients. The parameters  $\rho_1$  through  $\rho_7$  capture the long-run multipliers guiding the system back to equilibrium. Finally, the symbol  $q$  indicates the optimal lag length specifically chosen for the short-run dynamics. The dynamic multiplier plots for PLO, IND, and TO are derived after capturing these positive and negative variations to map the adjustment paths toward the long-period ecological footprint.

The analytical procedure begins with stationarity testing using the Augmented Dickey-Fuller (ADF) and Phillips-Perron (PP) tests to ensure that all variables are stationary at the appropriate order of integration. We subsequently apply the bounds test to identify the existence of long-run cointegration among the variables. Once the stationarity and cointegration assumptions are validated, the nonlinear autoregressive distributed lag model estimation is executed to extract the asymmetric coefficients in accordance with the established equations. To identify the best model specifications and

confirm the statistical significance of these asymmetries, we conduct the Wald test for symmetry. Additionally, the directional causal relationships between variables are independently assessed utilizing the Granger Causality test. Finally, the robustness and reliability of the empirical model are rigorously evaluated through a series of residual diagnostic tests. These diagnostic evaluations include the Jarque-Bera test for normality, the Breusch-Pagan test for heteroskedasticity, the Portmanteau test for serial correlation, and the Regression Equation Specification Error Test (Ramsey RESET) to confirm the model's functional form.

## 4. Results and Discussion

### 4.1 Analysis Results

#### 4.1.1 Descriptive statistics and correlation analysis

The discussion begins with a statistical overview, including descriptive statistics and correlation analysis. Table 1 presents the descriptive statistics, highlighting the variability of the key variables over the thirty-year observation period. The lnEF has a mean of 19.576 and a low standard deviation of 0.222, indicating a relatively stable trend in environmental degradation. The lnPLO has a mean of 16.358, while IND and TO have means of 43.072 and 53.494, respectively. Following this, the Pearson correlation matrix in Table 2 reveals the preliminary associations between the variables. The lnPLO has a correlation coefficient of 0.982 with lnEF, indicating a very strong, statistically significant positive relationship at the 1% significance level. Conversely, TO and IND exhibit negative correlations with lnEF, suggesting a complex relationship that warrants further econometric investigation. Overall, these statistical findings provide a sound foundation for subsequent empirical estimation.

**Table 1. Descriptive Statistics**

Variable	Observations	Mean	Standard Deviation	Minimum	Maximum
lnEF	30	19.576	0.222	19.187	19.934
lnPLO	30	16.358	0.878	14.793	17.668
IND	30	43.072	3.026	38.238	48.061
TO	30	53.494	12.200	32.972	96.186

**Notes:** All variables are presented in logarithmic form, except IND and TO, which are in percentage form, respectively.

**Table 2. Pearson Correlation Matrix**

Variable	lnEF	lnPLO	IND	TO
lnEF	1.000			
lnPLO	0.982***	1.000		
IND	-0.222	-0.143	1.000	
TO	-0.597***	-0.579***	0.547***	1.000

**Notes:** \*\*\*  $p < 0.01$ , \*\*  $p < 0.05$ , \*  $p < 0.10$ .

#### 4.1.2 Unit root results

To assess the stationarity of the variables, this study employs several unit root tests, primarily the Augmented Dickey-Fuller and Phillips-Perron tests. The results of these conventional tests, presented in Table 3, show that the variables contain unit roots at their level forms and exhibit mixed integration

orders. However, after first differencing, all variables become strictly stationary. Specifically, lnEF, lnPLO, IND, and TO are strictly stationary in first differences at the 1% significance level. Based on these findings, the study concludes that the variables meet the integration requirements and are well-suited for nonlinear autoregressive distributed lag cointegration analysis.

**Table 3. Augmented Dickey-Fuller and Phillips-Perron Unit Root Tests**

Variable	ADF (Level)	ADF (First Difference)	PP (Level)	PP (First Difference)	Decision
lnEF	-3.498**	-5.275***	-3.135*	-5.354***	I(1)
lnPLO	-2.341	-6.102***	-2.159	-6.663***	I(1)
IND	-1.605	-5.336***	-1.247	-5.503***	I(1)
TO	-3.553**	-8.192***	-3.540**	-8.986***	I(1)

**Notes:** Test statistics are reported with trend specification. \*\*\*  $p < 0.01$ , \*\*  $p < 0.05$ , \*  $p < 0.10$ .

#### 4.1.3 NARDL long and short run results

The results of the nonlinear autoregressive distributed lag model are presented in Table 4, providing valuable insights into the asymmetric impact of the exogenous variables on environmental quality. The findings reveal that lnPLO has a complex effect on the environment. Specifically, a 1 percent positive shock in lnPLO results in a 0.461 percent rise in lnEF in the long run at the 1 percent significance level. This suggests that agricultural expansion adversely impacts environmental quality, likely due to intense land conversion, deforestation, and carbon emissions. Conversely, a 1 percent negative shock in lnPLO corresponds to a 10.773 percent decrease in lnEF in the long run. However, this large coefficient is only weakly significant at the 10 percent level ( $p = 0.062$ ). While the magnitude suggests a potential for ecological recovery when plantation activities contract, the weak statistical significance indicates that this finding should be interpreted with caution rather than as a guarantee of rapid environmental restoration.

**Table 4. Long Run and Short Run Asymmetric Impact on lnEF**

Variable	Coefficient	Standard Error	t-Statistic	P- Value
<b>Panel A: Long Run Coefficients</b>				
lnPLO (+)	0.461***	0.086	5.353	0.001
lnPLO (-)	-10.773*	4.848	-2.222	0.062
IND (+)	-0.026*	0.013	-1.960	0.091
IND (-)	0.017	0.011	1.487	0.180
TO (+)	0.004*	0.002	1.914	0.097
TO (-)	-0.006	0.003	-1.573	0.160
<b>Panel B: Short Run Dynamics and Error Correction Term</b>				
Speed of Adjustment	-1.292***	0.364	-3.550	0.009
Constant	24.794***	6.970	3.560	0.009
<b>Panel C: Model Goodness of Fit</b>				
R-squared	0.914			
Adjusted R-squared	0.670			
F-statistic	3.740**			0.040
Observations	28			

**Notes:** The dependent variable is lnEF. The (+) and (-) denote positive and negative partial sums, respectively. Significance levels: \*\*\*  $p < 0.01$ , \*\*  $p < 0.05$ , \*  $p < 0.10$ .

Regarding IND, the findings show that a 1 percent positive shock results in a minor 0.026 percent reduction in lnEF in the long run, which is only weakly significant at the 10 percent level ( $p =$

0.091). This suggests a preliminary, albeit statistically weak, indication that industrial advancement might contribute to marginal environmental improvements. Meanwhile, TO exerts a subtle pressure on the environment. A 1 percent positive shock in TO increases InEF by a marginal 0.004 percent in the long run ( $p = 0.097$ ). Given the extremely small numerical values and weak significance of the IND and TO coefficients, their impacts should be viewed as indicative rather than definitive. In the short run, the error correction term is highly significant at the 1% level, with a coefficient of -1.292. A coefficient between -2 and -1 indicates an overshooting mechanism in the adjustment process. This signifies that any deviation from the long-run equilibrium is corrected rapidly, but in an oscillatory manner. The system initially overcorrects the disequilibrium before dampening and stabilizing, highlighting the short-term instability and the ecological footprint's high sensitivity to macroeconomic shocks. The model demonstrates an excellent goodness of fit, explaining 91.4 percent of the total variation in InEF.

#### 4.1.4 Diagnostic test and causality results

This study assessed the presence of asymmetries by applying the Wald test to detect nonlinearities in the variables examined. As presented in Table 5 Panel A, the results confirm the existence of significant asymmetries for InPLO in the long run, as well as significant short-run asymmetries for IND and TO. These findings indicate that positive and negative shocks exert differing effects on InEF. The significance of these asymmetric relationships underscores the suitability and strength of using the nonlinear modeling framework.

**Table 5. Wald Test for Asymmetry and Residual Diagnostics**

Test Specification	F-Statistic	P- Value		Conclusion
<b>Panel A: Asymmetry Tests (Wald Test)</b>				
Long Run Asymmetry (InPLO)	4.607*	0.069		Asymmetric
Long Run Asymmetry (IND)	0.155	0.705		Symmetric
Short Run Asymmetry (IND)	4.673*	0.067		Asymmetric
Short Run Asymmetry (TO)	4.956*	0.061		Asymmetric
<b>Panel B: Cointegration Test</b>				
	F-Statistic	Lower Bound I(0)	Upper Bound I(1)	
Bounds Test	4.929**	3.068	4.334	Cointegrated
<b>Panel C: Residual Diagnostics</b>				
Jarque Bera (Normality)	0.065	0.967		Normally distributed
Breusch Pagan (Heteroskedasticity)	0.434	0.509		Homoskedastic
Portmanteau (Serial Correlation, lag 12)	15.560	0.212		No serial correlation
Ramsey RESET (Model Specification)	0.583	0.656		Well specified

**Notes:** Significance levels: \*\*\*  $p < 0.01$ , \*\*  $p < 0.05$ , \*  $p < 0.10$ .

Following the confirmation of asymmetry, it is crucial to establish the presence of a long-run relationship. Panel B of the table presents the results of the nonlinear bounds cointegration test. The estimated F-statistic of 4.929 is statistically significant at the 5% level. This value strictly exceeds the critical upper bound value of 4.334, while the lower bound stands at 3.068. The explicit surpass of the upper critical threshold confirms the existence of a robust long-run cointegrating relationship among InEF, positive and negative shocks of InPLO, IND, and TO. This thoroughly justifies the use of the NARDL model to analyze the long- and short-run impacts.

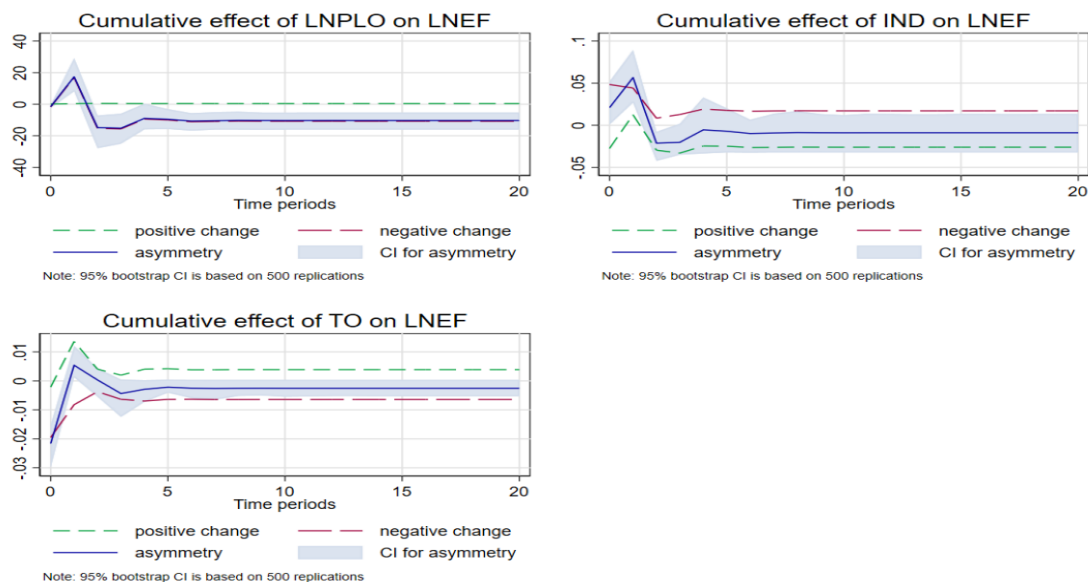
To ensure the robustness, reliability, and correct specification of the estimated model, several diagnostic tests were conducted, with the results summarized in Panel C. The Breusch-Pagan test indicates that the model does not suffer from heteroskedasticity, confirming homoscedasticity of the error variance. Additionally, the Portmanteau test reveals no evidence of serial correlation up to twelve lags, suggesting that the residuals are independently distributed. The Jarque-Bera test indicates that the residuals are normally distributed, with a high p-value of 0.967. Furthermore, the Ramsey RESET test results confirm that the model is correctly specified, with no indication of omitted variable bias.

Lastly, this study investigates the directional causal interactions among the variables using the short-run Granger causality Wald tests. As shown in Table 6, the results reveal a significant unidirectional predictive flow from TO to IND at the 5% significance level. Subsequently, IND exerts a significant unidirectional predictive effect on lnPLO at the 10% significance level. Rather than establishing a deterministic structural causal chain, these findings suggest a temporal precedence where integration with international markets precedes domestic industrial shifts, which in turn precede upstream agricultural adjustments.

**Table 6. Short Run Granger Causality Wald Tests**

Dependent Variable	Excluded Independent Variable	Statistic	Degrees of Freedom	P- Value
IND	TO	7.043**	2	0.030
IND	All Variables (Joint Effect)	14.778**	6	0.022
lnPLO	IND	5.796*	2	0.055
lnPLO	All Variables (Joint Effect)	6.467	6	0.373
lnEF	All Variables (Joint Effect)	2.587	6	0.859

**Notes:** This table highlights the significant causal paths identified in the vector autoregression Granger causality test. Significance levels: \*\*\*  $p < 0.01$ , \*\*  $p < 0.05$ , \*  $p < 0.10$ .



**Figure 1. NARDL Dynamic Multiplier Plot**

Furthermore, the adjustment paths toward this long-run equilibrium are visually captured in the dynamic multiplier plots (Figure 1). These plots illustrate the trajectory of the ecological footprint following positive and negative shocks in palm oil production, industrialization, and trade openness.

The continuous asymmetrical response curves, bounded by the 95 percent confidence intervals, demonstrate that the system experiences initial short-term volatility before gradually dampening and stabilizing. Consistent with the overshooting mechanism identified in the error-correction term, the plots reveal that environmental adjustments to macroeconomic shocks are oscillatory rather than perfectly linear. Notably, the multiplier graph for lnPLO visually confirms that the ecological footprint exhibits a more pronounced and rapid adjustment to contractionary (negative) shocks compared to expansionary (positive) ones, reinforcing the core hypothesis of environmental asymmetry."

## 4.2 Discussion

### 4.2.1 Asymmetric Impacts of Palm Oil Expansion on Environmental Degradation

The empirical evidence establishes a significant asymmetric relationship where positive shocks in palm oil production exacerbate environmental degradation. This finding indicates a structural vulnerability of natural ecosystems to land conversion, suggesting that commercial agricultural expansion often prioritizes economic output over ecological preservation. When production targets are increased to meet market demands, the agricultural frontier is frequently extended into sensitive biomes, causing substantial biodiversity loss and compromising natural carbon sinks. This logical deduction aligns with the reality that corporate-driven land acquisition heavily targets primary forests and peatlands, which ultimately account for a large portion of carbon dioxide emissions in producing countries (Gaveau et al., 2022). Consequently, the expansion leads to notable ecological consequences as natural landscapes are converted to establish monoculture plantations (Xin et al., 2022).

Conversely, the reduction in the ecological footprint following a negative shock suggests a responsive environmental recovery mechanism. However, given the weak statistical significance of this finding, claims of rapid and massive ecological restoration must be moderated. While deliberately alleviating agricultural pressures provides a necessary foundation for ecosystem recovery, it likely requires supplementary active conservation efforts rather than functioning as an automatic, immediate remedy. Shifting the focus from extensive geographical expansion to intensive cultivation on already-degraded lands remains a sound strategy for restoring ecological balance (Ariesca et al., 2023; Gaveau et al., 2022).

### 4.2.2 The Role of Industrialization and Sustainable Waste Management

Although the coefficient on an upward shock in industrialization is numerically small and only weakly significant at the 10 percent level, it provides a preliminary indication that the downstream sector may be exploring eco-efficiency measures. This tentative finding challenges the conventional assumption that manufacturing advancement inherently exacerbates environmental damage in all contexts. While the palm oil milling process traditionally generates substantial pollution through solid waste and liquid effluents (Mukhlis et al., 2025), the observed marginal environmental improvement implies that portions of the manufacturing sector could be gradually shifting toward sustainable frameworks and better waste management protocols to maintain global competitiveness (Rifa'i, 2025).

A gradual transition toward circular-economy practices in some processing facilities may drive this potential technological decoupling. Treating industrial waste as an economic resource, rather than merely an environmental externality, serves as a plausible mechanism for reducing the aggregate footprint. By reintegrating byproducts into the production cycle, the industry can potentially minimize

its reliance on external inputs. For instance, literature indicates that repurposing empty fruit bunches into organic fertilizers can reduce the need for synthetic chemicals and lower their associated carbon emissions (Yusuf et al., 2025). Coupled with emerging zero-waste milling innovations and stricter effluent management, these practices suggest that manufacturing capacity could grow while mitigating aquatic and atmospheric pollution. However, given the weak statistical evidence, these dynamics highlight a potential pathway for sustainable processing rather than definitively proving that industrialization currently acts as an absolute catalyst for environmental improvement (Ming et al., 2024).

#### 4.2.3 Trade Openness, Global Telecoupling, and Policy Interventions

The subtle influence of trade openness on the ecological footprint suggests a potential global telecoupling effect, in which domestic environmental degradation is partially linked to exported burdens. Although the statistical evidence is weakly significant, a positive shock in trade openness slightly increases the ecological footprint, suggesting that international market demand can influence local environmental limits. The predictive sequence identified by the Granger causality test, specifically from trade openness to industrialization and subsequently to palm oil production, indicates a dynamic where foreign consumption patterns temporally precede local land-use changes. This mechanism illustrates the paradigm of global telecoupling (Edwards, 2026), in which environmental costs remain largely localized, whereas consumption benefits are globalized across international supply chains (Purnomo et al., 2025).

Addressing this imported environmental degradation requires a paradigm shift in how producing nations negotiate with the global market. Producing countries cannot bear the cost of conservation alone; global consumers and international frameworks must share the financial burden of sustainability. Achieving this equitable balance requires robust collaborative governance that integrates domestic economic development with rigorous environmental conservation rules (Yuslaini et al., 2026). Empowering smallholder farmers through targeted financial incentives and simplified certification processes is critical to ensure that grassroots actors can participate in this green transition, avoiding policy utopias that burden them with unrealistic compliance costs (Erdi et al., 2026). Ultimately, enforcing zero-deforestation commitments and leveraging digital supply-chain traceability will be imperative to align domestic production with international sustainability standards, ensuring long-term ecological resilience without sacrificing national economic sovereignty (Xin et al., 2022).

## 5. Concluding Remarks and Recommendation

This study empirically establishes the asymmetric impacts of palm oil production, downstream industrialization, and trade openness on Indonesia's ecological footprint using a nonlinear autoregressive distributed lag model. The findings confirm that environmental degradation responds asymmetrically to macroeconomic shocks. Specifically, an upward shock in palm oil production escalates the ecological footprint, whereas a downward shock facilitates environmental recovery, underscoring the sensitivity of natural ecosystems to agricultural dynamics. Furthermore, downstream industrialization exhibits a marginal capability to reduce the ecological footprint over the long run, offering preliminary evidence that industrial eco-efficiency and circular economy practices can partially offset processing externalities. Conversely, trade openness slightly exacerbates environmental

pressures, reflecting a global telecoupling mechanism where international market demand influences domestic environmental carrying capacities.

The methodological value of this research lies in demonstrating that symmetric assumptions may obscure the complex realities of resource extraction and ecological elasticity. From a policy perspective, mitigating trade-driven environmental degradation requires integrated governance. Producing nations must complement industrial advancement with strategic spatial planning, such as enforcing forest moratoriums and facilitating land swaps, while ensuring that smallholder compliance with sustainability standards is financially supported.

This study acknowledges limitations primarily stemming from the reliance on aggregate national data, which may mask localized land-use variations. Future research should pursue landscape-scale studies to quantify indirect land-use alterations and conduct comparative assessments of various certification schemes to foster resilient, multi-stakeholder agricultural governance.

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## Statement of Use of Generative AI

During the preparation of this manuscript, the author(s) used NotebookLM in order to organize the literature. After using this tool, the author(s) thoroughly reviewed, verified, and edited the content as needed, and take full responsibility for the final content and integrity of this publication."

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