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Exploring Indonesia's CO₂ Emissions: The Impact of Agriculture, Economic Growth, Capital and Labor

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Abstract

This study examines the dynamic impact of agriculture, economic growth, capital, and labor on carbon dioxide (CO₂) emissions in Indonesia from 1990-2022. Employing the Autoregressive Distributed Lag (ARDL) method, the findings indicate that agriculture plays a substantial role in decreasing CO₂ emissions in the short and long run. Additionally, a consistent positive correlation exists between economic growth and CO₂ emissions, underscoring the difficulty in decoupling economic progress from its environmental repercussions. Capital formation, on the other hand, exerts a noteworthy negative influence on CO₂ emissions, particularly in the long run, implying that increased investment in capital formation, potentially in environmentally friendly technologies, could contribute to a gradual reduction in emissions. However, the expanding labor is identified as a significant driver of CO₂ emissions, particularly in the long run. Highlighting the challenges associated with mitigating the environmental impact of workforce growth. Furthermore, the Granger causality results indicate unidirectional causality from CO₂ emissions and labor to agriculture, from agriculture to economic growth and capital formation, and from economic growth to capital formation. Therefore, promoting sustainable agriculture, aligning economic growth with green technologies, incentivizing eco-friendly investment, integrating comprehensive planning, and maintaining flexible policies are crucial for Indonesia's effective environmental and economic management.

Introduction

Presently, climate change is a worldwide concern and has garnered significant attention from all nations [1,2]. Carbon dioxide (CO₂) emissions serve as the primary driver of global climate change [3,4]. This phenomenon, commonly referred to as global warming, has a substantial impact on elevating the Earth's temperature on a global scale [5].

Since the 1800s, human activities, particularly the burning of fossil fuels, have been the main driver of climate change. Approximately 12 million hectares of forest are destroyed annually, contributing to a quarter of global greenhouse gas emissions. Deforestation limits nature's ability to absorb CO₂ emissions. In response, United Nations member countries, including Indonesia, have committed to the "Sustainable Development Goals (SDGs)," aiming for sustained, inclusive economic growth while addressing climate change [6].

A country's energy consumption level reflects its industrial development. The higher a country's energy consumption, the greater its economic growth [7]. The impact of CO₂ linkages shows that the development of key CO₂-emitting industries increases total production, as well as the consumption of primary energy and environmental costs. Industries cannot produce goods and services without inputs. If there is no production, there are no emissions. Hence, intermediate

inputs of goods and services and available productive resources—capital, labor, and natural resources—are utilized to produce goods and services [8–10]. As by-products, CO₂ emissions accompany these economic activities, influenced by the fossil fuels used by producers and households [11].

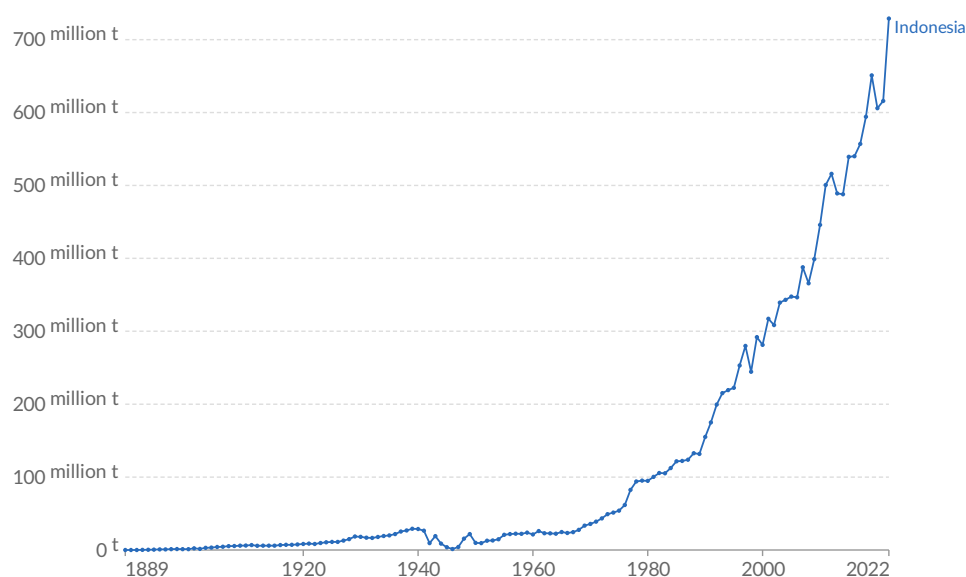


Figure 1. Annual CO₂ emissions trend in Indonesia [12].

Figure 1 shows a significant and steady increase in annual CO₂ emissions in Indonesia, starting from nearly negligible levels in the late 19th century to surpassing 600 million tonnes by 2022. After a period of relatively stable and low emissions, a noticeable uptick begins around the 1960s, accelerating sharply into the 21st century. The trend suggests a rapid industrialization and increase in activities contributing to CO₂ emissions in recent decades.

Companies, vital drivers of GDP, emit CO₂, contributing to climate change [13]. Balancing economic growth with environmental sustainability is crucial. Governments and businesses aim to decouple GDP growth from rising emissions, fostering a shift to greener practices [14,15]. Sustainability not only mitigates environmental impact but also positions companies for long-run success amid eco-conscious consumers. Aligning economic development and climate responsibility is a global challenge, emphasizing the symbiotic relationship between companies, CO₂ emissions, and GDP in shaping a resilient economy [16–22].

Economic growth and human activities have caused an increased concentration of greenhouse gas (GHG) emissions in the atmosphere [23]. It has brought numerous concerns in many countries because CO₂ emissions due to economic activity are relatively high [24]. According to Al-mulali [25], GDP growth and fossil fuel energy consumption are major sources of CO₂ emissions.

One of the current concerns is that the exploitation of natural resources in Indonesia remains highly dominant [26]. The increase in Indonesia's CO₂ emissions is primarily caused by deforestation, with land and forestry being the main contributors [27,28]. Additionally, many land management practices still rely on traditional technology, and there are industries that continue to use fossil fuels [29].

The agriculture sector remains a dominant force in all regions and holds a pivotal role in the economies of many countries, particularly those in the developmental stage [30]. In Indonesia, both the agriculture and manufacturing sectors stand as the cornerstones of the nation's economic framework [23]. Building on this, a comprehensive study conducted by Aydoğan &

Vardar [30] scrutinized the dynamic connections between CO₂ emissions, economic growth, and agriculture in E7 countries from 1990 to 2014. The findings underscore a positive correlation between CO₂ emissions and real GDP, non-renewable energy consumption, and agricultural value added over the long run. Conversely, an inverse relationship is identified between CO₂ emissions and the square of real GDP.

Furthermore, an investigation by Ridzuan et al. [31] delves into the nuanced impact of various agriculture subsectors, including livestock, crops, and fisheries, on CO₂ emissions. Extensive analysis reveals that while livestock demonstrates no discernible impact on CO₂ emissions in the long run, crops and fisheries contribute to a reduction in CO₂ emissions. Notably, economic growth is identified as a factor associated with an increase in CO₂ emissions.

Additionally, the study conducted by Luo et al. [32] focuses on the intricate relationship between CO₂ emissions and the economic growth of agriculture in 30 Chinese provinces from 1997 to 2014. The results highlight that fertilizer, in-season rice cultivation, and cattle are major contributors to CO₂ emissions within the domains of agricultural production activities, farming, and livestock husbandry, respectively. Finally, findings from the research conducted by Prastiyo et al. [23] indicate that GDP plays a role in the overall increase in CO₂ emissions in Indonesia. In contrast, the expansion of the agricultural sector, as indicated by agriculture value added, is correlated with a decrease in the total CO₂ emissions within the country.

The inclusion of Capital and Labor variables as control factors in this research is motivated by their recognized influence on the studied phenomenon, particularly their impact on CO₂ emissions. These variables are integral to understanding the intricate dynamics and nuances that contribute to variations in CO₂ emissions within the context of the research focus. The background provided by previous studies does not offer an extensive analysis of the effects of agriculture, capital, and labor on CO₂ emissions. Hence, this study aims to examine the impact and causal connections between agriculture, economic growth, capital, and labor in relation to CO₂ emissions in Indonesia.

Materials and Methods

Data

This research employs annual data spanning from 1990 to 2022 in Indonesia. The information and data on CO₂ emissions (CO₂), measured in Million Tons, is sourced from the Our World in Data (OWID). Additionally, data on the Labor Force (LF) represented as the total labor in person, Economic Growth (GDP), Agriculture Value Added (AGI), and Gross Fixed Capital Formation (GFCF) were quantified in constant local currency units (LCU) and obtained from the World Development Indicators (WDI). Table 1 provides a comprehensive overview of these variables. To address potential heteroscedasticity concerns, all data underwent a transformation into natural logarithms.

Table 1. Variable Descriptions.

Variable	Logarithms	Objective	Unit	Source
CO ₂ emissions	lnCO ₂	To measure the amount of carbon dioxide released into the atmosphere, serving as a key indicator of environmental impact and climate change contributions.	Million Tons	OWID
Agriculture Value Added	lnAGI	To quantify the contribution of the agricultural sector to the overall economy, reflecting its economic significance and impact on national wealth.	LCU	WDI
Economic Growth	lnGDP	To measure the expansion of a country's overall economic output, reflecting increased prosperity, job opportunities, and improvements in living standard.	LCU	WDI

Variable	Logarithms	Objective	Unit	Source
Gross Fixed Capital Formation	lnGFCF	To gauge the total value of new physical assets created within an economy, serving as a key indicator of investment in infrastructure and productive capacity.	LCU	WDI
Labor Force	lnLF	To quantify the total number of individuals employed or seeking employment within an economy, providing a key measure of workforce size and potential productivity.	Total person	WDI

Empirical model

In this study, we utilize an empirical model inspired by Hardi et al. [33]. We have modified and incorporated it into our own model to investigate the interplay among CO₂ emissions, economic growth, agriculture, capital formation, and labor. To fulfill this objective, we introduce the initial function as expressed in equation 1.

$$CO2_t = f (AGI_t, GDP_t, GFCF_t, LF_t) \quad (1)$$

Where $CO2_t$ represents CO₂ emissions at time t , AGI_t denotes agriculture at time t , GDP_t indicates economic growth at time t , $GFCF_t$ signifies capital formation at time t , and LF_t represents labor at time t . The equation 2 represents an econometric model that incorporates natural logarithmic transformations.

$$\ln CO2_t = \beta_0 + \beta_1 \ln AGI_t + \beta_2 \ln GDP_t + \beta_3 \ln GFCF_t + \beta_4 \ln LF_t + \varepsilon_t \quad (2)$$

Where β_0 serves as the intercept and ε_t represents the error term. Meanwhile, $\beta_1 - \beta_4$ correspond to the specific coefficients. The variable $\ln CO2$, $\ln AGI_t$, $\ln GDP_t$, $\ln GFCF_t$, and $\ln LF_t$ denote the natural logarithmic transformations of CO₂ emissions, agriculture, economic growth, capital formation, and the labor at time t , respectively.

Autoregressive Distributed Lag (ARDL)

In this study, we employ the ARDL model, an econometric methodology designed to examine the short- and long-run impacts among economic variables, which surpass alternative techniques [4,34]. Through the estimation of both enduring and brief impacts, its proficiency in handling limited sample sizes, and its effective resolution of autocorrelation concerns, the ARDL model provides a resilient statistical approach for depicting relationships within economic time series data. As illustrated by equation 3, the ARDL approach serves as a valuable instrument for comprehending the complex dynamics inherent in economic variables.

$$\Delta \ln CO2_t = \beta_0 + \sum_{i=1}^q \beta_1 \Delta \ln CO2_{t-i} + \sum_{i=0}^p \beta_2 \Delta \ln AGI_{t-i} + \sum_{i=0}^p \beta_3 \Delta \ln GDP_{t-i} + \sum_{i=0}^p \beta_4 \Delta \ln GFCF_{t-i} + \sum_{i=0}^p \beta_5 \Delta \ln LF_{t-i} + \delta_1 \ln CO2_{t-1} + \delta_2 \ln AGI_{t-1} + \delta_3 \ln GDP_{t-1} + \delta_4 \ln GFCF_{t-1} + \delta_5 \ln LF_{t-1} + \varepsilon_t \quad (3)$$

Where, i denotes the country and Δ represents the first difference operator. The coefficients $\beta_1 - \beta_5$ coefficients signify the long-run impact, while the $\delta_1 - \delta_5$ coefficients indicate short-run effects. Lastly, q and p indicate the optimum lag length.

Diagnostic Test

Diagnostic tests are essential in econometric modeling, including the ARDL model. They serve multiple purposes, such as evaluating model specification, detecting heteroscedasticity, assessing autocorrelation in residuals, analyzing multicollinearity, examining residual normality, identifying outliers, and checking variable stationarity in time series models like ARDL. These tests also contribute to ensuring parameter stability over time, detecting structural breaks or shifts in relationships. By conducting diagnostic tests, econometricians refine and enhance models, validating assumptions and addressing potential issues, ultimately providing more reliable and robust results for making economic inferences and predictions.

Granger Causality Test

Employing the Granger causality test after ARDL is crucial to determine the direction of influence between variables [35,36]. While ARDL captures relationships, the Granger test adds precision, revealing causality by assessing whether past values of one variable predict the future values of another. This sequential approach enhances the model's interpretability, offering valuable insights into the temporal dynamics and causal mechanisms within economic variables.

Results and Discussion

Descriptive Statistics

Table 2 presents descriptive statistics for all the variables. The average value of CO₂ emissions is 19.70, with a standard deviation of 0.42. The highest recorded CO₂ emissions value is 20.31, and the lowest recorded value is 18.80. The average value of AGI is 34.40, with a standard deviation of 0.30. The maximum and minimum values for this variable are 34.90 and 33.94, respectively. The average value of GDP is 36.30, with a standard deviation of 0.43. The maximum and minimum values for this variable are 37 and 35.60, respectively. The average value of GFCF is 35.11, with a standard deviation of 0.47. The highest and lowest recorded values are 35.84 and 34.40, respectively. The average value of the LF is 18.50, with a standard deviation of 0.17. The highest and lowest recorded values are 18.74 and 18.17, respectively.

Table 2. Descriptive statistics.

	CO2	AGI	GDP	GFCF	LF
Mean	19.6912	34.3930	36.2997	35.1113	18.4941
Median	19.6706	34.3442	36.2395	35.0446	18.4803
Maximum	20.3069	34.9005	36.9993	35.8435	18.7374
Minimum	18.7908	33.9432	35.5755	34.4002	18.1680
Std. Dev.	0.42126	0.3040	0.43203	0.47848	0.17277
Observations	33	33	33	33	33

Unit Root Test

Furthermore, in Table 3, unit root and stationarity tests were conducted for each series using the Augmented Dickey Fuller (ADF) and Phillips-Perron (P-P) tests. Initially performed at levels I(0) and then at the first difference I(1), the ADF test results indicate that CO₂, AGI, GDP, and LF variables exhibit stationarity at a confidence level of 99%, while the GFCF variable shows stationarity at a confidence level of 95%. Similarly, the P-P test results reveal that all variables become stationary at the first difference I(1) with a confidence level of 99%, except for LF, which is stationary both at levels and at the first difference I(1). Since the data are stationary in the first difference, it is assumed that cointegration or a long-run relationship exists. Additionally, we can apply ARDL approach to examine the long-run and short-run impacts. Furthermore, Granger causality will be employed to assess causality directions.

Table 3. Results of unit root test.

Variable	ADF		P-P	
	Level	1 st Diff.	Level	1 st Diff.
CO2	0.2141	0.0000*	0.0864	0.0000*
AGI	0.9835	0.0011*	0.9949	0.0010*
GDP	0.8883	0.0025*	0.8883	0.0032*
GFCF	0.8911	0.0435**	0.8658	0.0059*
LF	0.1332	0.0039*	0.0009*	0.0015*

Note: * and ** indicates 1% and 5%, respectively.

Co-integration Test with Bound Test

The outcomes of the cointegration test, as per the Bound Test approach presented in Table 4, demonstrate a strong indication of cointegration through the ARDL bounds test. This test is employed to evaluate the long-run equilibrium relationship among variables in an ARDL model. The null hypothesis, suggesting the absence of cointegration, faces a challenge from an F-statistic of 7.8943, surpassing the $I(1)$ critical values at all specified significance levels. With four independent variables in the model, the evidence robustly contradicts the null hypothesis, affirming the existence of a cointegration relationship within the dataset.

Table 4. The results of cointegration with ARDL bound test.

F-bounds test		Null Hypothesis: No levels relationship		
Test Statistic	Value	Signif.	I(0)	I(1)
F-statistic	7.8943	At 10%	2.2	3.09
K	4	At 5%	2.56	3.49
		At 2.5%	2.88	3.87
		At 1%	3.29	4.37

Short-run and Long-run Estimations of ARDL Results

The ARDL approach is utilized to estimate both the short-run and long-run impacts of AGI, GDP, GFCF, and LF on CO₂ emissions. The results presented in Table 5 indicate that Agriculture (AGI) has a significant ($\alpha=5\%$) negative effect on CO₂ emissions, both in the short-run and long-run, as shown in Table 4. An increase in agriculture by 1% will reduce CO₂ emissions by 3.94% in the short-run, while in the long-run, a 1% increase in agriculture will result in a 2.51% reduction in CO₂ emissions. In accordance with Prastiyo et al. [23], the growth of the agricultural sector will reduce total carbon emissions in Indonesia. Although rice cultivation is the main emitter, the management of low-emission environmentally friendly rice fields should be feasible.

In contrast, studies from Aydoğan & Vardar [30], Luo et al. [32], and Waheed et al. [37], found that agriculture has a significant and positive impact on CO₂ emissions because agricultural production still use fossil energy, which is a major emitter of CO₂ emission in E7 countries (including Indonesia). Whilst in China, CO₂ emissions from agricultural production activities were estimated from five different sources: diesel, fertilizer, plastic film, pesticides, and irrigation [32].

Table 5. The results of short-run and long-run of ARDL estimations.

Variable	Coefficient	Std. Error	t-Statistic	Prob.
Short-run				
$\Delta\text{CO}_2(-1)$	0.1605	0.1764	0.9098	0.3743
$\Delta\text{CO}_2(-2)$	0.2875	0.1845	1.5578	0.1358
$\Delta\text{CO}_2(-3)$	-0.4510*	0.1476	-3.0559	0.0065
ΔAGI	-3.9354**	1.6188	-2.4311	0.0251
$\Delta\text{AGI}(-1)$	3.6748**	1.5081	2.4367	0.0248
$\Delta\text{AGI}(-2)$	-2.2606*	0.7483	-3.0209	0.0070
ΔGDP	3.2524**	1.2060	2.6969	0.0143
ΔGFCF	-0.4112	0.3922	-1.0483	0.3076
$\Delta\text{GFCF}(-1)$	-0.4488*	0.1262	-3.5551	0.0021
ΔLF	1.1971	0.6944	1.7237	0.1010
Long-run				
AGI	-2.5135**	1.0457	-2.4036	0.0266
GDP	3.2426**	1.3264	2.4447	0.0244
GFCF	-0.8574**	0.4016	-2.1351	0.0460
LF	1.1935***	0.6186	1.9293	0.0688
C	-3.6277	8.5511	-0.4242	0.6762

Note: *, **, and *** indicates 1%, 5% and 10%, respectively.

Furthermore, GDP has a significant ($\alpha=5\%$) positive effect on CO₂ emissions. A 1% increase in GDP will lead to a 3.25% and 3.24% increase in CO₂ emissions in the short run and long run, respectively. These results are consistent with findings from Feriansyah et al. [24], Filimonova et al. [38], Bieth [39], Erdoğan et al. [40], Khan et al. [41], and Sahoo & Sahoo [42], which suggest that an increase in economic growth raises CO₂ emission levels in both the short and long run. Regression results from Prasetyani et al. [43] reveal that the variable GDP per capita has a significant positive effect of 5% on carbon dioxide emissions from solid fuel consumption.

The observed positive correlation between Indonesia's economic growth and CO₂ emissions, both in the short and long run, is likely driven by factors inherent to developing economies. The rapid industrialization associated with GDP growth often leads to increased energy demand, predominantly met by fossil fuels. The expansion of the transportation sector, coupled with growing population and changing consumption patterns, contributes to higher emissions. Additionally, energy-intensive infrastructure development and a limited adoption of clean technologies amplify the environmental impact. The effectiveness of environmental policies in curbing these emissions is crucial for sustainable development. Addressing this correlation necessitates a strategic shift towards cleaner technologies and stringent environmental regulations to mitigate the long-run impact of GDP growth on CO₂ emissions in Indonesia.

Furthermore, GFCF(-1) demonstrates a significant ($\alpha=1\%$) negative impact on CO₂ emissions in the short run. Specifically, a 1% increase in GFCF(-1) results in a 0.45% reduction in CO₂ emissions. Moreover, in the long run, GFCF exhibits a significant ($\alpha=5\%$) negative impact on CO₂ emissions, with a 1% increase in GFCF leading to a 0.86% reduction in CO₂ emissions. These results emphasize the sustained positive influence of capital formation on environmental outcomes. The findings suggest that strategic investments in capital, potentially indicative of adopting cleaner technologies and more efficient processes, play a vital role in curbing CO₂ emissions over time. This alignment of economic growth with environmental responsibility is particularly relevant in the context of Indonesia.

In accordance to Du et al. [44], Zubair et al. [45], Shahbaz et al. [46], and Liu et al. [47], an increase in capital formation will reduce CO₂ emission. This imply that financing clean energy projects with fixed capital enhances clean energy innovation that reduces emissions [45]. Increased capital formation will enhance environmental efficiency in G7 countries [46]. Human activities in capital terms contribute to CO₂ emissions positively but turn negative and persistent over the time horizon [48]. Furthermore, a study conducted by Umar et al. [49], revealed that capital formation does not impact CO₂ emission in Pakistan.

On the other hand, the impact of LF on CO₂ emissions is not significant in the short run. However, it exhibits a significant ($\alpha=10\%$) positive effect in the long run. Hence, a 1% increase in LF will result in a 1.2% increase in CO₂ emissions in the long run. These findings align with Ahmed et al. [50], suggesting that in the long run, a highly educated workforce has a positive impact on CO₂ emissions over time, whereas in the short run, it exerts a large negative influence on CO₂ emissions. Furthermore, a study by Hao et al. [51] indicates that a higher ratio of the labor working in the non-agricultural sector is associated with higher emissions. Conversely, results from Muhammad [52] show that the labor has a significant ($\alpha=1\%$) negative effect on CO₂ emissions in emerging countries. Additionally, findings from Sajid & Gonzalez [8] reveal that both fixed capital and labor induce emissions; however, when compared to fixed capital, labor produces more carbon emissions.

Diagnostic Test

The Table 6 presents the results of diagnostic tests for a statistical regression model, indicating a robust and well-specified model. The Adjusted R-squared value is greater than 0.9857, suggesting a very high proportion of variance in the dependent variable is explained by the model, which is an indication of an excellent fit. The CUSUM and CUSUMQ tests yield a

probability value of less than 0.05, confirming the stability of the model's coefficients over time. The Jarque-Bera test result, with a value of 1.6537 and a probability of 0.4374, indicates that the residuals are normally distributed, as the p-value is above the common threshold for significance. Furthermore, the Breusch-Godfrey LM test shows a high p-value of 0.9255, which implies that there is no serial correlation present in the residuals. The Ramsey RESET test has a p-value of 0.8818, which means that the model is appropriately specified without any bias in linear predictions. Lastly, the Breusch-Pagan-Godfrey test has a p-value of 0.8185, signifying that the residuals have constant variance, hence no heteroscedasticity is detected. Overall, these results collectively suggest that the model is statistically sound, with well-fitted parameters and assumptions holding true, which is ideal for predictive accuracy and reliability in analysis.

Table 6. Diagnostic test results.

Diagnostic tests	Coeff.	Prob.	Conclusions
Adjusted R-squared	> 0.9857	-	The model is well fitted
CUSUM and CUSUMQ	-	< 0.05	The model is stable
Jarque-Bera	1.6537	0.4374	Residuals are normally distributed
Breusch-Godfrey LM test	0.0090	0.9255	No serial correlation exists
Ramsey RESET test	0.1508	0.8818	The model is properly specified
Breusch-Pagan-Godfrey test	0.5695	0.8185	No heteroscedasticity exists

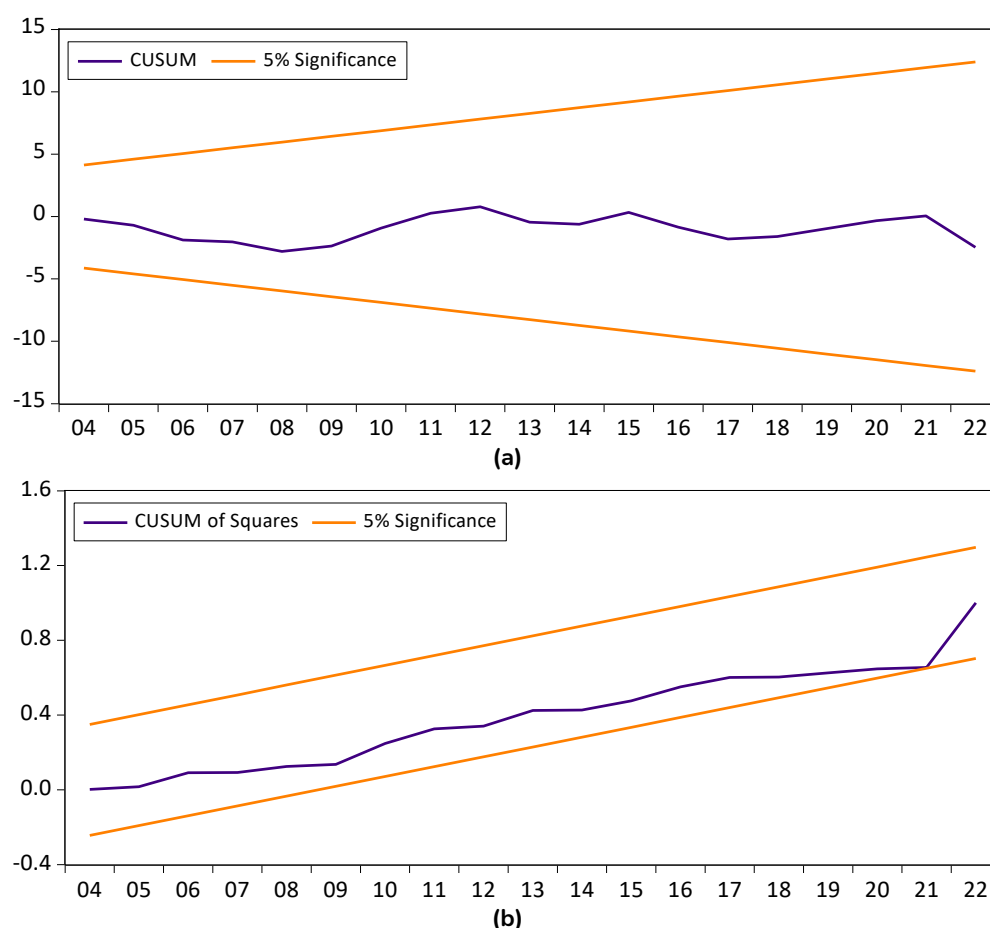


Figure 2. The parameters stability test with CUSUM and CUSUMQ test.

Moreover, the cumulative sum (CUSUM) and the cumulative sum of squares (CUSUMSQ) stability diagnostic test are used to examine the long-run stability test for the ARDL model [53]. The plots displayed in Figure 2 are spotted within the 95% threshold limit and suggest that CO₂ emissions are stable at a 5% critical bound in Indonesia during the 1990-2022 period. In

addition, the CO₂ emissions function reveals the efficiency and consistency of the parameters used in the short and long run as validated by CUSUM and CUSUMQ.

Granger Causality Test

Table 7 provides the results of Granger causality relationship between CO₂ emissions, agriculture, economic growth, capital formation and labor in Indonesia.

Table 7. The results of pairwise Granger causality test.

Null Hypothesis	F-Stat.	Prob.
AGI ≠ CO ₂	1.8394	0.1682
CO ₂ ≠ AGI	2.5873**	0.0776
GDP ≠ CO ₂	0.0264	0.9940
CO ₂ ≠ GDP	1.1212	0.3610
GFCF ≠ CO ₂	0.2623	0.8518
CO ₂ ≠ GFCF	1.6214	0.2118
LF ≠ CO ₂	2.2999	0.1041
CO ₂ ≠ LF	1.5042	0.2400
GDP ≠ AGI	0.2800	0.8393
AGI ≠ GDP	3.2153*	0.0416
GFCF ≠ AGI	1.7640	0.1821
AGI ≠ GFCF	2.9091**	0.0562
LF ≠ AGI	4.2582*	0.0157
AGI ≠ LF	0.4948	0.6894
GFCF ≠ GDP	1.9307	0.1528
GDP ≠ GFCF	4.1924*	0.0166
LF ≠ GDP	0.5313	0.6653
GDP ≠ LF	1.4675	0.2495
LF ≠ GFCF	0.6853	0.5702
GFCF ≠ LF	1.1866	0.3367

Note: * and ** indicate 5% and 10%, respectively.

Based on Table 6, it is evident that the estimated coefficients of ARDL in CO₂, AGI, GDP, GFCF, and LF are statistically significant. Furthermore, the results indicate unidirectional causality from CO₂ and LF to AGI, AGI to GDP and GFCF, and from GDP to GFCF. Hence, all these variables could play a significant part in the adjustment process as the system departs from the long-run equilibrium [54]. The overview of unidirectional causality between these variables is displayed in Figure 3.

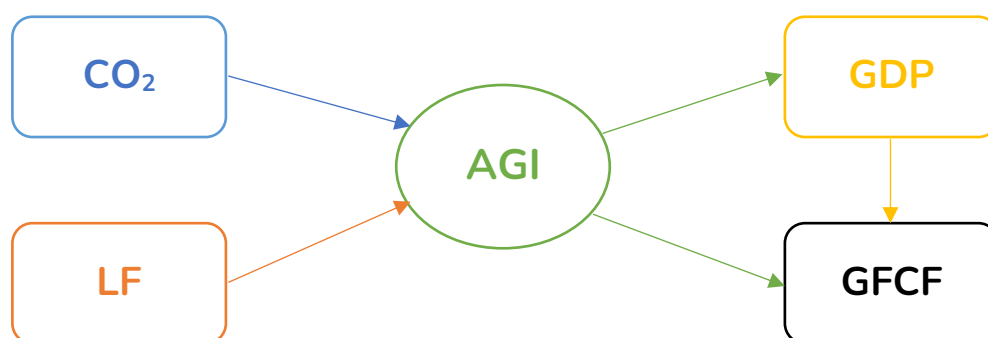


Figure 3. Causality direction.

In conclusion, the Granger causality analysis has provided a comprehensive understanding of the directional relationships among key economic variables. The identified unidirectional causality from CO₂ emissions and labor to agriculture underscores the intricate connections between environmental factors and labor dynamics in shaping agricultural outcomes. This

implies that changes in CO₂ emissions and labor practices may exert a significant influence on agricultural activities.

Moreover, the subsequent unidirectional causal links from agriculture to both GDP and capital formation highlight the pivotal role of the agricultural sector as a driver of broader economic growth and capital accumulation. The findings suggest that fluctuations in agricultural output can have cascading effects on the overall economic performance and the formation of capital within the studied system.

The final link in this causal chain reveals a unidirectional causality from GDP to capital formation. This implies that variations in the overall economic output, as measured by GDP, play a consequential role in shaping the trajectory of capital formation. Understanding this linkage is crucial for policymakers and stakeholders as they seek to formulate strategies that promote sustainable economic development and capital investment.

In essence, the Granger causality results paint a picture of an interconnected economic system where changes in CO₂ emissions and labor practices ripple through agriculture, subsequently influencing both GDP and capital formation. This nuanced understanding of causality patterns contributes valuable insights for policymakers and researchers alike, aiding in the formulation of targeted strategies for economic development, sustainability, and capital formation in the studied context.

Conclusions

The results of the analysis reveal an impact and relationship between economic factors and CO₂ emissions in Indonesia during the period 1990-2022. Agriculture emerges as a significant contributor to reducing CO₂ emissions in both the short run and long run, suggesting its potential role in environmental sustainability. Conversely, economic growth demonstrates a consistent positive association with CO₂ emissions, indicating a challenge in decoupling economic development from environmental impacts. Notably, capital formation exhibits a significant negative impact on CO₂ emissions, particularly in the long run, suggesting that increased investment in capital formation, potentially in environmentally friendly technologies, can contribute to a gradual reduction in CO₂ emissions. However, the expanding labor is found to have a significant positive impact on CO₂ emissions, especially in the long run, pointing to the challenges associated with managing the environmental consequences of workforce growth. Furthermore, the Granger causality results indicate unidirectional causality from CO₂ emissions and labor to agriculture, and from agriculture to GDP and capital formation, with a similar relationship observed from GDP to capital formation.

The analysis reveals significant policy implications for Indonesia's sustainable development. Policymakers should prioritize promoting sustainable agricultural practices and incentivizing environmentally friendly farming. Balancing economic growth with environmental conservation is crucial, requiring the adoption of green technologies, emission reduction targets, and sustainable business practices. Encouraging increased investment in eco-friendly technologies and infrastructure, particularly in response to the negative impact of capital formation on CO₂ emissions, is essential. Addressing the environmental consequences of workforce growth is also imperative, necessitating measures like enhancing energy efficiency and promoting sustainable work practices. The Granger causality results emphasize the need for an integrated approach to environmental and economic planning, while a flexible and adaptive policy framework, regularly monitored and adjusted, is essential to ensuring ongoing success in mitigating the environmental impact of economic growth.

Despite the valuable insights gained, this analysis has certain limitations. The study focused on the period 1990-2022 in Indonesia, and variations over time or in different regions might not be

fully captured. Additionally, the study's scope was confined to a selection of economic factors, and other potentially influential variables could exist. Future studies could expand the temporal and geographical scope, consider a broader array of factors, and delve into specific sectoral analyses. Incorporating more recent data and employing advanced modeling techniques may enhance the precision of predictions. Furthermore, examining the policy implications in real-world contexts and assessing the effectiveness of implemented measures could provide practical insights for policymakers.

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