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Innovating for Sustainability: The Intersection of Technology and Environmental Quality in Indonesia

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ABSTRACT

In this study, we placed significant emphasis on the impact of technology on environmental quality in Indonesia. Technology plays a vital role in the country's progression towards becoming a developed nation; however, it brings both advantages and disadvantages. Indonesia has witnessed substantial economic growth, closely linked to the development and adoption of technology, whether domestically generated or through foreign direct investment (FDI). The primary objective of this study is to investigate the influence of technology and other key macroeconomic variables such as economic growth, FDI, income distribution, globalization, electricity, and urbanization on the level of carbon emissions. The study utilizes annual time series data spanning from 1990 to 2020. The main findings of the study confirm that technology has the potential to reduce environmental pollution levels in the country. However, the impact of other variables on environmental pollution displays a mixed result. Policymakers should pay attention to the significant role of technology and promote government programs that support innovation as a means to address environmental concerns effectively. By doing so, the nation can leverage technology to foster sustainable development and mitigate the adverse impacts of industrialization on the environment.

Keywords: Technology, Environmental Quality, ARDL, Innovation
JEL Classifications: O14, O34, Q01, Q56

1. INTRODUCTION

Carbon dioxide (CO_2) emissions, predominantly from human activities, have become a significant concern due to their detrimental impact on the environment (Shaari et al., 2022a; Shaari et al., 2022b; Shaari et al., 2023; Ridzuan et al., 2018; Rennert et al., 2022; Voumik et al., 2023; Mohamed Yusoff et al. 2023). The excessive release of CO_2 into the Earth's atmosphere is primarily responsible for global warming and climate change. Increased CO_2 levels act as a greenhouse gas, trapping heat within the atmosphere and leading to global warming. This rise in temperatures disrupts weather patterns, resulting in more frequent and severe extreme weather events such as heatwaves, hurricanes, floods, and droughts. These phenomena bring about significant economic losses, property damage, loss of lives, and the displacement of communities. CO_2 emissions also have significant implications for human health (Centers for Disease Control and Prevention, 2022). Rising temperatures and altered weather patterns increase the frequency and intensity of heatwaves, posing a direct threat to human well-being. Heat-related illnesses and deaths are more likely during prolonged periods of extreme heat. Ibrahim et al. (2022) assert that the Earth confronts an urgent and concerning peril in the form of global warming, which presents substantial dangers to human habitation. Global warming denotes a gradual elevation in the Earth's average atmospheric temperature, primarily instigated by the accumulation of greenhouse gases that trap heat. Human activities, including deforestation, agricultural practices, and the combustion of fossil fuels, have played a significant role in augmenting the levels of these gases in the atmosphere (Saliba et al., 2022). Carbon dioxide (CO_2) emerges as the most prominent contributor, accounting for 74.4% of total emissions, trailed by methane (CH4), nitrous oxide (N_2O), and industrial gases, accounting for 17.3%, 6.2%, and 2.1% of total emissions, respectively (Majekodunmi et al., 2023).

In light of the pressing challenges posed by climate change, it is crucial to promptly address the escalating impact on developing nations. The IPAT model that has been widely used by previous studies, such as Mitić et al. (2023), Petra et al. (2020), et al., which serves as a valuable framework to understand the determinants of environmental degradation. The determinants included technology, affluence, and population growth. Population growth plays a significant role in heightened environmental degradation, as exemplified by China, the most populous country and the largest emitter of global CO_2 emissions (Wang et al., 2023). The growth of a nation's population and its level of affluence both influence the extent of environmental degradation, as economic growth often leads to increased energy consumption. Reliance on non-renewable energy sources during periods of economic growth consequently results in elevated CO_2 emissions (Wang et al., 2023). However, several studies included other potential determinants, such as tourism (Shaari et al., 2022), income distribution (Ridzuan et al., 2017), governance (Ridzuan et al., 2019; Pujiati et al., 2023; Handayani et al., 2022) and many more.

Previous studies have commonly used energy consumption as a proxy for technology, but none of them have utilized patents for this purpose. Therefore, this study address this gap and stands as the first to employ patents as a proxy for technology and examine its impact on the environment. While energy consumption is frequently employed as an indicator of technology, patents offer a more direct measure of technological innovation and progress. The justifications for using patents as a proxy for technology are manifold. Firstly, patents reflect the novel ideas, inventions, and technological advancements developed by individuals, organizations, and companies. They serve as indicators of the creation and implementation of new technologies, which directly influence CO_2 emissions. Focusing on patents enables researchers to capture the specific technological innovations that contribute to emission reductions or increased efficiency.

Moreover, patents signify the dissemination and adoption of new technologies across diverse industries and sectors. They denote that a technology has reached a certain level of maturity and commercial viability, enhancing its potential impact on CO_2 emissions. Analyzing patent data enables researchers to comprehend the diffusion of environmentally beneficial technologies and their broader potential for reducing CO_2 emissions. Additionally, patents represent investments in research and development (R&D) efforts. Companies and organizations that patent their technologies dedicate significant resources and funding to their development and deployment. Examining patents allows researchers to gain insights into the areas of R&D that receive attention and investment, thus understanding which technologies are prioritized. While energy consumption is an important factor in CO_2 emissions, it does not capture the entire spectrum of technological innovations contributing to emission reductions. Patents encompass a wide array of technological solutions, including energy-efficient processes, renewable energy technologies, carbon capture and storage methods, transportation advancements, and sustainable agricultural practices. By utilizing patents, researchers can obtain a more comprehensive understanding of the diverse technologies involved in addressing CO_2 emissions. By utilizing patents as a proxy for technology, researchers can acquire valuable insights into the specific innovations and advancements that contribute to reducing CO_2 emissions. This approach facilitates a more focused analysis of technological solutions and deepens our understanding of their impact on mitigating climate change.

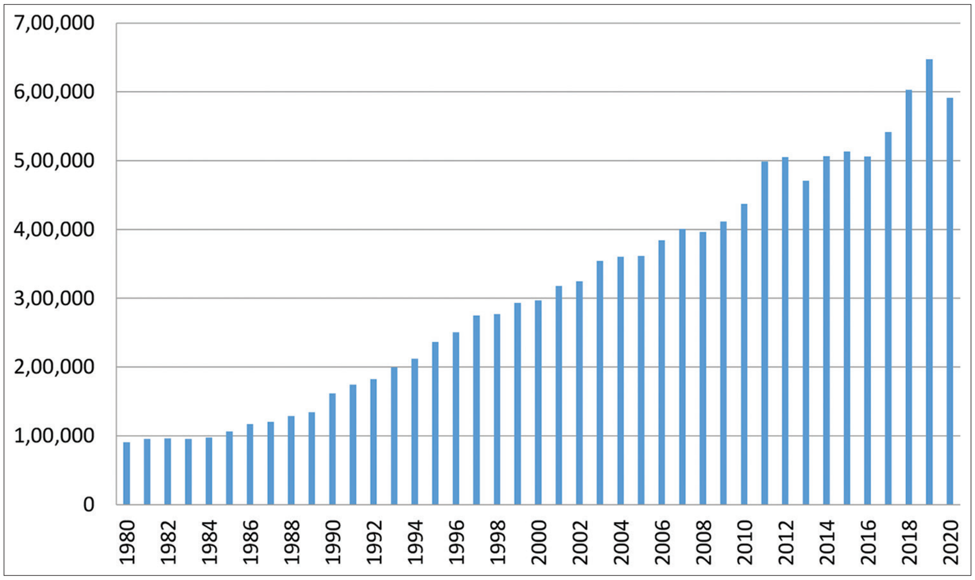
1.1. An Overview of CO_2 Emissions in Indonesia

Figure 1 represents the total CO_2 emissions in Mt in Indonesia from 1980 to 2020. It reveals several trends and patterns that emphasize the significance of studying CO_2 emissions in the country despite a reduction in 2020 due to the COVID-19 pandemic. Firstly, there is an evident increasing trend in CO_2 emissions over the years, with occasional fluctuations. This upward trajectory highlights the growing carbon footprint of Indonesia and underscores the importance of understanding and managing emissions to mitigate climate change. Notably, the rate of growth in CO_2 emissions has accelerated in recent years. While there has been a consistent increase over time, this rapid growth calls for urgent action to curb emissions and transition to more sustainable practices.

Understanding the drivers behind this acceleration is crucial for formulating effective intervention measures. The figure also shows periods of fluctuation, where emissions slightly decrease or remain relatively stable in certain years. These fluctuations may be influenced by various factors, such as economic conditions, energy consumption patterns, government policies, or global events. Analyzing these variations can provide insights into the dynamics of emissions and the effectiveness of intervention measures. The impact of economic development on CO_2 emissions is evident in the data. Indonesia's economic growth and industrialization have contributed to the rise in emissions. As the economy expands, the demand for energy and resources increases, leading to higher emissions. Understanding the relationship between economic development and emissions is essential for formulating strategies that promote sustainable economic growth while minimizing environmental impacts.

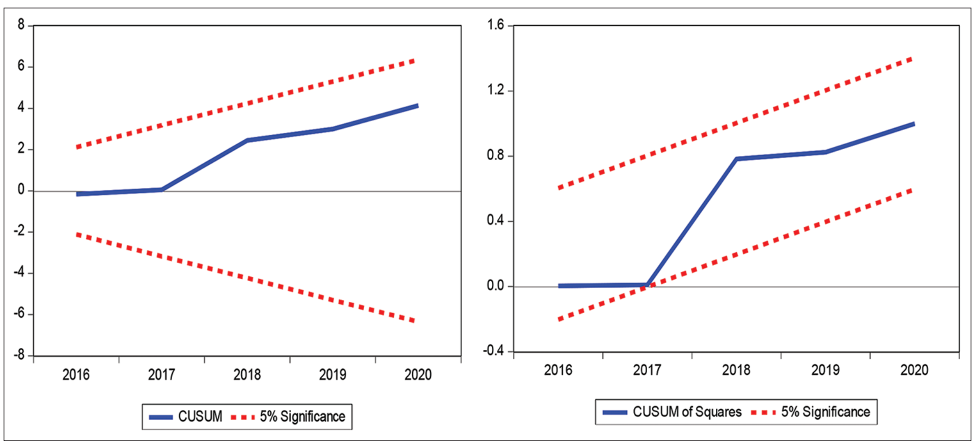
Comparing Indonesia's CO_2 emissions with international standards and agreements, such as the Paris Agreement, is another crucial aspect of studying emissions. Assessing the country's progress in relation to global targets enables policymakers and researchers to identify areas that require further attention. It ensures that Indonesia aligns with international efforts to combat climate change and fulfill

Figure 1: Total CO_2 emissions in Indonesia



Source: Countryeconomy.com

Figure 2: CUSUM and CUSUM SQ



its commitments. Lastly, studying CO_2 emissions in Indonesia helps to address the environmental and health implications associated with high emissions. Such emissions have detrimental effects on ecosystems, air quality, and public health. By gaining insights into the potential impacts, researchers and policymakers can develop effective mitigation and adaptation strategies to protect the environment and promote sustainable development in the country. Therefore, the analysis of CO_2 emissions in Indonesia from the provided table underscores the importance of studying emissions trends and patterns. It reveals the country's significant contribution to global emissions, the accelerating rate of growth, and the associated environmental and health implications. Understanding these aspects is vital for developing strategies to mitigate climate change, promote sustainable development, and align with international efforts to combat global warming (Pujiati et al., 2023).

2. LITERATURE REVIEW

Gross Domestic Product (GDP) is an indicator of welfare and economic growth which is used to make public policies including political policies (Van den Bergh, 2009). An increase in real GDP reflects the ability of the economy to produce more goods and services. In addition, there are two ways to increase GDP which are through increased capital accumulation and technological innovation. Capital accumulation increases the amount of input that goes into the production process while technological innovation is a way to get more output with relatively the same input (Trinh, 2017). In regard to relationship of GDP increase/economic growth and environmental quality, there are two well-known views. Firstly, according to Khalil and Inam (2006), Munir and Ameer (2020), and Stern (2004), an increase in GDP has a positive impact on the environment which is in line with the Environmental Kuznets Curve (EKC) indicating that the early stages of economic growth will be accompanied by an increase in pollution while high income will encourage environmental improvement. Secondly, if an inverted U-shaped EKC is not formed, an increase in GDP and economic growth will continue to make environmental conditions worse over time (Akin, 2014, Munir and Ameer, A, 2020).

In addition, GDP growth is also often associated with equality which is usually measured using the Gini index. The Gini index shows the extent of the income distribution or the distribution of annual disposable income among households in the economy (Farris, 2010; Osberg, 2017). Many studies show that income distribution has a significant effect on environmental quality. Based on the study conducted by Jun et al. (2011), it was found that there was negative relationship between income distribution and environmental quality in China. Their follow-up study in 23 provinces in China using panel data also found that environmental pollution would increase gradually as the income gap widened (Hao et al., 2016). In the ASEAN countries, there are differences in the impact of income distribution on environmental quality. The negative relationship between the Gini Index and environmental quality was only found in Malaysia. Meanwhile in Indonesia and Thailand, there was a positive relationship between Gini index and environmental quality. On the other hand, there was no significant relationship between Gini index and environmental quality in Philippine (Ridzuan et al., 2017).

Foreign Direct Investment (FDI) indicates an inflow of investment that brings additional foreign capital to a country. As a matter of fact, FDI increases environmental degradation which turns local countries into highly polluted area and the increased trades result in increased CO_2 emissions (Abdouli and Hammami, 2017). A study using ecological footprint as an indicator of environmental quality found that globalization, FDI, and urbanization had a positive and significant relationship with environmental quality (Ali et al., 2020). Furthermore, an increase in FDI had a positive and significant effect on CO_2 emissions in the long term, while a decrease in FDI had a negative and insignificant effect on CO_2 emissions (Munir and Ameer, 2020).

In addition, there are two hypotheses regarding the effect of globalization on environmental quality. The first one is the Pollution Haven Hypothesis which states that weak regulations related to the environment in developing countries result in the movement of heavy pollution from developed countries to developing countries (Liu et al., 2020). Moreover, studies in Central and Eastern European Countries from 2005 to 2015 found that increased globalization, including economic globalization, raised carbon emissions (Destek, 2020). The second one is Halo Effects Hypothesis which reveals that developing countries are able to reduce carbon emissions through technology transfer (Liu et al., 2020). Globalization can encourage the inclusion of green technology which can reduce emissions thereby improving environmental quality (Ahmed and Le, 2021).

The use of new techniques, technologies or systems to increase productivity and competitiveness is referred to as innovation. According to Jun et al. (2019), there are three aspects of innovation namely production, processes and systems. Process and system are important variables in increasing the output and efficiency of a company (Yang et al., 2022). Additionally, innovation is regarded as a variable that can drive economic growth. The number of new patents or inventions related to energy consumption and energy conservation can significantly improve environmental quality (Yang et al., 2022).

The environmental impacts of economic growth include increased consumption of electrical energy and higher levels of pollution (Bekun, 2022, Adedoyin et al., 2021). According to Ahmad and Wu (2022), the production and use of electricity as the main energy source put significant pressure on the environment. In fact, industrial electric power, education, communications, health, and entertainment are the heart of the modern economy. Therefore, many regions, especially developing ones, have experienced significant growth in electricity consumption which results in the decrease of environmental quality (Satrovic and Adedoyin, 2022).

Economic development in urban areas causes people to come to the city with various purposes. In urban areas, urbanization is an important element in economic development (Wen et al., 2022). Hence, good urban planning must be prepared for high urbanization rates. As a matter of fact, the high level of urbanization is indicated by the large development of new housing and business areas resulting in a greater increase in energy use (Ridzuan et al., 2022). Thus, unrestricted urbanization can cause serious resource and environmental problems (Cui et al., 2019). The results of the study conducted by (Ali et al., 2019), revealed that urbanization had a positive effect on environmental quality. However, the results of other studies found that urbanization had a negative effect on CO_2 emissions (Li and Nils, 2022) (Fang et al., 2019). In fact, when the level of wealth increases, the level of environmental pollution decreases due to structural changes, technological improvements and environmental regulations (Sadorsky, 2013). In the urban areas, the residents choose to use energy-efficient equipment because it can reduce the cost of using energy; thus, many people switch to using environmentally friendly products that can reduce pollution problems (Ridzuan et al., 2022). The existence of an urbanization process will encourage the accumulation of human capital so as to create people's behavior that cares more about the environment (Zhang and Yan, 2022). On the other hand, the findings of a study conducted by Li and Boqiang (2015) showed that urbanization for middle-income groups does not significantly affect energy consumption.

3. METHODOLOGY

3.1. Data

In this study, the focus is on examining the factors that contribute to environmental quality in Indonesia. Specifically, the potential influence of income distribution, economic growth, foreign direct investment, globalization, innovation, electricity consumption, and urbanization is investigated. To achieve this objective, data spanning from 1990 to 2020 is analyzed, and various statistical tests are employed to validate the data's accuracy. The research adopts the ARDL (Autoregressive Distributed Lag) methodology for cointegration, as proposed by Pesaran et al. in 2001. The variable description is revealed in Table 1 as follow:

3.2. Theoretical Framework and ARDL Model

The model of environmental quality for Indonesia is proposed as follows:

$$CO2_t = f(GINI_t, GDP, FDI_t, GLO_t, TEC_t, ELC_t URB_t) \quad (1)$$

Where

CO_{2t} represents environmental quality,
$GINI_t$ represents income distribution,
GDP_t represents economic growth,

FDI_t represent foreign direct investments inflows,
GLO_t represents globalization,
TEC_t represents technology,
ELC_t represents electricity consumption,
URB_t represents urbanization.

In line with the model introduced in prior research, careful consideration has been given to selecting the variables. However, it is worth mentioning that the set of variables listed in equation 1 is being utilized for the 1st time in the context of Indonesia, as far as our knowledge extends.

In order to estimate the short-run and long-run elasticities, we transform the variables in equation 1 into log-linear forms (LN). This transformation is known to yield consistent and reliable estimations. Hence, we obtain the log version of Equation 1 as follows:

$$LNCO2_t = \delta_0 + \alpha_1 LNGINI_t + \beta_2 LNGDP_t + \sigma_3 LNFDI_t + \phi_4 LNGLO_t + \lambda_5 LNTEC_t + \nu_6 LNELC_t + o_7 LNURB_t + \mu_t \quad (2)$$

$$\begin{aligned}\Delta LNCO2_t = {} & \beta_0 + \theta_0 LNCO2_{t-1} + \theta_1 LNGINI_{t-1} + \theta_2 LNGDP_{t-1} + \\ & \theta_3 LNFDI_{t-1} + \theta_4 LNGLO_{t-1} + \theta_5 LNTEC_{t-1} + \\ & \theta_6 LNELC_{t-1} + \theta_7 LNURB_{t-1} + \sum_{i=1}^{a} \beta_i \Delta LNCO2_{t-i} + \\ & \sum_{i=0}^{b} \gamma_i \Delta LNGINI_{t-i} + \sum_{i=0}^{c} \delta_i \Delta LNGDP_{t-i} + \\ & \sum_{i=0}^{d} \lambda_i \Delta LNFDI_{t-i} + \sum_{i=0}^{e} \vartheta_i \Delta LNGLO_{t-i} + \\ & \sum_{i=0}^{f} \psi_i \Delta LNTEC_{t-i} + \sum_{i=0}^{g} \tau_i \Delta LNELC_{t-i} + \\ & \sum_{i=0}^{h} \vartheta_i \Delta LNURB_{t-i} + \upsilon_t \end{aligned} \quad (3)$$

The subsequent expression represents the ARDL model, incorporating the Unrestricted Error Correction Model (UECM):

Table 1: Variables description

Variable	Symbol	Definition
Carbon emissions	CO_2	CO_2 emissions (metric tons per capita)
Gini coefficient	GINI	Gini coefficient index
Gross domestic product	GDP	GDP per capita (constant 2015 US$)
Foreign direct investment	FDI	Foreign direct investment, net inflows (% of GDP)
Globalization	GLO	Globalization Index
Technology	INV	(Patent applications, nonresidents+Patent applications, residents)/Population
Electricity consumption	ELC	Access to electricity (% of population)
Urbanization	URB	Urbanization

Source: World development indicator (2023)

Equation (3) incorporates the first difference operator (Δ) to capture the short-run effects, while ut represents the white-noise disturbance term. In order for the UECM model to be considered valid, it is essential that its residuals exhibit no serial correlation and that the model remains stable. Diagnostic tests are employed to validate these assumptions, as outlined in the analysis section.

The final version of the model, presented in Equation (3), can also be interpreted as an autoregressive distributed lag (ARDL) model with a specific order (a b c d e f g h i). This model suggests that environmental degradation ($LNCO_2$) is influenced not only by its past values but also by other disturbances or shocks.

To calculate the long-run elasticity, divide the coefficient of the one lagged explanatory variable (multiplied by a negative sign) by the coefficient of the one lagged dependent variable. The short-run effects, on the other hand, are captured by the coefficients of the first differenced variables.

The null hypothesis of no co-integration in the long-run relationship is represented by:

H_0: $\theta_0 = \theta_1 = \theta_2 = \theta_3 = \theta_4 = \theta_5 = \theta_5 = \theta_6 = 0$ (there is no long-run relationship), is tested against the alternative of

H_1: $\theta_0 \neq \theta_1 \neq \theta_2 \neq \theta_3 \neq \theta_4 \neq \theta_5 \neq \theta_6 \neq \theta_7 \neq 0$ (there is a long-run relationship exists),

The model's stability can be verified by employing both the CUSUM and CUSUM SQ tests, as depicted in Figure 2 below. Notably, the blue dotted line falls comfortably within the 5% significance level, delineated by the two dotted red lines. This unequivocally establishes the model's stability over both short and long time horizons.

4. EMPIRICAL RESULTS AND DISCUSSION

In Table 2, we employed the ADF and PP unit root tests to assess the stationarity of all variables. The ADF unit root test indicated that, except for LNGLO, LNTEC, and LNELV, most variables were not significant at the given level. However, at the first difference level, all variables exhibited stationarity except for LNELC. To further enhance the analysis, we also conducted the PP unit root test for all variables, which is a more powerful test. The results of the PP unit root test were similar to those of the ADF test. For $LNCO_2$, LNGLO, LNTEC, and LNELC, there was a mix of stationarity at the level. On the other hand, the remaining variables were not stationary at the level. However, almost all variables were found to be stationary at the first difference level, except for LNELC at the level. Based on the results of these unit root tests, it can be concluded that the data consists of a combination of stationary and non-stationary variables. These findings support the decision to proceed with cointegration analysis using ARDL estimation.

In order to verify the presence of a long-run relationship in the ARDL model, an ARDL cointegration test using the F-statistic was performed. The results of the test, displayed in Table 3,

Table 2: Unit root test results

Variable	ADF unit root test			
	Intercept		Intercept+Trend	
	Level	1st difference	Level	1st difference
$LNCO_2$	−2.001 (0)	−2.692 (1)	−4.333 (1)***	−4.664 (1)***
LNGINI	−1.184 (0)	−2.066 (1)	−4.094 (0)***	−4.029 (0)**
LNGDP	−0.266 (0)	−1.506 (0)	−3.802 (0)***	−3.715 (0)**
LNFDI	−1.900 (0)	−2.854 (3)	−4.860 (0)***	−4.784 (0)***
LNGLO	−2.817 (0)*	−2.328 (0)	−4.391 (0)***	−5.537 (0)***
LNTEC	0.388 (6)	−6.958 (1)***	−4.734 (3)***	−8.308 (1)***
LNELC	−3.098 (0)**	−1.351 (0)	−2.577 (0)	−3.375 (0)*
LNURB	−0.389 (0)	−2.266 (0)	−5.519 (0)***	−5.411 (0)***
Variable	**PP Unit root test**			
	Intercept		Intercept+Trend	
	Level	1st Difference	Level	1st Difference
$LNCO_2$	−4.538 (29)***	−2.997 (15)	−5.456 (7)***	−7.131 (17)***
LNGINI	−1.327 (2)	−1.802 (2)	−4.094 (0)***	−4.029 (0)**
LNGDP	−0.266 (0)	−1.701 (1)	−3.721 (3)***	−3.623 (3)**
LNFDI	−2.095 (2)	−2.172 (1)	−4.860 (0)***	−4.784 (0)***
LNGLO	−2.729 (3)*	−2.453 (3)	−4.371 (3)***	−5.567 (2)***
LNTEC	−2.873 (2)*	−9.969 (18)***	−10.473 (28)***	−14.517 (27)***
LNELC	−2.925 (1)*	−1.451 (1)	−2.546 (1)	−3.375 (0)*
LNURB	−0.340 (3)	−2.348 (1)	−5.593 (4)***	−5.480 (4)***

***, ** and * denote significance at 1%, 5% and 10%, respectively

indicate that the F-statistic for the bound test is 33.380, with a significance level of 1%. This significant F-statistic provides confirmation of the existence of a long-run relationship within the model. Consequently, the null hypothesis is rejected in favor of the alternative hypothesis for the bound test.

The primary findings of the study are presented in Table 4, which provides insights into the long-term relationship between the variables of the proposed model and their impact on environmental quality in Indonesia. Out of the seven variables tested, five were found to be stationary, while the remaining two variables, LNFDI and LNURB, were found to be non-stationary. Consequently, these two variables failed to exert any influence on the level of pollution in Indonesia. The analysis revealed important results regarding the impact of the variables on environmental quality. Specifically, LNGINI, LNTEC, and LNELC were found to have a negative and significant long-term effect on environmental quality, while LNGDP and LNGLO exhibited a positive relationship. More specifically, the study found that a 1% increase in LNGINI, LNTEC, and LNELC leads to decreases in carbon emissions by 2.135%, 0.524%, and 0.525%, respectively. With improved income distribution, more individuals can afford to invest in green technologies and sustainable products. This includes energy-efficient appliances, renewable energy systems, and eco-friendly transportation options. As the demand for these technologies increases, it stimulates innovation and market competition, driving further advancements in environmental technology and contributing to overall environmental improvement. The rise usage of electricity consumption also lead to increase in electricity bill, which end up customer have to pay more due to reduction in subsidies. As electricity usage increases, there is a greater incentive to improve energy efficiency across various sectors by adopting energy-efficient technologies, equipment, and practices, less electricity is needed to achieve the same level of output or service. This reduces the overall demand for electricity and, consequently, the associated carbon emissions from power generation. On the other hand, a 1% increase in LNGDP and LNGLO results in an increase in carbon emissions by 3.284% and 0.940%, respectively. These findings provide valuable insights into the relationship between these variables and their influence on carbon emissions in Indonesia.

The short-run elasticities of the model are outlined in Table 5. The findings reveal that nearly all variables exhibit significance, with the exception of LNGINI and LNELC (1). Upon analyzing the short-run elasticities, we observe a positive and significant relationship between LNGINI, LNGDP, LNGLO, LNELC, and $LNCO_2$. Specifically, a 1% increase in these variables corresponds to a 1.763%, 1.190%, 0.686%, and 1.289% increase in carbon emissions, respectively. Conversely, LNFDI, LNTEC, and LNURB display a negative and significant association with carbon emissions. A 1% increase in these variables leads to a reduction in carbon emissions of 0.056%, 0.158%, and 0.472%, respectively. The negative and significant sign for LNFDI towards $LNCO_2$ is like the previous studies conducted by Pujiati et al. (2023) for Indoensia, however, the differences is it occur for the long run elasticities. Notably, the error correction term (ECT) exhibits a negative and significant relationship, indicating the convergence of all variables examined in the model over the long run. This is an important finding as it suggests that the policy recommendations proposed in this study are practical and reliable.

Following the analysis, several diagnostic tests were conducted to validate the reliability of the model's output. Table 6 provides evidence that the proposed model does not suffer from serial correlation, normality issues, or heteroscedasticity effects in the disturbances. Moreover, the model's specifications were deemed appropriate as indicated by the P-values of all tests, which exceeded the 10% significance level. Passing these diagnostic tests enhances our confidence in the accuracy and validity of the estimated short and long-run elasticities provided by the model.

Table 3: Bound test

Lag model: (2, 2, 1, 2, 2, 2, 2, 2)		
F-statistic	33.380***	Upper bound
Critical value	Lower bound	
10%	2.03	3.13
5%	2.32	3.50
1%	2.96	4.26

*** denotes significance at 1%

Table 4: Long-run estimation results

Variable	Coefficient	Std. error	t-statistic	Prob
LNGINI	−2.135	0.559	−3.814	0.008
LNGDP	3.284	0.583	5.627	0.001
LNFDI	0.009	0.027	0.337	0.747
LNGLO	0.940	0.15	6.225	0.000
LNTEC	−0.524	0.104	−5.023	0.002
LNELC	−0.525	0.241	−2.173	0.072
LNURB	−0.244	0.154	−1.586	0.163
C	−13.359	1.962	−6.808	0.000

***, ** and * denote significance at 1%, 5% and 10%, respectively

Table 5: Short-run estimation results

Variable	Coefficient	Std. error	t-statistic	Probability
D (LNCO$_2$ (−1))	−0.666	0.146	−4.557	0.003
D (LNGINI)	0.130	0.168	0.775	0.467
D (LNGINI(−1))	1.763	0.197	8.925	0.000
D (LNGDP)	1.190	0.252	4.715	0.003
D (LNFDI)	−0.056	0.013	−4.281	0.005
D (LNFDI(−1))	−0.029	0.009	−3.183	0.019
D (LNGLO)	0.686	0.094	7.264	0.000
D (LNGLO(−1))	0.138	0.043	3.162	0.019
D (LNTEC)	−0.158	0.025	−6.275	0.000
D (LNTEC(−1))	0.102	0.020	5.038	0.002
D (LNELC)	1.289	0.209	6.168	0.000
D (LNELC(−1))	−0.247	0.181	−1.363	0.221
D (LNURB)	−0.472	0.127	−3.717	0.009
D (LNURB(−1))	−0.291	0.128	−2.274	0.063
CointEq(−1)	−0.783	0.136	−5.746	0.001

***, ** and * denote significance at 1%, 5% and 10%, respectively

These results indicate that the model's output can be relied upon for making robust conclusions and inferences regarding the relationships between the variables under investigation.

The F-test is a widely employed technique to assess the presence of co-integration in the long-run relationship. If the computed F-statistic is below the critical value of the lower bound, it is not possible to reject the null hypothesis of no co-integration. Conversely, if the calculated F-statistic surpasses the critical value of the upper bound, with a significance level of at least 10%, the null hypothesis of no co-integration is rejected.

5. CONCLUSION AND POLICY RECOMMENDATION

In conclusion, this study examined the influence of technology and various macroeconomic variables on carbon emissions and environmental quality in Indonesia using annual time series data from 1990 to 2020. The findings highlight the potential of technology in reducing environmental pollution levels, while the impact of other variables on environmental pollution was mixed. The study underscores the significant role of technology in addressing environmental concerns and promoting sustainable development. Policymakers should prioritize government programs that support innovation and the adoption of environmentally friendly technologies. By leveraging technology effectively, Indonesia can mitigate the adverse impacts of industrialization and foster a path towards sustainable development.

Table 6: Diagnostic tests results

Test statistic	F-statistic	Probability
Breusch-Godfrey Serial Correlation LM	0.749	0.529
Ramsey RESET stability	2.614	0.166
Heteroscedasticity	0.422	0.935
Jarque-Bera	0.264	0.876

To achieve this, the involvement of government and private agencies in advancing science and technology, development, study, application, and innovation is crucial. Technological innovations such as efficient and affordable wastewater treatment plants, air quality improvement measures, and environmental restoration technologies are essential in preserving the environment and reducing pollution. Universities should make environmental conservation a leading research theme and encourage innovations that contribute to pollution reduction and improved environmental quality. Industries, as major contributors to environmental pollution, should be encouraged to conduct research and development for the production and utilization of environmentally friendly technologies. Additionally, the government should focus on green development through well-planned urbanization, prioritizing environmentally friendly and energy-efficient infrastructure to minimize ecological footprints, reduce pollution, and promote sustainable urban living. Furthermore, promoting equal income distribution is another solution to reduce pollution. By reducing disparities, income redistribution can alleviate environmental burdens that disproportionately affect marginalized communities. This aligns with the Indonesian government's target of eradicating extreme poverty by 2024 through improving human resource quality and expanding employment opportunities to increase household incomes and lift them above the poverty line. By implementing these strategies and embracing sustainable practices, Indonesia can enhance its environmental quality and achieve a more sustainable and equitable future.

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