

Do Fisheries Production, Renewable Energy, and Economic Growth Affect CO₂ Emissions? Evidence from Indonesia

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Abstract

This study aims to examine the impact of blue economy activities, proxied by fisheries production, and on environmental quality, as measured by carbon dioxide (CO₂) emissions within the Environemntak Kuzents Curve (EKC) framework in Indonesia, while controlling for the role of fossil and renewable energy, using annual data from 1990 to 2023 sourced from the World Bank. To capture both dynamic and heterogeneous effects, the analysis employs the Autoregressive Distributed Lag (ARDL)-bounds testing and quantile regression techniques. The findings denote that fisheries production is negatively associated with CO₂ emissions in both the short and long run. Notably, 1% increase in fisheries production leads to a -0.08% decrease in CO₂ emissions per capita. The quantile regression results further indicate that this beneficial effect is significant, with a relatively stronger marginal effect observed at the lower (0.25) quantile. The EKC hypothesis is confirmed in both the ARDL and quantile regression models, indicating the presence of an inverted U-shaped nexus between income per capita and CO₂ emissions. Renewable energy consumption is negatively linked with CO₂ emissions, whereas fossil fuel consumption is positively associated with per capita CO₂ emissions. In light of these findings, enhancing renewable energy adoption and implementing sustainable fisheries practices are pivotal policy measures for preserving the environmental benefits of fisheries production and ensuring long-term sustainability.

Keywords: Fisheries; CO₂ emissions; Economic Growth; Renewable Energy.

Introduction

Promoting sustainable development has become a critical challenge for emerging economies such as Indonesia amid escalating climate change pressures and the persistence of environmentally unsustainable production activities (Triyanti et al., 2023). Climate

change constitutes one of the most pressing environmental challenges of the twenty-first century, as rising Greenhouse Gas (GHG) emissions continue to threaten ecological stability, sustainable development, public health, and food security (Saleem et al., 2025). Table 1 indicates that Indonesia exhibited an increasing trend in greenhouse gas (GHG) and carbon dioxide (CO₂) emissions over the period 1990–2023, threatening the achievement of long-term climate targets. Among the major contributors, the food sector accounts for approximately one-quarter of anthropogenic GHG emissions, with animal protein production responsible for nearly half of the emissions generated from food production (Parker et al., 2018).

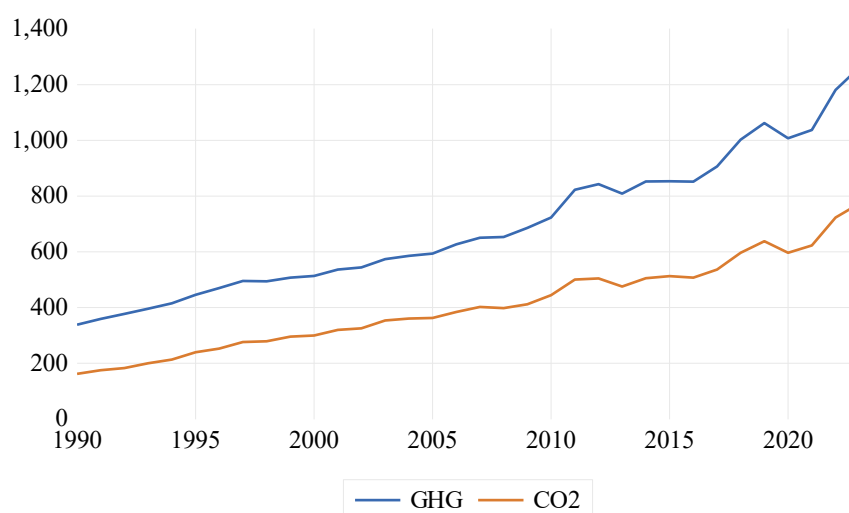


Figure 1. Trends of GHG and CO₂ emissions

Source: World Bank

Within the food-emissions landscape, the marine fisheries sector has emerged as a significant yet chronically underrepresented contributor. The world's fishing fleets consumed an estimated 40 billion litres of fuel in 2011, generating 179 million tonnes of CO₂-equivalent GHGs, representing approximately 4% of global food-production emissions, while average emissions per tonne landed increased by 21% between 1990 and 2011 despite little coinciding growth in production (Parker et al., 2018). Beyond direct fuel combustion, overfishing and habitat degradation have rendered the ocean increasingly vulnerable to climate change, disrupting carbon cycling and reducing the ocean's capacity to function as a critical carbon sink (Andersen et al., 2024). However, the fisheries sector retains considerable potential to contribute to sustainable development via advancements in

production technology, resource management, and institutional governance (Ren et al., 2026).

The Blue Economy has emerged as an increasingly prominent framework in both academic discourse and international policy, broadly referring to the sustainable use of ocean and marine resources for economic growth, improved livelihoods, and the preservation of ocean ecosystem health (Andersen et al., 2024). Since this framework encompasses fisheries, aquaculture, maritime transport, and coastal tourism, its expansion carries substantial negative ecological externalities (Hamaguchi and Thakur, 2024). Harmful fisheries subsidies enable high-emission distant-water fishing, with fuel subsidies constituting 22% of the US\$35.4 billion in global fishing subsidies provided in 2018, whereas incorporating unreported catches increases estimated CO₂ emissions by 41% above reported-landings-based estimates (Andersen et al., 2024; Greer et al., 2019a). A substantial body of literature has documented that fisheries activities contribute to environmental degradation by increasing CO₂ emissions (Badîrcea et al., 2021; Wang et al., 2023)

In addition to the fisheries sector, economic growth is considered to significantly contribute to emissions, as rising income levels are closely associated with greater energy demand, industrial expansion, and increased fossil fuel consumption (Kais & Sami, 2016). These interconnected drivers of CO₂ emissions, encompassing economic activity, population pressure, and technological conditions, are explicitly captured within the Stochastic Impacts by Regressions on Population, Affluence, and Technology (STIRPAT) model (Raza & Tang, 2024). The STIRPAT model has been widely used to empirically investigate the contributions of population, affluence, and technology to environmental degradation (Elsherif, 2024a; Nasrollahi et al., 2020).

Based on the Environmental Kuznets Curve (EKC) hypothesis, the linkage between income and emissions is not monotonically increasing. Instead, there is a potential non-linear association following an inverted U-shaped pattern (Ben Jebli et al., 2022). Environmental quality initially deteriorates as income increases, but subsequently improves after surpassing a certain income threshold, as economies transition toward cleaner production methods, stricter environmental regulations, and greater public demand for

environmental quality (Kais & Sami, 2016). A prior study by Sugiawan & Managi (2016) confirmed the presence of the EKC hypothesis in Indonesia with the income turning point of USD 7,729 GDP per capita. Nonetheless, Parker et al. (2018) documented rising fishery emissions intensity during a period of economic growth, inconsistent with the EKC at the sectoral level. By contrast, Suryanto et al. (2025a) reported EKC consistent patterns in Indonesia's fisheries sector following targeted management interventions. These mixed findings underscore the need for country-specific empirical investigations.

In this regard, the transition toward renewable energy has attracted growing scholarly attention as a principal mechanism through which economies can simultaneously sustain growth and curtail emissions. The theoretical rationale rests on fossil fuel substitution through renewable energy utilization, which additionally promotes energy structure transformation, industrial upgrading, and reductions in carbon intensity through resource substitution and circular economy pathways (Lian et al., 2024). Empirical evidence generally supports a negative long-run nexus between renewable energy consumption and CO₂ emissions. For instance, studies across Economic Co-operation and Development (OECD) countries and China showed that clean energy utilization reduces emissions through energy structure optimization and green technological advancement (Akan et al., 2024; Xiao et al., 2024). Similarly, Ridzuan et al. (2020) reported a negative association between clean energy consumption and CO₂ emissions, supporting the benefit of the energy transition in fostering sustainable economic growth.

Against the background outlined above, the research objectives are proposed as follows: (i) to examine the dynamic short-run and long-run relationships between fisheries production and CO₂ emissions Indonesia; (ii) to test the validity of the EKC hypothesis by analyzing the non-linear nexus between income per capita and CO₂ emissions; (iii) to evaluate the role of renewable energy consumption in decoupling economic and fisheries-driven growth from CO₂ emissions; and (iv) to estimate the heterogeneous impacts of fisheries production, GDP per capita, and renewable energy consumption on CO₂ emissions across different points of the conditional distribution.

Regarding the research contribution, this study offers empirical and methodological novelties. It augments the EKC framework by incorporating the fisheries sector, an aspect that has received limited attention in the Indonesian context. This approach helps to unravel the impact of fisheries production on emissions. Multiple econometric techniques are employed to provide more nuanced insights. Specifically, the Autoregressive Distributed Lag (ARDL)-Bounds testing is employed to examine the dynamic long-run relationship. Its main advantage lies in its ability to estimate both short-run and long-run cointegration parameters, as well as its appropriateness in small samples and mixed orders of integration (I(0) and I(1)). In addition, quantile regression is incorporated to examine the potential heterogeneous impacts of fisheries production, income, and renewable energy consumption across different points of the conditional distribution of CO₂ emissions.

Literature Review

The drivers of environmental degradation have been analyzed through various theoretical lenses in the environmental economics literature, among which the STRIPAT model and EKC hypothesis serve as the two most foundational frameworks (Dietz & Rosa, 1994; Grossman & Krueger, 1991). The origins of the STRIPAT model can be traced to the IPAT identity introduced by Ehrlich & Holdren (1971), which demonstrated that environmental impact (I) is a multiplicative function of population (P), affluence (A), and technology (T).

$$I = P \times A \times T \quad (1)$$

Despite its intuitive appeal, the original IPAT identity was constrained by its deterministic and proportional structure, which precluded formal statistical hypothesis testing (York et al., 2003). To overcome these limitations, Dietz & Rosa (1994) reformulated IPAT into a stochastic framework, the STRIPAT model.

$$I = a \times P^b \times A^c \times T^d \times e \quad (2)$$

Logarithmic form:

$$\ln I = \alpha + b \ln P + c \ln A + d \ln T + e \quad (3)$$

where b , c , and d denote the ecological elasticities of each driver, and ε is the stochastic error term. Both P and A are expected to have a positive impact on I ($b > 0$ and $c > 0$), while T is expected to have a negative impact on I ($d < 0$).

While the STRIPAT model posits the linear association, the EKC hypothesis was subsequently developed to examine the potential non-linear relationship between affluence and environmental degradation such as CO₂ emissions (Grossman & Krueger, 1991; Panayotou, 1993). The EKC hypothesis posits an inverted U-shaped linkage between income and environmental degradation (Leal & Marques, 2022). The underlying mechanism operates through three sequential phases: in early industrialization, the scale effect dominates as economies prioritize output over ecological quality, driving emissions upward with income growth (Kaika & Zervas, 2013); at an intermediate income threshold, structural transformation toward services, rising environmental preferences, and strengthened regulatory capacity produce a turning point (Leal & Marques, 2022); and beyond this point, the technological effect takes over, whereby further income growth coincides with declining emissions (Kaika & Zervas, 2013). Figure 2 illustrates the linkage between income per capita (Y) and CO₂ emissions under the EKC hypothesis.

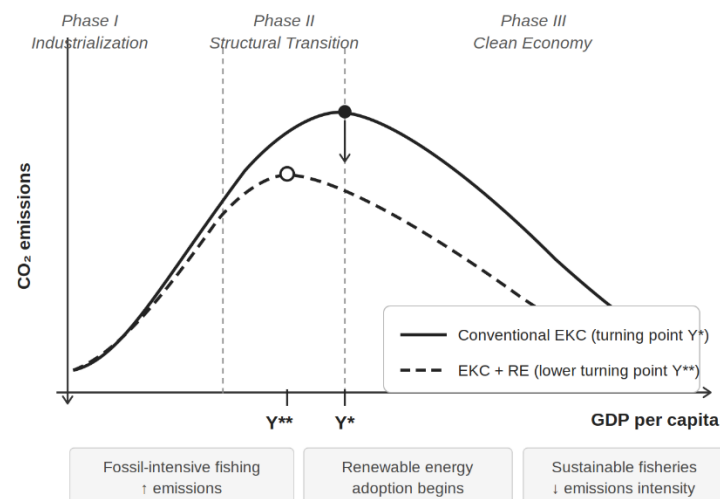


Figure 2. Illustration of the EKC hypothesis

The general EKC model is specified as Eq. 4:

$$\ln E = a + \beta_1 \ln Y + \beta_2 \ln Y^2 + \beta_3 x + \varepsilon \quad (4)$$

where E represents indicators of environmental degradation (e.g., CO₂ emissions); Y and Y² are income per capita and its square term, respectively; and x denotes additional explanatory variables that may influence emissions, such as energy consumption. ε is an idiosyncratic error term. The EKC hypothesis will be confirmed if the coefficient on Y is positive ($\beta_1 > 0$) while the coefficient on Y² is negative ($\beta_2 < 0$).

The presence of the EKC hypothesis remains contested, varying across country contexts and estimation methods. Prior studies in the case of Indonesia confirm the existence of an EKC pattern, with CO₂ emissions initially rising alongside GDP growth but declining as income reaches higher levels (R. Li et al., 2024). Contrarily, ARDL-based analysis controlling for fossil and renewable energy found that CO₂ emissions continue to rise alongside income in the long run, casting doubt on the hypothesis and emphasizing the critical role of energy transition policy (Massagony & Budiono, 2023). These divergent findings are consistent with the broader recognition that the EKC hypothesis may take multiple functional forms, inverted-U, U-shaped, or N-shaped, each carrying distinct policy implications (Hashmi et al., 2023). Critically, aggregate-level EKC analyses risk masking heterogeneous sectoral dynamics, given that economic sectors contribute differently to both GDP and CO₂ emissions (Murato et al., 2024).

By employing the ARDL model on annual data from 1971 to 2010, Sugiawan & Managi (2016) validated the inverted U-shape for CO₂ emissions with a turning point at 7,729 USD per capita, a level outside the sample period. Prastiyo et al. (2020) found that GDP per capita is positively linked with CO₂ emissions in both the short and long run, though they also confirmed the EKC with a lower turning point of 2,057 USD per capita. Employing cross-correlation analysis across 158 countries, Almeida et al. (2024) demonstrated that high-income nations have largely decoupled economic growth from CO₂ emissions. Utilizing quantile-on-quantile estimation, Yu et al. (2022) reported that the negative effect of solar energy on CO₂ emissions is strongest at

higher emission quantiles, highlighting the role of income levels in moderating this relationship.

The STIRPAT model and the EKC hypothesis have been widely augmented to incorporate additional variables, such as urbanization, energy intensity, industrial structure, and agriculture (Fan et al., 2006; Nasrollahi et al., 2020). Focusing on the impact of blue economic activities, the linkage between fisheries production and emissions is strongly influenced by fishing methods, fuel types, and management practices. For Malaysia, Ridzuan et al. (2020) reported that the fisheries subsector significantly reduces CO₂ emissions, suggesting that sustainable management and clean technologies can reverse the positive emissions link.

In the case of Indonesia, Suryanto et al. (2025b) found that vessels ≤ 30 Gross Tonnage (GT) emit 530% more CO₂ emissions per unit catch than larger vessels, yet a B30 biodiesel mandate could reduce emissions by 68–84.5% by 2030. Using the ecological footprint as an alternative indicator, Abdunnur (2020) showed that fisheries production in Indonesia significantly rises the ecological footprint, thereby indicating broader environmental pressures beyond carbon emissions. Globally, Greer et al. (2019b) documented that unreported catches increase global fisheries-related emissions by 41%, with small-scale fleets systematically undercounted. These findings underscore that the fisheries–emissions link is highly dependent on fuel mix, vessel technology, and policy interventions such as biodiesel adoption and improved monitoring.

Going further, renewable energy use consistently emerges as a critical moderator capable of decoupling economic growth from CO₂ emissions. For Indonesia, Raihan et al. (2023) estimated that a 1% increase in renewable energy consumption reduces CO₂ emissions by 1.40% in the long run, while technological innovation contributes an additional 0.17% reduction. Using FMOLS and DOLS methods on data from 1965 to 2022, Idroes et al. (2024) found that a 1% rise in renewable energy lowers CO₂ emissions by about 0.16% and simultaneously reduces the ecological footprint, whereas coal and gas significantly increase both. Liu et al. (2017) analyzed four ASEAN countries, including Indonesia, confirmed that renewable energy has a significant negative effect on CO₂ emissions, while non-renewable

energy increases them. Together, these findings confirm that renewable energy serves as a critical moderator capable of reversing the positive link between fisheries production and CO₂ emissions.

Research Methods

Model Specification

This study aims to examine the relationship between fisheries production, renewable energy, and CO₂ emissions within the EKC framework in the case of Indonesia. To mitigate the problem of omitted variable bias (OVB), the impact of fossil fuel consumption is included in the estimation. Therefore, the function form is specified as Eq. 5.

$$CO_2 = f(GDP, GDP^2, FISH, REU, FOS) \quad (5)$$

The empirical model is specified in Eq. 6.

$$CO_2 = \beta_0 + \beta_1 GDP_t + \beta_2 GDP_t^2 + \beta_3 FISH_t + \beta_4 REU_t + \beta_5 FOS_t + \varepsilon_t \quad (6)$$

Log-transformation:

$$\ln CO_{2t} = \beta_0 + \beta_1 \ln Y_t + \beta_2 \ln Y_t^2 + \beta_3 \ln FISH_t + \beta_4 \ln REU_t + \beta_5 \ln FOS_t + \varepsilon_t \quad (7)$$

where CO₂ denotes CO₂ emissions per capita; GDP and GDP² are income per capita and its squared term, respectively. FISH represents total fisheries production. REU and FOS are renewable energy consumption and fossil energy consumption per capita, respectively. β_0 is the constant term. ε is the idiosyncratic error term. $\beta_1 \dots \beta_5$ are parameters to be estimated. Within the EKC framework, the CO₂–income turning point is calculated as:

$$T_{EKC}^* = \exp\left(-\frac{\beta_1}{2\beta_2}\right) \quad (8)$$

Estimation Method

This study employs the ARDL-Bounds testing and quantile regression for the main estimation method. However, it should be noted that testing the order of integration is critical in time-series modeling, as ARDL is not appropriate for variables integrated of order two, $I(2)$. Therefore, the Zivot-Andrews (ZA) unit root test is employed to check the order of integration while allowing for the presence of structural breaks in the series. The general specification of the ZA regression is given as Eq. 9

$$\Delta y_t = \omega + \vartheta t + \theta DU_t(\tau) + \gamma DT_t(\tau) + \lambda y_{t-1} + \sum_{i=1}^p \tau_i \Delta y_{t-1} + e_t \quad (9)$$

where y_t is the variable to be examined; Δ represents the first-difference operator such that $\Delta y_t = y_t - y_{t-1}$. e is assumed to be the white noise error term; ω is the constant term; ϑt is a time trend variable; p indicates the number of lags included; and the break point τ is chosen endogenously by searching over all possible break dates. Hypotheses for the ZA test are proposed as follows:

H_0 : y has a unit root

H_1 : y has no unit root

The H_0 of a non-stationary series must be rejected once the estimated F statistic exceeds the upper Bounds critical value.

The ARDL-Bounds testing is employed to estimate the dynamic relationships among variables, while simultaneously assess the existence of the long-run cointegration (Pesaran et al., 2001). The lag order is specified using the Schwarz Bayesian Information Criterion (SBIC). In accordance with Eq. 6, the ARDL(p) model is specified in Eq. 10.

$$\begin{aligned} \ln CO_{2t} = & \eta_0 + \eta_1 \sum_{i=1}^p \Delta \ln CO_{2t-i} + \eta_2 \sum_{i=0}^p \Delta \ln Y_{t-i} + \eta_3 \sum_{i=0}^p \Delta \ln Y_{t-i}^2 + \eta_4 \sum_{i=0}^p \Delta \ln FISH_{t-i} \\ & + \eta_5 \sum_{i=0}^p \Delta \ln REU_{t-i} + \eta_6 \sum_{i=0}^p \Delta \ln FOS_{t-i} + \vartheta_1 \ln CO_{2t-1} + \vartheta_2 \ln Y_{t-1} \\ & + \vartheta_3 \ln Y_{t-1}^2 + \vartheta_4 \ln FISH_{t-1} + \vartheta_5 \ln REU_{t-1} + \vartheta_6 \ln FOS_{t-1} + \varepsilon_t \end{aligned} \quad (10)$$

The Bounds testing procedure is used to examine whether a cointegrating relationship among the variables. Hypotheses are proposed as follows:

H_0 : $\vartheta_1 = \dots = \vartheta_5 = 0$, there is no cointegration relationship

H_1 : $\vartheta_1 \neq \dots \neq \vartheta_5 \neq 0$, there is cointegration relationship

The H_0 of no level relationship is tested against the alternative hypothesis of a cointegrating relationship. The decision criterion is based on the computed F -statistic, which is compared to the upper critical bound, $I(1)$. Upon confirmation of cointegration, the corresponding error correction model is subsequently specified, as presented in Eq. 11.

$$\ln CO_{2t} = \eta_0 + \eta_1 \sum_{i=1}^p \Delta \ln CO_{2t-i} + \eta_2 \sum_{i=0}^p \Delta \ln Y_{t-i} + \eta_3 \sum_{i=0}^p \Delta \ln Y_{t-i}^2 + \eta_4 \sum_{i=0}^p \Delta \ln FISH_{t-i} + \eta_5 \sum_{i=0}^p \Delta \ln REU_{t-i} + \eta_6 \sum_{i=0}^p \Delta \ln FOS_{t-i} + \varphi ECT_{t-1} + \varepsilon_t \quad (11)$$

where the term φ is the speed of adjustment. The long-run equilibrium relationship is confirmed if φ spans between 0 and -1 . Following the application of ARDL, a set of diagnostic and stability tests will subsequently be conducted to ensure the reliability of the estimated model.

Quantile regression is incorporated in this study to provide a more comprehensive analysis of the heterogeneous effects of the explanatory variables, i.e., GDP per capita, fisheries production, renewable energy use, and fossil fuel consumption, across different points of the conditional distribution of CO₂ emissions per capita. Unlike the conventional mean-based estimators, quantile regression is robust to outliers, as it does not rely on the minimization of squared errors, and it does not require strict distributional assumptions. Accordingly, the general quantile regression model is specified as follows:

$$Q_{\tau}(CO_2|x_t) = \beta(\tau)x_t' \quad (12)$$

Following the empirical model of Eq. 4, an equation for quantile regression model is specified as Eq. 13.

$$Q_{\tau}(CO_2|x_t) = \beta_0(\tau) + \beta_1(\tau) \ln Y_t + \beta_2(\tau) \ln Y_t^2 + \beta_3(\tau) \ln FISH_t + \beta_4(\tau) \ln REU_t + \beta_5(\tau) \ln FOS_t + \varepsilon_t \quad (13)$$

where $Q_{\tau}(CO_2|x_t)$ is the conditional quantile of CO₂ emissions per capita at quantile $\tau \in (0,1)$. The parameter vector $\beta(\tau)$ captures the heterogeneous effects of the explanatory variables across different points of the conditional distribution of CO₂ emissions per capita.

Data

The present study relies on annual time-series data on CO₂ emissions, fisheries production, economic growth, renewable energy use, and fossil fuel consumption, covering the period from 1990 to 2023 for Indonesia. CO₂ emissions per capita are measured in metric tons per capita, excluding emissions from land use, land-use change, and forestry (LULUCF). Economic growth is proxied by GDP per capita (constant 2015 USD), and its

squared term is incorporated to capture potential non-linear effects in line with the EKC hypothesis. Fisheries production is measured by total fisheries output, reflecting the scale of economic activity in the fisheries sector. Renewable energy consumption is proxied by the share of renewable energy in total final energy consumption, indicating the transition toward cleaner energy sources. Fossil fuel consumption is proxied as per capita primary fossil energy consumption (kWh), capturing reliance on carbon-intensive energy sources. To ensure consistency and comparability, all variables are transformed into natural logarithms prior to estimation. This transformation helps stabilize variance, mitigate potential problem of heteroskedasticity, and enables the estimated coefficients to be interpreted as elasticities. The data are sourced from reputable international databases, namely the World Bank and Our World in Data, ensuring reliability and consistency across variables and over time. Table 1 presents a detailed summary of the variable definitions, measurements, and data sources.

Table 1. Variable measurements

Variable	Notation	Unit	Source
CO ₂ emissions per capita	CO2P	Metric tons per capita	World Bank
GDP per capita	GDPP	Constant 2015 USD	World Bank
Fisheries production	FISH	Metric tons	World Bank
Renewable energy consumption	REU	% of total energy consumption	World Bank
Fossil fuel consumption	FOS	kWh per capita	Our World in Data

Results and Discussion

Table 2 jointly present the results of the ZA unit root test. The vast majority variables tested, i.e., CO₂ emissions per capita, GDP per capita, fisheries production, and fossil fuel consumption, are stationary at level after accounting for structural breaks, except for renewable energy. However, renewable energy use becomes stationary only after first differencing. Thus, the variables exhibit a mixed order of integration, namely $I(0)$ and $I(1)$.

Since none of variable are integrated at $I(2)$, these results justify the application of the ARDL bounds testing framework.

Table 2. Unit root test results

	Level			First-difference		
	Statistic	p-value	Breakpoint	Statistic	p-value	Breakpoint
CO ₂	-4.643	0.001	2015	-8.117	0.084	2015
GDP	-7.554	0.000	1998	-5.563	0.002	2000
FISH	-4.404	0.012	2010	-5.175	0.007	2013
REU	-3.515	0.201	2022	-7.267	0.013	2009
FOSP	-6.065	0.001	2015	-6.928	0.012	2013

Table 3 presents the results of the bounds test procedure. The estimated F-statistic (35.169) exceeds the upper bound critical values at all significance levels, leading to the rejection of the H_0 of no cointegration relationship. Hence, there exists a long-run cointegration relationship among CO₂ emissions per capita, GDP per capita, fisheries production, renewable energy consumption, and fossil fuel consumption. Likewise, the estimated t-statistic (-12.656) is more negative than the corresponding critical values, further supporting the stability of the equilibrium relationship. These findings validate the appropriateness of estimating both long-run and short-run ARDL models. Additionally, the ARDL cointegrating series is displayed in Figure 2.

Table 3. Cointegration test results

	Statistic	Significance	t-critical value		F-critical value	
			Lower	Upper	Lower	Upper
F	35.169	10%	-2.57	-3.86	2.08	3.00
t	-12.656	5%	-2.86	-4.19	2.39	3.38
		2.5%	-3.13	-4.46	2.70	3.73
		1%	-3.43	-4.79	3.06	4.15

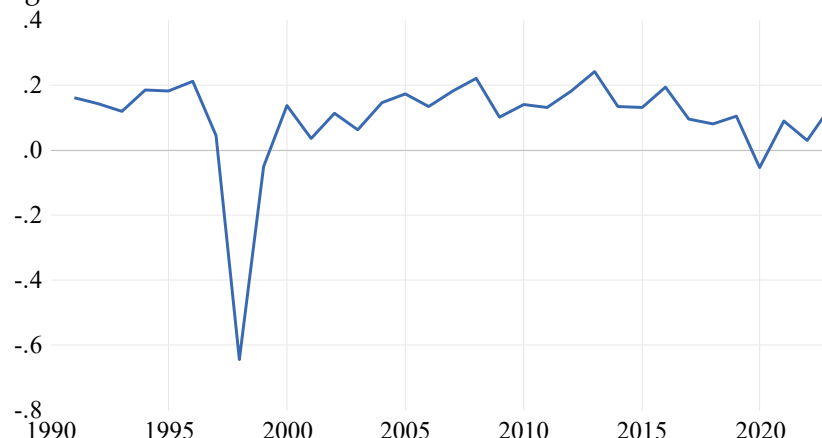


Figure 3. ARDL cointegrating series

Following the bounds testing procedure, Table 4 reports the estimated long-run coefficients of the ARDL model. With a maximum lag length of 1, the Bayesian Information Criterion (BIC) suggests that the selected specification is the ARDL (1,1,0,0,0,0) model. The results indicate that GDP per capita, GDP per capita squared, renewable energy consumption, fisheries production, and fossil fuel consumption have significant long-run effects on CO₂ emissions in Indonesia.

Table 4. Long-run ARDL estimates

	Coeff.	Std. error	t-stat.	p-value
LnGDP	4.5318	1.5450	2.93	0.007
LnGDP ²	-0.2858	0.1013	-2.82	0.009
LnREU	-0.4662	0.0856	-5.45	0.000
LnFISH	-0.0839	0.0237	-3.54	0.002
LnFOS	0.6424	0.0522	12.32	0.000
Cons	-6.6732	6.1579	-1.08	0.289

GDP per capita is positively associated with CO₂ emissions per capita, while its squared term is negatively associated. These findings confirm the presence of the EKC hypothesis in Indonesia. In other words, the relationship between income and CO₂

emissions follows an inverted U-shaped pattern. The damaging effect of economic growth in driving emissions is only in the early stages of economic development. These findings are consistent with prior empirical evidence, including earlier studies by Kais & Sami (2016), Espoir et al. (2023), and Li et al. (2024), which collectively confirm the validity of EKC hypothesis across various country contexts, estimation methods, and income thresholds. This body of evidence suggests that, as economies mature and surpass critical income levels, structural shifts toward cleaner technologies, stricter environmental policies, and greater public awareness tend to decouple economic growth from environmental degradation.

Fisheries production exerts a negative effect on CO₂ emissions per capita. This finding suggests that fisheries-related activities are not a major source of environmental degradation. Instead, it may reflect relatively sustainable production and resource management practices that contribute to lower emission levels. In addition, the fisheries sector in Indonesia may be less dependent on fossil fuels and heavy industrial technologies compared to other economic sectors, which in turn can generate lower carbon intensity. The estimated elasticity indicates that a 1% increase in fisheries production reduces CO₂ emissions by 0.08%. This finding is consistent with previous studies by Alsaleh et al. (2024) and H. Li et al. (2025) which confirmed that sustainable fisheries management contributes to lower emission intensity, as seafood production inherently carries lower carbon emissions compared to other food production sectors and certain aquatic species can even extract carbon from their surrounding environments.

Another result denotes that renewable energy consumption is negatively associated with CO₂ emissions per capita, as expected. This empirical finding confirms that the adoption of clean energy contributes to lower CO₂ emission levels. Following the estimated coefficient, a 1% increase in renewable energy consumption leads to decrease in CO₂ emissions by approximately 0.47% in the long run. This negative relationship in Indonesia aligns with broader international evidence from previous studies by Kongkuah & Alessa (2025), Rahman et al. (2024), and Gür et al. (2025), who consistently confirm that clean energy utilize significantly reduces CO₂ emissions across diverse country contexts, income groups, and estimation methods. This evidence reinforces the view that accelerating the

transition toward clean energy sources constitutes one of the most empirically supported and structurally sound pathways for achieving long-term decarbonization goals.

In contrast, fossil fuel consumption has a positive impact on CO₂ emissions per capita. Based on the estimated coefficients, a 1% increase in fossil fuel consumption increases CO₂ emissions by approximately 0.64%. This finding is consistent with prior empirical evidence from Idroes et al. (2024), Mohamad et al. (2025), and Bimanatya and Widodo (2018) who confirm that fossil fuel consumption, particularly coal and natural gas, remains the dominant driver of CO₂ emissions in Indonesia. This result underscores the urgency of implementing comprehensive energy transition policies to reduce dependence on carbon-intensive energy sources and achieve sustained long-term emission reductions.

Table 5. Short-run ARDL estimates

	Coeff.	Std. error	t-stat.	p-value
ΔLnY	4.1771	1.6284	2.57	0.017
ΔLnY^2	-0.2847	0.1072	-2.66	0.014
ΔLnREU	-0.4644	0.0934	-4.97	0.000
ΔLnFISH	-0.0836	0.0223	-3.76	0.001
ΔLnFOSP	0.6399	0.0669	9.57	0.000
ECT	-0.9961	0.0787	-12.66	0.000

Table 5 presents the estimated parameters of short-run ARDL models. The positive coefficient of ΔLnGDP (4.1771) and the negative coefficient of ΔLnGDP^2 (-0.2847) confirm the presence of a the inverted U-shaped relationship between income and CO₂ emissions, which supports the EKC hypothesis even in the short run. Renewable energy consumption exerts a negative and statistically significant effect on CO₂ emissions, indicating that a 1% increase in clean energy consumption reduces emissions by approximately 0.46%. Similarly, fisheries production negatively affects CO₂ emissions, suggesting that growth in the fisheries sector contributes to lower emission levels, with a 1% increase in fisheries production leads to a 0.08% decrease in CO₂ emissions per capita. In contrast, fossil fuel

consumption significantly increases environmental degradation, as a 1% rise in fossil fuel consumption raises CO₂ emissions per capita by approximately 0.64%. Furthermore, the ECT is negative and statistically significant, confirming the existence of a stable long-run equilibrium relationship among the observed variables. The magnitude of the ECT implies that 99.6% of short-run disequilibrium is corrected within one period, showing a very rapid adjustment process toward long-run equilibrium.

Table 6. Quantile Regression Results

	Q = 0.25		Q = 0.5		Q = 0.75	
	Coeff.	Std. error	Coeff.	Std. error	Coeff.	Std. error
LnGDP	6.924***	1.282	5.364***	1.148	4.226**	1.656
LnGDP ²	-0.444***	0.084	-0.344***	0.075	-0.274**	0.109
LnFISH	-0.108***	0.019	-0.055***	0.017	-0.064**	0.024
LnREU	-0.625***	0.073	-0.514***	0.065	-0.538***	0.094
LnFOS	0.591***	0.045	0.576***	0.041	0.654***	0.059
Cons	-15.376***	5.121	-10.753**	4.588	-4.924	6.615

Note: ***p<1%, **p<5%, and *p<10%, respectively.

Table 6 presents the results of the quantile regression analysis, considering the 0.25, 0.50, and 0.75 quantiles. Regarding the marginal effects, the impact of economic growth on per capita CO₂ emissions varies across different emission levels. However, across all quantiles, GDP per capita consistently exerts a positive and significant effect on per capita CO₂ emissions, while its squared term remains negative and significant, thereby supporting the EKC hypothesis. These findings demonstrate that economic growth initially increases environmental degradation; however, after reaching a certain income threshold, sustained economic growth contributes to lower emission levels. Moreover, the magnitude of the coefficients gradually declines from the lower quantile (q = 0.25) to the upper quantile (q = 0.75), indicating that the impact of income on emissions is stronger at lower emission levels and weakens as emissions increase.

With respect to the remaining variables, fisheries production exhibits a negative and significant effect across all quantiles, indicating that fisheries-related activities contribute to lower per capita CO₂ emissions regardless of the emission distribution. The marginal effect is relatively stronger at the lower quantile, suggesting that the emissions-reducing impact of fisheries production is more pronounced under lower-emission conditions or during the early stages of economic development. At low quantile, a 1% increase in fisheries production leads to a 0.108% decrease in CO₂ emissions per capita while at high quantile, a 1% increase in fisheries production leads a 0.064% decrease in CO₂ emissions

Renewable energy consumption is consistently confirmed to have a critical role in addressing environmental degradation given that it is negatively associated with CO₂ emissions across all quantities. The strongest mitigating effect is observed at the lower quantile (q: 0.25), highlighting the important role of clean energy adoption in promoting environmental sustainability. In contrast, fossil fuel consumption positively and significantly increases CO₂ emissions per capita across all quantiles, with the largest effect occurring at the upper quantile (q: 0.75). This finding suggests that higher-emission conditions are more sensitive to fossil fuel dependence. Overall, the quantile regression results confirm the robustness of the ARDL findings while also revealing heterogeneous effects across different levels of CO₂ emissions.

Conclusion

This empirical study examines the relationship between CO₂ emissions and its determinants, considering the role of economic growth, fisheries production, and renewable energy in Indonesia, as well as controlling the impact of fossil fuel consumption. Using annual data from 1990–2023 obtained from the World Bank and Our World in Data, the empirical model adopts an augmented version of the EKC model. The empirical analysis is conducted using the ARDL bounds testing approach and quantile regression techniques.

The long-run cointegrating relationship exists among CO₂ emissions, GDP per capita, fisheries production, renewable energy consumption, and fossil fuel consumption. The EKC hypothesis is confirmed, indicating the presence of an inverted U-shaped relationship

between income and per capita CO₂ emissions in Indonesia, confirming the potential for decoupling economic growth from environmental degradation. Fisheries production is found to play a beneficial role in accelerating the EKC transition, as it is negatively associated with CO₂ emissions. Similarly, renewable energy consumption is also negatively associated with CO₂ emissions, highlighting the beneficial role of the clean energy transition. In contrast, fossil fuel consumption is confirmed as a key driver of emissions, as it is positively associated with CO₂ emissions.

In light of these empirical findings, it is pivotal for Indonesia to accelerate the transition toward renewable energy and reduce dependence on fossil fuel-based energy generation. This objective can be achieved through stronger investment incentives, clean energy infrastructure expansion, and stricter emissions regulations. Furthermore, the government should strengthen sustainable fisheries production as part of Indonesia's low-carbon development strategy. Given the negative association between fisheries production and emissions, policies aimed at enhancing sustainable fisheries management, improving production efficiency, and promoting environmentally friendly fisheries infrastructure simultaneously support economic growth and environmental sustainability.

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