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N-Shaped or Inverted N-Shaped EKC? The Role of Renewable and Non-Renewable Energy in Environmental Sustainability

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Abstract

Climate change and global warming have become urgent challenges for all nations. Rapid population growth continues to raise energy demand, generating outputs that often create negative externalities and worsen environmental conditions. The Ecological footprint (EFP) and carbon dioxide (CO₂) emissions are key indicators of environmental quality, with higher levels of these indicators generally reflecting a deterioration in environmental conditions. This study examines the effects of economic growth, renewable energy, and non-renewable energy on Indonesia's environmental quality from 1965 to 2023 using the Autoregressive Distributed Lag (ARDL) approach, Granger causality and wavelet coherence analysis. The results reveal Environmental Kuznets Curve (EKC) dynamics, with an N-shaped EKC for the ecological footprint and an inverted N-shaped EKC for CO₂ emissions. Capital formation reduces both EFP and CO₂ emissions, while renewable energy significantly decreases CO₂ emissions. Granger causality analysis shows directional relationships between economic growth, energy use, and environmental quality. Wavelet coherence results indicate strong co-movement between economic growth and non-renewable energy with EFP and CO₂, confirming that fossil-fuel-driven expansion remains the main driver of degradation. In contrast, renewable energy and capital formation show negative coherence with environmental indicators, reflecting their growing role in mitigating ecological stress. Overall, the findings highlight Indonesia's dual challenge of sustaining economic growth while curbing long-term environmental degradation, emphasizing the need for structural reforms, greater investment in renewable energy, and stronger environmental governance to ensure a sustainable development path.



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1. Introduction

This development is theoretically explained by the Environmental Kuznets Curve (EKC) hypothesis, which was initially introduced by Grossman & Krueger [1] to explain the changing relationship between economic growth and environmental quality. It assumes that there is a likelihood of environmental degradation in the early developmental stages when industrialization, urbanization, and energy use grow to facilitate economic development [2, 3]. As the standard of living improves with time, the economies usually experience a transition towards more labor-intensive and technologically developed industries, the application of cleaner methods of production, and the introduction of more stringent environmental policies [4]. These shifts help in slowly reducing the level of pollution, and the relationship between income and environmental degradation takes the shape of an inverted U [5, 6]. Yet, it has been empirically shown that this relationship is not necessarily always stable and monotonic. It often takes a more complicated path, e.g. an N-shaped curve, as early gains are made in environmental quality but then at higher incomes there is again further decline [7–9]. These patterns suggest that economic growth by itself cannot guarantee sustainability of the environment without constant technological advancement, institutional efficiency and uniformity of policy implementation [10]. The EKC framework, therefore, highlights the need to combine economic development with environmental management to attain a sustainable growth path.

Climate change and environmental degradation are still among the global issues of the 21st century [11]. The increased temperature, extreme weather conditions, loss of biodiversity, and the increasing ecological demands stress the narrowness of the balance between growth and sustainability [12, 13]. The need to decouple economic development from environmental degradation is highlighted by such international systems as the Paris Agreement and the Sustainable Development Goals (SDGs) [14–16]. However, it is becoming more challenging to balance this situation with countries trying to maximize production, alleviate poverty, and remain competitive under the pressure of growing environmental restrictions [17, 18]. At the international level, there is rapid population growth, urbanization, industrialization, and an unabated need for energy, which are the greatest causes of environmental degradation [19]. In the world energy consumption, fossil fuels remain the major source of energy, particularly in the developing and emerging economies, which leads to massive emission of greenhouse gases and ecological destruction [20–23]. Moreover, capital accumulation and

investment-based growth, despite their essential roles in the development process, tend to increase environmental stress by promoting the process of industrialization, infrastructure development, and the extraction of natural resources [24–26]. These forces support the difficulty of the sustainability of growth without undermining environmental integrity.

Indonesia provides a good example of a case study in this context. Indonesia is the biggest emerging economy and one of the G20 members, so the process of its economic development has been rapidly growing with the growing environmental pressure [27–29]. The fossil fuel, especially coal, which controls the production of electricity, continues to form a big part of the economy. This has led to an increase in CO₂ emissions and ecological footprint of the country, making Indonesia one of the largest emitters in the world [21, 27, 30, 31]. Ongoing deforestation, depletion of resources, and slow implementation of renewable energy put an additional burden on the quality of the environment [32, 33]. Indonesia, therefore, represents the growth quandary of most of the developing economies, which is how to maintain the growth, but at the same time reduce the environmental cost of the growth.

According to Global Footprint Network (GFN), in 2024, the Indonesian ecological footprint is estimated to be 497 million global hectares (Mha) with a per capita biocapacity of just 1.2 global hectares, which indicates a chronic ecological deficit [34]. This disequilibrium reflects the high rates of the country's economic growth, industrialization, and the high reliance on the economic activities that are resource-consuming. This trend can be further explained by the energy structure, as of 2023, 40.5% of the Indonesian energy mix comes from coal, and only 13.1% of this energy comes from renewable sources, which is short of the national target of 23% renewable energy by 2025 [35]. Even though there are plans like the Comprehensive Investment and Policy Plan (CIPP) and the Electricity Supply Business Plan (RUPTL) that are designed to speed up the transition, fossil fuels still have a hold on the energy production industry. The fact that the government recently proposed to phase out coal between 2050 and 2060, with more plans to keep increasing natural gas output, implies that the shift towards clean energy will not be fast. These circumstances illustrate structural issues with Indonesia in terms of balancing economic growth and environmental sustainability and justify the ever-growing ecological footprint and CO₂ emissions, which support the need to increase the use of renewable energy sources, achieve improvements in energy efficiency, and

invest in the low-carbon technologies that will contribute to the achievement of a net-zero goal by 2060 [35].

This study examines how economic growth, renewable energy, non-renewable energy, and capital formation affect the environmental quality in Indonesia during the 1965-2023 period. This study uses both CO₂ and ecological footprint as complementary measures to capture the multidimensional nature of environmental quality, unlike most of the past studies that only use CO₂ as a measure of the same. In the present research, the long-run and short-run dynamics and the direction of causality between the major variables are analyzed using the Autoregressive Distributed Lag (ARDL) framework, Granger causality, and wavelet coherence analysis. The value-added research is that it determines that Indonesia is in an N-shaped or inverted N-shaped EKC path, and it defines the importance of energy consumption and capital formation in determining the environmental outcomes. By so doing, the study will contribute to the empirical gap in the literature and give policy-relevant information in terms of balancing between economic growth and environmental sustainability.

2. Literature Review

Before addressing the main topic of the EKC, specifically the N-shaped and inverted N-shaped forms, it is important to note two foundational relationships: the U-shaped and the inverted U-shaped. The U-shaped relationship implies that environmental degradation initially declines and then increases with income, whereas the inverted U-shaped relationship suggests that degradation rises during the early stages of development, reaches a turning point, and subsequently decreases as income continues to grow.

The empirical studies of the EKC hypothesis in various economies have led to varying and in some cases contrary conclusions [36]. In developed industrialized countries, the traditional inverted U-shaped EKC, which implies that increasing income levels are followed by cleaner technologies, better energy consumption, and more stringent environmental guidelines and, thus, lower emissions in the long-term, is usually supported by evidence. Conversely, the results of emerging and developing economies are more inclined towards nonlinear forms, such as N-shaped and inverted N-shaped, and the results may indicate that the improvements in the environment obtained in middle-income phases are provisional and reversible at greater economic growth levels.

The following studies report evidence of both U-shaped and inverted U-shaped relationships. Specifically, Pata et al. [37] in India, Caglar et al. [38] in 10 countries with the

worst environmental degradation, Pata & Caglar [39] in China, and Georgescu & Kinnunen [40] in Finland have found a U-shaped correlation in between gross domestic product (GDP) and CO₂ emissions, which suggests that the environment is being continuously degraded even with economic development. On the other hand, an inverted U-shaped relationship was also proven by Mohamed et al. [5] in Malaysia, Danish et al. [41] in Pakistan, Al-mulali et al. [42] in 93 selected countries, Sinha & Shahbaz [43] in India, Dong et al. [44] and Sarkodie et al. [45] in China, Hakkak et al. [46] in Russia, Acaroğlu et al. [47] in Turkey, Wang et al. [48] in 147 countries, Schneiter & Mellon-Bedi [49] in Sweden, Miyan et al. [50] in ASEAN countries which aligns with the conventional EKC model. Such differences between countries highlight that the growth-environment nexus is a very context-dependent phenomenon that is formed by the variation in economic organization, energy structure, institutional quality, and energy policy.

Going to the example of Indonesia, a number of scholars have studied the relationship between economic growth and environmental degradation by applying different econometric models, among which is the ARDL model, which is the most commonly used. Nevertheless, the empirical data are inconclusive. As an example, Massagony & Budiono [20] and Saboori & Sulaiman [51] found that the relationship between GDP and CO₂ emissions has a U-shaped EKC, which shows that environmental degradation accelerates with increasing incomes after a certain decrease. Conversely, according to Adebayo [52], Sugiawan & Managi [53], Saboori et al. [54], Malahayati [32], Elfaki & Heriqbaldi [2] and Udemba & Philip [3], an inverted U-shaped EKC appeared, which indicates that the economic growth of Indonesia ultimately leads to a decrease in emissions above a threshold level. With these contributions, the majority of the existing research has viewed the emission of CO₂ as the only indicator of environmental quality and not the larger aspect of resource utilization and ecological sustainability. Some exceptions are Satrio et al. [55] and Dogan et al. [21], who used the ecological footprint as an alternative proxy and found an inverted U-shaped relationship, meaning that the environmental quality can improve with an increase in income, but only when some policy and structural conditions are met. These contradictory results point to the necessity of a more detailed study that should include several environmental indicators and increase the time interval to reflect the changing nature of the growth-environment relationship in Indonesia. Also requires diving into the N-shaped on the inverted N-shape of the Indonesia study.

Table 1. Evidence of U-shaped and inverted U-shaped EKC in global environmental quality research.

No.	Author(s)	Study Case	Period	Method	EKC Results			
					CO ₂		EFP	
					U-Shape	Inverted U-Shape	U-Shape	Inverted U-Shape
<i>Empirical evidence from global studies</i>								
1.	Mohamed et al. [5]	Malaysia	1985 - 2020	ARDL	-	✓	-	✓
2.	Hasan et al. [6]	BRICS c.	1990 - 2020	FMOLS, DOLS	-	✓ _(↓RE;↑NRE)	-	-
3.	Raghutla et al. [56]	N-11 c.	1998 - 2018	Panel QR	-	-	-	✓ _(↑RE)
4.	Al-mulali et al. [42]	93 c.	1980 - 2008	FEM, GMM	-	✓	-	-
5.	Pata et al. [37]	India	1965 - 2014	RALS	-	-	✓	-
6.	Caglar et al. [38]	10CWED	1995 - 2014	PMG	-	-	✓	-
7.	Jena et al. [36]	T3EA: CIJ	1980 - 2016	ARDL	✓ _(↓RE;↑NRE)	✓ _(↓RE;↑NRE)	✓ _(↓RE;↑NRE)	✓ _(↓RE;↑NRE)
8.	Pata & Caglar [39]	China	1980 - 2016	ARDL	✓	-	✓	-
9.	Danish et al. [41]	Pakistan	1970 - 2012	ARDL-ECM	-	✓ _(↓RE;↑NRE)	-	-
10.	Sinha & Shahbaz [43]	India	1971 - 2015	ARDL	-	✓ _(↓RE)	-	-
11.	Dong et al. [44]	China	1993 - 2016	ARDL, FMOLS, DOLS, VECM GC	-	✓ _(↓RE)	-	-
12.	Sarkodie et al. [45]	China	1961 - 2016	ARDL	-	✓	-	✓
13.	Hakkak et al. [46]	Russia	1992 - 2018	ARDL	-	-	-	✓ _(↓RE)
14.	Khalid et al. [57]	11HIEU c.	1990 - 2022	PMG, ARDL, MMQR, DKSE	-	-	-	✓
15.	Georgescu & Kinnunen [40]	Finland	1990 - 2021	ARDL	-	-	✓	-
16.	Schneider & Mellon-Bedi [49]	Sweden	2015 - 2021	Sem	-	✓ _(Y-3C)	-	-
17.	Acaroğlu et al. [47]	Turkey	1971 - 2015	ARDL	-	✓	-	✓
18.	Wang et al. [48]	147 c.	1995 - 2018	TE	-	✓	-	✓
19.	Miyan et al. [50]	ASEAN-4 e.	2000 - 2020	MMQR, BSQR, D-H GC	-	✓ _(↓RE;↑NRE)	-	-
20.	Simbi et al. [58]	36 AC	1990 - 2020	PMG-ARDL	-	✓ _(↓RE)	-	-
<i>Empirical evidence from Indonesian studies</i>								
1.	Adebayo [52]	Indo.	1980 - 2016	ARDL, WC	-	✓	-	-
2.	Sugiawan & Managi [53]	Indo.	1971 - 2010	ARDL	-	✓	-	-
3.	Saboori et al. [54]	Indo.	1971 - 2007	ARDL	-	✓	-	-
4.	Massagony & Budiono [20]	Indo.	1965 - 2020	ARDL	✓ _(↓RE;↑NRE)	-	-	-
5.	Saboori & Sulaiman [51]	ASEAN (include Indo.)	1971 - 2009	ARDL, VECM, GC	✓	-	-	-
6.	Malahayati [32]	Indo.	1994 - 2018	ECM	-	✓	-	-
7.	Elfaki & Heriqbaldi [2]	Indo.	1983 - 2018	ARDL	-	✓	-	-
8.	Satrio et al. [55]	Indo.	1971 - 2021	ECM	-	-	-	✓
9.	Dogan et al. [21]	MINT c. (include Indo.)	1971 - 2013	ARDL ECM	-	-	-	✓ _(↓RE;↑NRE)
10.	Alam et al. [59]	BCII	1970 - 2012	ARDL	-	✓	-	-
11.	Udemba & Philip [3]	Indo.	1990Q1 - 2018Q4	ARDL	-	✓ _(↓RE)	-	-

Note: ↓RE→Renewable energy reducing emissions; ↑RE→renewable energy increasing emissions; ↑NRE→ non-renewable energy increasing emissions; c.→Countries; BRICS→forum for cooperation among a group of leading emerging economies; ARDL→Autoregressive Distributed Lag; FMOLS→Fully Modified Ordinary Least Squares; DOLS→Dynamic Ordinary Least Squares; N-11→group of eleven high-potential emerging economies; QR→Quantile Regression; FEM→Fixed Effects Model; GMM→Generalized Method of Moments; RALS→Residual Augmented Ordinary Least Squares; CIJ→China, India and Japan; PMG→Pooled Mean Group; 10CWED→10 countries with the worst environmental degradation; T3EA→Top three emitters from Asia; ECM→Error Correction Model; VECM→VECM→Vector Error Correction Model; GC→Granger Causality; MMQR→Method of Moments Quantile Regression; DKSE→Driscoll-Kraay Standard Errors; EU→European Union; HI→High-Income; SEM→Spatial econometric model; TE→Threshold Estimation; ASEAN→Association of Southeast Asian Nations; BSQR→Bootstrap Quantile Regression; D-H→Dumitrescu-Hurlin; AC→African countries WC→Wavelet Coherence; Y-3C→dependent variables are CO, CO₂ and CH₄; MINT→Mexico, Indonesia, Nigeria, and Turkey; BCII→Brazil, China, India and Indonesia; Indo.→Indonesia.

Table 1 shows all the details about EKC relationships that are U-shaped and inverted U-shaped in all studies regarding the environmental quality of the globe.

The conventional U-shaped EKC paradigm offers very useful information about the development of environmental degradation and economic growth, but is too limited in the scale of the complexity involved in the relationship. Though the U-shape and the inverted U-shape patterns define an overall direction of environmental change in the economic development, they tend to ignore various turning points or reversing effects that can be experienced in later stages of development. Nonlinear transitions often characterize many economies, with environmental degradation falling off in the short-term, only to increase back to its former level when industrial activity, energy consumption and resource use increase with a rise in income. This trend can be attributed to the N-shaped or inverted N-shaped EKC that makes a more detailed picture of the environmental quality reaction to the continuous economic and structural change. It is hence important to consider these extended EKC forms in the formulation of a finer interpretation of the growth-environment nexus, especially in emergent economies like Indonesia, where the nexus of rapid industrialization, urbanization, and emerging energy structures still dominates the environmental outcomes.

There have been empirical investigations of these nonlinear dynamics, which have yielded mixed results. As examples, Allard et al. [60], Özokcu & Özdemir [61], and Deng et al. [62] found both N-shaped and inverted N-shaped correlations between GDP and environmental degradation. Equally, the ecological footprint and CO₂ emissions was employed by Tahir et al. [7], Hossain et al. [63], Du et al. [64], Zeraibi et al. [65], Shehzad et al. [66], Gao et al. [67], and Sharma et al. [68] to assess environmental quality and identified N-shaped EKC trends, whereas Abbasi et al. [69], Al Numan et al. [23], Bulut & Tekdemir [70], Sun et al. [71], Aljadani et al. [72], Zhao et al. [73], Qayoom & Altaf [74], Bandyopadhyay & Rej [75], Tsujimoto [76], Bekhet & Othman [77], Minlah et al. [78], Tsiantikoudis et al. [79], Fang et al. [80], Zhu et al. [81] and Sancar et al. [82] identified relationships of inverted N-shaped. All these studies indicate that the shape of the EKC differs with the environmental indicator and the level of economic development of a country. A detailed N-shaped and inverted N-shaped patterns of EKCs in studies of the environmental quality of the planet are gathered in Table 2.

The reviewed empirical literature provides in Table 2 a wide spectrum of economic environments, both at an individual country, a regional level, and an economic bloc

like the OECD and G7, which all have insights that have succeeded in providing insights into the changing of the EKC. All these findings show that the structure and dynamics of the EKC differ considerably depending on the level of development, the structure of the industries, and the structure of the energy mix among the countries. Even though these amounts of global evidence are rising, there is relatively little work done in research on developing economies that focuses on the longer versions of the EKC and the N-shaped and the inverted N-shaped models. This drawback emphasizes the need to use country-specific analyses to capture unique structural and environmental features. In this regard, Indonesia is an interesting case to study in more detail, as its industrial development has a high pace, an energy-related nature, and the environmental problem persists. Very few studies have been conducted on the EKC behavior of Indonesia outside the conventional model, and none of them have at the same time used CO₂ emissions and ecological footprint as two indicators of environmental quality.

Expanding on this, the discussion that follows looks at the reaction of Indonesia towards the connection between the development of the economic growth and environmental degradation, whether the environmental path taken by the country is a transitional stage of growth or a possible relapse in the ecological pressure. One example is Ibrahim & Abbas [83], which analyzed Java Province and found signs of a high level of EKC, in which the correlation between income and emissions took the shape of an N. Their findings indicate that an increase in income causes environmental deterioration to increase at lower levels of income, which later comes to a relief at the middle-income stages, before it gets worse at high levels of development. To add to these results, Malahayati [32] has used ARDL-ECM with FMOLS and DOLS estimates, and also found that, in Indonesia, the N-shaped EKC is present, especially the trends of deforestation and CO₂ emissions. In addition, Zurrah et al. [84] also examined the correlation between economic growth and environmental quality in Indonesia by using the ecological footprint as a proxy, employing the ARDL approach between 1991Q1 and 2014. Their findings just validated the existence of N-shaped EKC, in that the ecological footprint rises with income, and then falls, and then turns up at a higher level of economic growth. Collectively, these issues bring into focus the danger of environmental rebound at its later developmental stages and the importance of decisive action by policymakers. New coal power stations are not to be built in Indonesia, which recently introduced a moratorium on coal-fired power plants and a push to promote renewable energy, which are important signs of

Table 2. Evidence of N-shaped and inverted N-shaped EKC in global environmental quality research.

No.	Author(s)	Study Case	Period	Method	EKC Results			
					CO ₂		EFP	
					N-Shape	Inverted N-Shape	N-Shape	Inverted N-Shape
<i>Empirical evidence from global studies</i>								
1.	Tahir et al. [7]	38 OECD	2000 - 2021	FEM, FGLS, 2SLS, GMM	✓	-	✓	-
2.	Burki & Tahir [85]	ASEAN	2001 - 2020	PLS, FEM, GLS, 2SLS	✓	-	-	-
3.	Hossain et al. [63]	India	1970 - 2018	ARDL	✓	-	-	-
4.	Ullah et al. [8]	17 OECD	2009 - 2019	TSPA	✓	-	-	-
5.	Farooq et al. [86]	India	1971 - 2017	ARDL	-	-	-	✓
6.	Jahanger et al. [87]	TNEPC	1990 - 2018	DCCE	-	-	✓	-
7.	Abbasi et al. [69]	107 c.	1996 - 2014	FEM, REM, DKSE	-	✓ _(↓RE;↑NRE)	-	-
8.	Allard et al. [60]	74 c.	1994 - 2012	PLS, FEM, QR	✓ _(↓RE)	✓ _(↓RE)	-	-
9.	Narcisse et al. [88]	China	2000 - 2019	ARDL	✓	-	-	-
10.	Awan & Azam [89]	G-20 e.	1993 - 2017	DKSE	✓	-	-	-
11.	Du et al. [64]	35 OECD	1990 - 2018	CS-ARDL, FMOLS, DOLS	✓	-	-	-
12.	Al Numan et al. [23]	9 SEA	1995 - 2020	QR, FEM, REM, FMOLS, DOLS, CCR	-	-	-	✓ _(↑RE;↑NRE)
13.	Koc & Bulus [90]	Korea	1971 - 2017	ARDL	✓ _(↓RE)	-	-	-
14.	Sinha et al. [91]	N-11 c.	1990 - 2014	GMM	✓ _(↓RE;↑NRE)	-	-	-
15.	Bulut & Tekdemir [70]	33 OECD	1996 - 2015	FEM, DKSE	-	✓ _(↓RE;↑NRE)	-	-
16.	Zeraibi et al. [65]	EEC	1990 - 2020	AMG, FMOLS, DOLS	✓ _(↓RE)	-	-	-
17.	Özokcu & Özdemir [61]	26 OECD, 52 EC	1980 - 2010	DKSE	✓	✓	-	-
18.	Fakher et al. [92]	OPEC	1994 - 2019	DSURE	✓ _(↓RE;↑NRE)	-	✓ _(↓RE;↑NRE)	-
19.	Sun et al. [71]	China	2006Q1 - 2022Q4	ARDL, FMOLS, DOLS	-	✓ _(↓RE)	-	-
20.	Huang et al. [93]	199 DC in BTH, China	2001 - 2010	SDM	-	-	✓	-
21.	Wang et al. [94]	56 c.	2003 - 2018	AMG, TPM	✓	-	-	-
22.	Shehzad et al. [66]	Algeria	1970 - 2017	ARDL	-	-	✓	-
23.	Zeraibi et al. [95]	China	1980 - 2018	ARDL, VECM	✓	-	-	-
24.	Bekun et al. [96]	SSA	1990 - 2015	PMG-ARDL	✓	-	-	-
25.	Yang et al. [97]	67 c.	1971 - 2010	SR	-	✓	-	-
26.	Aljadani et al. [72]	KSA	1970 - 2020	ARDL, NARDL	-	✓	-	-
27.	Bekun et al. [9]	SAC	1990 - 2018	AMG	✓ _(↓RE)	-	-	-
28.	Zhao et al. [73]	Beijing, China	2003 - 2019	PCA	-	✓	-	✓
29.	Shaheen et al. [98]	HIC	1976 - 2019	3DPF	✓	-	-	-
30.	Pan et al. [99]	T11GRC	1992 - 2020	OLS, FEM, REM	✓	-	-	-
31.	Qayoom & Altaf [74]	India	1965 - 2022	ARDL, FMOLS, DOLS	-	✓ _(↓RE)	-	-
32.	Bandyopadhyay & Rej [75]	India	1978 - 2019	VREM	-	✓	-	-
33.	Jóźwik et al. [100]	11HNEC	1993 - 2019	PCSE	✓	-	-	-
34.	Zhang [101]	China	1971 - 2014	ARDL, QR	✓	-	-	-
35.	Bisset [102]	41 SSA	1996 - 2018	3S-SEM	✓	-	-	-
36.	Gao et al. [67]	31SHPE	1990 - 2021	ARDL	-	-	-	-
37.	Tsujimoto [76]	Japan	2019, 2020 and 2021	LQCR	-	✓	-	-
38.	Jiang et al. [103]	39 c.	1995 - 2011	PLS, FEM	-	✓	-	-
39.	Nica et al. [104]	BRICS	1991 - 2023	ARDL	✓ _(↓RE)	-	-	-
40.	Balsalobre-Lorente et al. [105]	EU-5 c.	1985 - 2016	PLS with CH	✓ _(↓RE)	-	-	-
41.	Nica et al. [106]	India	1990 - 2023	ARDL	✓ _(↓RE)	-	-	-

No.	Author(s)	Study Case	Period	Method	EKC Results			
					CO ₂		EFP	
					N-Shape	Inverted N-Shape	N-Shape	Inverted N-Shape
42.	Gravina & Lanzafame [107]	84AEE	1995 - 2015	BMA, DS-LASSO	-	✓	-	-
43.	Bekhet & Othman [77]	Malaysia	1971 - 2015	VECM, GC	-	✓ ^(↓RE)	-	-
44.	Kumar et al. [108]	12 MN SCO	1991 - 2021	D-H GC, DOLS, QR, GLS	✓	-	-	-
45.	Wang et al. [109]	CTIJ	1995 - 2020	DOLS, FMOLS	✓	-	-	-
46.	Ajmi et al. [110]	G7 c.	1960 - 2010	GC	-	✓	-	-
47.	Ali et al. [111]	Asian EEC	1975 - 2020	AMG	✓ ^(↓RE;↑NRE)	-	-	-
48.	Hatmanu et al. [112]	Rom. Bul.	1980 - 2019	ARDL	-	✓	-	-
49.	Minlah et al. [78]	Ghana	1962 - 2018	BRW GC	-	-	-	✓ ^a
50.	Tsiantikoudis et al. [79]	Bulgaria	1990 - 2015	ARDL	-	✓ ^a	-	-
51.	Le [113]	ASEAN-10	1993 - 2014	FEM, REM	✓	-	-	-
52.	Yasmeen et al. [114]	T10SCC	1990 - 2018	DKSE	✓	-	-	-
53.	Achuo & Ojong [115]	46 African c.	1996 - 2022	QR	✓	-	-	-
54.	Kang et al. [116]	China	1997 - 2012	SDM	-	✓	-	-
55.	Fang et al. [80]	China	1995 - 2016	FEM, REM	-	✓	-	-
56.	Sharma et al. [68]	8DCSSEA	1990 - 2015	CS-ARDL	-	-	✓ ^(↓RE)	-
57.	Wang & He [117]	Province in China	1995 - 2013	SARM	-	✓	-	-
58.	de Angelis et al. [118]	32 c.	1992 - 2012	PR	✓	-	-	-
59.	Alshubiri & Elheddad [119]	32 OECD	1990 - 2015	OLS, GMM	✓	-	-	-
60.	Deng et al. [62]	BTH region of China	2000 - 2018	TPM	-	-	✓ ^b	✓ ^b
61.	Lunku et al. [120]	SSA	2000 - 2020	DOLS, FMOLS, CCR	-	-	-	✓ ^c
62.	Zhu et al. [81]	N-11 c.	1971 - 2022	CS-ARDL	-	-	-	✓
63.	Ahmad et al. [121]	China	1971 - 2014	FMOLS, GMM, ARDL	✓	-	-	-
64.	Usama et al. [122]	Ethiopia	1981 - 2015	ARDL	✓	-	-	-
65.	Nguyen et al. [123]	Vietnam	1977 - 2019	ARDL	-	✓	-	-
66.	Ojaghlou et al. [124]	Turkey	1980 - 2021	DCC, ARDL	✓	-	-	-
67.	Sancar et al. [82]	BRICS-T c.	1996 - 2022	Panel Fourier	-	-	-	✓
<i>Empirical evidence from Indonesian studies</i>								
68.	Ibrahim & Abbas [83]	Java Region, Indo.	2011 - 2019	PR	✓	-	-	-
69.	Zurrah et al. [84]	Indo.	1991Q1 - 2021Q4	ARDL	✓	-	-	-
70.	Malahayati [32]	Indo.	1970 - 2018	ARDL, ECM, FMOLS, DOLS	-	-	✓ ^a	-

Note: ↓RE→Renewable energy reducing emissions; ↑RE→renewable energy increasing emissions; ↑NRE→ non-renewable energy increasing emissions; FEM→Fixed Effects Model; FGLS→Feasible Generalized Least Squares; 2SLS→Two-Stage Least Squares; GMM→Generalized Method of Moments; OECD→Organisation for Economic Co-operation and Development; ASEAN→Association of Southeast Asian Nations; PLS→Pooled Least Squares; GLS→Generalized Least Squares; ARDL→Autoregressive Distributed Lag; TSPA- Three→Stage Panel Approach; DCCE→Dynamic Common Correlated Effects Approach; TNEPC→Top Nuclear Energy-Producing Countries; c.→Countries; REM→Random Effects Model; DKSE→Driscoll-Kraay Standard Errors; QR→Quantile Regression; e.→economies; CS-ARDL→Cross-Sectional Autoregressive Distributed Lag; FMOLS→Fully Modified Ordinary Least Squares;

DOLS→Dynamic Ordinary Least Squares; CCR→Canonical Cointegrating Regressions; SEA→South East Asian; EEC→Emerging Economies Countries; AMG→Augmented Mean Group; EC→Emerging Countries; OPEC→ Organization of the Petroleum Exporting Countries; N-11→group of eleven high-potential emerging economies; DSURE→Dynamic Seemingly Unrelated Regression Equations; SDM→Spatial Durbin Model; DC → Districts and Counties; BTH→Beijing-Tianjin-Hebei; TPM→Threshold Panel Model; VECM→Vector Error Correction Model; SSA→sub-Saharan Africa; PMG→Pooled Mean Group; SR→Symbolic Regression; KSA→Kingdom of Saudi Arabia; NARDL→Nonlinear Autoregressive Distributed Lag; SAC→South Asian Countries; PCA→Principal Component Analysis; HIC→High-Income Countries; 3DPF→Three Degree Polynomial Factor; OLS→Ordinary Least Square; T11GRC→Top 11 GDP-Ranked Countries; PCSE→Panel-Corrected Standard Error; VREM→Various Robust Econometric Models; Rom. Bul. →Romania and Bulgaria; 11HNEC→11 Highest Nuclear Energy Consumption Countries; 31SHPE→31 Selected High-Polluting Economies; GC→Granger Causality; 3S-SEM→Three-Stage Simultaneous Equation Modeling; LQCR→Linear–Quadratic–Cubic Regressions; BRICS→forum for cooperation among a group of leading emerging economies; PR→Panel Regression; BMA→Bayesian Model Averaging; DS-LASSO→Double Selection LASSO; 84AEE→84 Advanced and Emerging Economies; MN→Member Nations; SCO→Shanghai Cooperation Organization; D-H→Dumitrescu-Hurlin; CTIJ→China, Turkey, India, and Japan; G7→seven major industrial countries; BRW→Bootstrap Rolling Window; T10SCC→ Top 10 Solar Consuming Countries; DCC→Dynamic Conditional Correlation; CH→Correction for Heteroscedasticity; EU→European Union; SARM→Spatial Autoregressive Model; 8DCSSEA→8 Developing Countries of South and Southeast Asia; $\sqrt{^a}$ →dependent variable is deforestation; $\sqrt{^b}$ →dependent variable is forest fragmentation; $\sqrt{^c}$ →dependent variable in this study is forest conversion. BRICS-T→Brazil, Russia, India, China, South Africa, and Turkey; ECM→Error Correction Model; Indo.→Indonesia.

structural changes. However, to speed up the shift, more powerful measures should be taken, such as specific subsidies, investment in grid modernization, and increased partnerships with other countries. These interventions would reduce reliance on coal, besides assisting Indonesia in balancing long-term economic development and long-term sustainability targets.

2.1. Research Gap and Study Contribution

Despite the extensive literature on EKC, several critical gaps remain, particularly in the context of developing economies such as Indonesia. First, most existing studies rely on a single proxy for environmental quality, typically either CO₂ emissions or the ecological footprint, which limits the ability to capture the multidimensional nature of environmental degradation. Second, the empirical evidence on the EKC in Indonesia is mixed and often restricted to linear or quadratic specifications, overlooking more complex nonlinear dynamics such as N-shaped or inverted N-shaped relationships. Third, prior research predominantly employs conventional time-series techniques that assume stable relationships over time, thereby failing to account for structural changes and evolving interactions driven by energy transitions and policy shifts. Moreover, the roles of renewable and non-renewable energy consumption, along with capital formation, have rarely been examined simultaneously within a unified framework. To address these limitations, this study integrates dual environmental indicators, higher-order EKC, ARDL, and wavelet coherence to assess Indonesia's time-varying growth–environment nexus.

2.2. Possible Shapes of the Environmental Kuznets Curve (EKC)

Figure 1a–f illustrates the possible functional forms of the EKC, showing how the relationship between economic growth and environmental degradation varies depending on the signs of the estimated coefficients.

In the linear positive relationship (Figure 1a), where $\beta_1 > 0$ and $\beta_2 = \beta_3 = 0$, environmental degradation increases continuously as income rises. Conversely, the linear negative form (Figure 1b), with $\beta_1 < 0$ and $\beta_2 = \beta_3 = 0$, indicates a consistent improvement in environmental quality as economic growth progresses.

The inverted U-shaped curve (Figure 1c), defined by $\beta_1 > 0$, $\beta_2 < 0$, and $\beta_3 = 0$, represents the traditional EKC hypothesis. It suggests that environmental degradation initially increases with income, reaches a turning point, and then declines as economies transition toward cleaner technologies and stronger environmental regulations. By contrast, the U-shaped pattern (Figure 1d), where $\beta_1 < 0$, $\beta_2 > 0$, and $\beta_3 = 0$, depicts an initial improvement in environmental quality followed by a deterioration at higher income levels.

The N-shaped curve (Figure 1e) presents more complex patterns that emerge in the cubic form of the EKC, characterized by $\beta_1 > 0$, $\beta_2 < 0$, and $\beta_3 > 0$, which reflects a dynamic process where environmental degradation first increases, then decreases, and eventually rises again at advanced stages of development, often due to consumption rebound effects or industrial expansion. Conversely, the inverted N-shaped curve (Figure 1f), where $\beta_1 < 0$, $\beta_2 > 0$, and $\beta_3 < 0$, shows the opposite sequence, in which environmental quality initially improves, then deteriorates, and finally improves again at higher income levels.

Overall, these functional forms underscore the nonlinear and context-specific dynamics of the growth–environment relationship, suggesting that the environmental response to economic development is not uniform but varies across stages of industrialization, energy transition, and policy evolution.

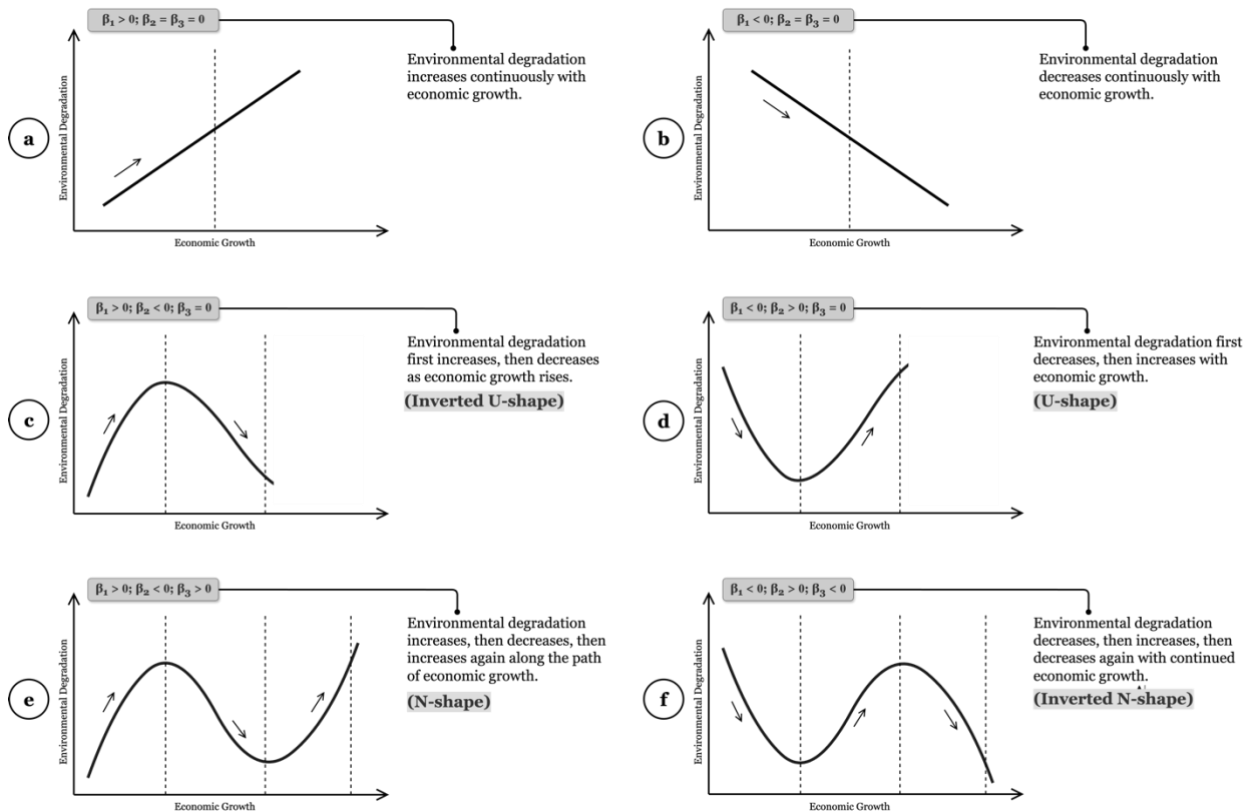


Figure 1. Possible functional forms of the EKC: (a) linear positive, (b) linear negative, (c) inverted U-shape, (d) U-shape, (e) N-shape, and (f) inverted N-shape.

(Source: Author's own creation, based on the studies of Yazici et al. [125] and Awan & Azam [89].)

3. Materials and Methods

3.1. Data

This study employs annual time series data for Indonesia covering the period 1965–2023 to examine the dynamic relationship between economic growth, energy use, capital formation, and environmental quality. Two indicators are used as proxies for environmental quality, namely the ecological footprint (EFP) and carbon dioxide (CO₂) emissions, which serve as the dependent variables. To capture the nonlinear effects of growth on the environment, the study includes gross domestic product (GDP) per capita, along with its squared (GDP²) and cubic (GDP³) terms. In addition, renewable energy consumption (RE), nonrenewable energy (NRE), and gross fixed capital formation (GFCF) are introduced as independent variables to assess the role of energy structure and investment activities in shaping environmental outcomes. All data are sourced from internationally recognized databases such as the Global Footprint Network (GFN), Our World in Data (OWID), and the World Bank (WDI), while GDP² and GDP³ are constructed by the authors. The selected variables provide a comprehensive framework for testing the EKC hypothesis in Indonesia and for analyzing the long- and short-run drivers of environmental quality within the

ARDL framework, with detailed variable descriptions presented in Table 3.

3.2. Justification of the Study

Indonesia is an interesting example in studying the EKC hypothesis due to its extensive economic growth rate, heavy reliance on fossil fuels, and continued but disproportionate shift to renewable energy. The nation has recorded a steady growth in its GDP over the past 5 decades due to industrialization, urbanization, and infrastructural development. Nevertheless, this development has come with a lot of environmental issues, whereby there is increased CO₂ emission, massive deforestation, and a growing ecological footprint. Coal is still the predominant energy source, with the role of renewable energy sources being insignificant, which highlights the conflict between economic growth and environmental safety. These dynamics are crucial to understanding how Indonesia is progressing on the path of sustainable development.

In addition, even though an increasing amount of research has been conducted on the EKC in Indonesia, most of the current studies have focused on either CO₂ emissions or the ecological footprint, but have not looked at both indicators together within one framework. It is also concerning that this small focus restrains

Table 3. Variable description.

Variable	Symbol	Unit Measurement	Source
Ecological Footprint	EFP	Global hectares per capita	GFN [34]
Carbon Dioxide Emissions	CO ₂	Metric tons per capita	OWID [126]
Economic Growth	GDP	GDP per capita (constant 2015 USD)	WDI [127]
Square of Economic Growth	GDP ²	Constructed by authors	-
Cubic of Economic Growth	GDP ³	Constructed by authors	-
Renewable Energy Consumption	RE	kilowatt-hour (kWh) per capita	OWID [128]
Non-renewable Energy Consumption	NRE	kilowatt-hour (kWh) per capita	OWID [129]
Gross Fixed Capital Formation	GFCF	Investment in fixed assets as % of GDP	WDI [127]

comprehension of the general environmental performance in Indonesia because CO₂ only captures carbon-based degradation, whereas the ecological footprint portrays a broader measure of ecological resource utilization. This study provides a more complete evaluation of the relationship between Indonesia and the environment by combining the two environmental indicators and using a long-term time series analysis from 1965 to 2023. In this way, it is possible to detect possible non-linear configurations, such as N-shaped and inverted N-shaped EKC types, which can help policymakers to strike a balance between economic growth and environmental sustainability.

3.3. Theoretical Framework

3.3.1. Environmental Kuznets Curve (EKC)

The EKC hypothesis was initially hypothesized by Grossman & Krueger [1] and assumes that there is a nonlinear relationship between income and environmental degradation. Early economic progress results in pollution and loss of resources as industrialization and production that use a lot of energy take place. Nonetheless, once the income level attains a particular level, structural change, better technologies, and more effective regulations lead to better environmental health. Equation 1 below is the standard functional representation of the EKC.

$$EQ = f(GDP, GDP^2, GDP^3) \tag{1}$$

with *EQ* being the environmental degradation, which is proxied by CO₂ emissions or ecological footprint (EFP), and *GDP_t*, the income per capita. Depending on the signs of the coefficients:

$\beta_1 > 0, \beta_2 < 0, \beta_3 = 0 \rightarrow$ Inverted U-shaped EKC

$\beta_1 < 0, \beta_2 > 0, \beta_3 = 0 \rightarrow$ U-shaped EKC

$\beta_1 > 0, \beta_2 < 0, \beta_3 > 0 \rightarrow$ N-shaped EKC

$\beta_1 < 0, \beta_2 > 0, \beta_3 < 0 \rightarrow$ Inverted N-shaped EKC

This research is expected to show N-shaped EKC curves of EFP and inverted N-shaped EKC curves of CO₂

emissions in terms of potential rebound effects of environmental quality at higher income levels.

3.3.2. Green Solow Model and Cobb–Douglas Production Framework

In order to provide an extension of the EKC framework, the current paper embraces the ideas of the Green Solow Model (GSM) created and presented by Brock & Taylor [130], which incorporates the environmental factors into the Solow growth model. The GSM points out that the use of technology and energy efficiency is the key factor that defines the future of economic growth as sustainable or unsustainable in terms of the environment. Equation 2 can be used to explain the environmental dynamics.

$$Q = f(K, L, R) \tag{2}$$

In this context, the *Q* is considered as the environmental degradation, and the capitals, labor, and natural resources are the quantities of *K*, *L*, and *R*, respectively. *R* is especially used to refer to energy consumption in this context.

3.4. Estimation Technique

The empirical analysis in this study begins with the specification of an initial functional relationship that links environmental quality to its key determinants, as presented in Equation 3.

$$EQ_t = f(GDP_t, GDP^2_t, GDP^3_t, REC_t, NRE_t, GFCF_t) \tag{3}$$

where *EQ_t* represents environmental quality, measured alternately by the ecological footprint (EFP) and carbon dioxide emissions (CO₂). For clarity, we separate *EQ_t* into two individual models, which are specified in Equations 4 and 5.

$$EFP_t = f(GDP_t, GDP^2_t, GDP^3_t, REC_t, NRE_t, GFCF_t) \tag{4}$$

$$CO2_t = f(GDP_t, GDP^2_t, GDP^3_t, REC_t, NRE_t, GFCF_t) \tag{5}$$

To reduce heteroskedasticity and to capture elasticities directly, all variables are transformed into their natural logarithmic form (ln), with the baseline econometric models presented in Equations 6 and 7.

$$\ln EFP_{it} = \psi_0 + \psi_1 \ln GDP_t + \psi_2 \ln GDP_t^2 + \psi_3 \ln GDP_t^3 + \psi_4 \ln REC_t + \psi_5 \ln NRE_t + \psi_6 \ln GFCF_t + \varepsilon_t \quad (6)$$

$$\ln CO2_{it} = \psi_0 + \psi_1 \ln GDP_t + \psi_2 \ln GDP_t^2 + \psi_3 \ln GDP_t^3 + \psi_4 \ln REC_t + \psi_5 \ln NRE_t + \psi_6 \ln GFCF_t + \varepsilon_t \quad (7)$$

This log-linear specification ensures that the estimated coefficients can be interpreted as elasticities, reflecting the percentage change in environmental quality resulting from a one percent change in the explanatory variables. Building on this baseline formulation, the study then employs the Autoregressive Distributed Lag (ARDL) approach to estimate both the short-run dynamics and

$$\Delta \ln EFP_t = \beta_0 + \sum_{i=0}^q \phi_1 \Delta \ln EFP_{t-i} + \sum_{i=0}^p \phi_2 \Delta \ln GDP_{t-i} + \sum_{i=0}^p \phi_3 \Delta \ln GDP_{t-i}^2 + \sum_{i=0}^p \phi_4 \Delta \ln GDP_{t-i}^3 + \sum_{i=0}^p \phi_5 \Delta \ln REC_{t-i} + \sum_{i=0}^p \phi_6 \Delta \ln NRE_{t-i} + \sum_{i=0}^p \phi_7 \Delta \ln GFCF_{t-i} + \phi ECT_{t-1} + \psi_1 \ln EFP_{t-1} + \psi_2 \ln GDP_{t-1} + \psi_3 \ln GDP_{t-1}^2 + \psi_4 \ln GDP_{t-1}^3 + \psi_5 \ln REC_{t-1} + \psi_6 \ln NRE_{t-1} + \psi_7 \ln GFCF_{t-1} + \varepsilon_t \quad (8)$$

$$\Delta \ln CO2_t = \beta_0 + \sum_{i=0}^q \phi_1 \Delta \ln CO2_{t-i} + \sum_{i=0}^p \phi_2 \Delta \ln GDP_{t-i} + \sum_{i=0}^p \phi_3 \Delta \ln GDP_{t-i}^2 + \sum_{i=0}^p \phi_4 \Delta \ln GDP_{t-i}^3 + \sum_{i=0}^p \phi_5 \Delta \ln REC_{t-i} + \sum_{i=0}^p \phi_6 \Delta \ln NRE_{t-i} + \sum_{i=0}^p \phi_7 \Delta \ln GFCF_{t-i} + \phi ECT_{t-1} + \psi_1 \ln CO2_{t-1} + \psi_2 \ln GDP_{t-1} + \psi_3 \ln GDP_{t-1}^2 + \psi_4 \ln GDP_{t-1}^3 + \psi_5 \ln REC_{t-1} + \psi_6 \ln NRE_{t-1} + \psi_7 \ln GFCF_{t-1} + \varepsilon_t \quad (9)$$

are small [132–135]. Here are our ARDL equation models for examining the long-run and short-run dynamics between economic growth, energy use, capital formation, and environmental quality in Indonesia. Since this study employs two proxies for environmental quality, namely ecological footprint and CO₂ emissions, separate ARDL specifications are estimated for each dependent variable. The general ARDL form can be expressed in Equations 8 and 9.

where *EFP* and *CO2* represent dependent variables, *GDP*, *GDP*², and *GDP*³ capture the nonlinear growth effects under the EKC hypothesis, *RE* is renewable energy consumption, *NRE* is fossil fuel consumption, and *GFCF* is gross fixed capital formation.

The long-run coefficients are obtained by normalizing the lagged levels of the regressors, while the short-run dynamics are captured through the differenced terms. The inclusion of the error correction term (ECT) measures the speed of adjustment, indicating how quickly deviations from the long-run equilibrium are corrected. This ARDL framework, therefore, enables a comprehensive analysis of both short-run fluctuations and long-run equilibrium relationships in the growth-environment nexus for Indonesia.

3.4.2. Granger Causality

Along with the ARDL method, the direction of causality among the variables is also tested using the Granger causality test. Although ARDL will indicate the presence of a long-run and short-run association, causal

relationships, followed by Granger causality tests to examine the direction of causality among the variables.

3.4.1. Autoregressive Distributed Lag (ARDL)

The ARDL model that was proposed by Pesaran et al. [131] is a flexible econometric model applied to examine both the short-run dynamics and long-run equilibrium relationships between variables, irrespective of whether they are stationary at either level or first difference. Its strength is that it can take into account the variables of mixed integration order and create unbiased estimates of the long-run results even when the samples

relationships are not indicated. Granger causality analysis is considered to be a supplement to ARDL as it helps in establishing whether variations of one variable could be systematically predictive of variations of another, which helps in determining the direction in which the economic growth, energy use, capital formation, and environmental quality may be influenced. This will be necessary in order to understand the relationship as unidirectional, bidirectional, or not, to give more in-depth insights into the feedback of growth and environmental sustainability in Indonesia.

3.4.3. Wavelet Coherence

To capture the dynamic and time-varying interactions among economic growth, energy consumption, capital formation, and environmental quality, this study applies the wavelet coherence analysis. Unlike conventional time-series models that assume constant relationships, this approach allows the simultaneous examination of connections in both the time and frequency domains. It effectively identifies co-movements, lead-lag structures, and changes in correlation strength across short-, medium-, and long-term horizons. The method is well-suited for exploring how the relationships among key macroeconomic and environmental variables evolve over the 1965 - 2023 period, particularly in an economy undergoing structural transformation such as Indonesia.

3.5. Conceptual Framework

Figure 2 depicts the conceptual framework of the relationship between GDP, REC, NRE, and GFCF as factors

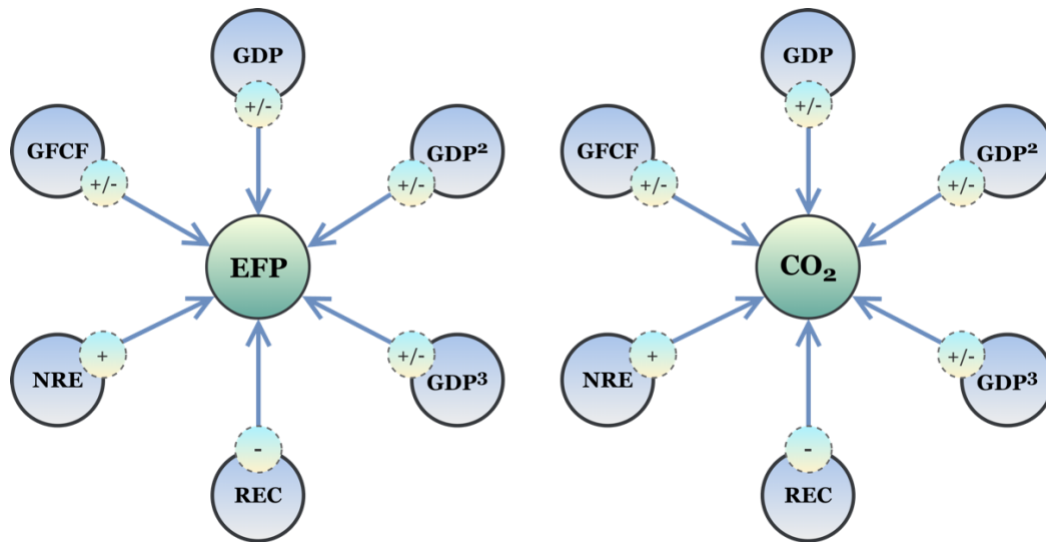


Figure 2. Conceptual framework.

Table 4. Descriptive statistics.

Status	Obs.	Unit of Measurement	Mean	Median	Max.	Min.	Std. Dev.
EFP	59	Natural log	0.2404	0.2147	0.6121	0.0564	0.1470
CO2	59	Natural log	-0.0516	0.1069	0.9721	-1.4907	0.7026
GDP	59	Natural log	7.3744	7.4773	8.3411	6.3436	0.5879
RE	59	Natural log	4.8605	5.0323	6.9631	3.1491	1.0379
NRE	59	Natural log	8.0683	8.2834	9.1192	6.5596	0.8024
GFCF	59	Natural log	25.0057	25.3264	26.6398	22.2030	1.2516

to determine environmental quality, i.e. EFP and CO₂. Based on the EKC hypothesis, the framework supposes a non-linear correlation between GDP and environmental quality, with the effect varying at different development phases. To measure these dynamics, GDP, GDP², and GDP³ have been added to spot possible multiple turning points in the growth-environment relationship. In the case of the EFP model, the coefficients have the anticipated changes of positive to GDP, negative to GDP², and positive to GDP³, so that the EKC assumes the N-shape whereby the EFP changes positively at the beginning of economic growth, negatively at the stages of efficiency, structural change, and positively in the later stages of economic growth when there are more consumption and production activities. It is anticipated that, on the other end, the CO₂ model should take the form of an inverted N-shaped EKC, where GDP follows a negative coefficient, GDP² follows a positive coefficient and GDP³ follows a negative coefficient. This tendency implies that CO₂ emissions can initially decrease because of the early technological progress, increase with the industrialization characterized by consuming a lot of energy, and decrease once again with the introduction of cleaner technologies and more stringent rules. REC will have a negative correlation with EFP and CO₂, as it will decrease ecological and carbon pressure, whereas NRE will have a positive correlation since it will be dependent

on fossil fuels. It is hypothesized that GFCF lowers the long-run EFP and CO₂ because investment in productive capacity and infrastructure is becoming more and more green with regard to sustainability and efficiency. Overall, this framework offers the analytical background to the exploration of EKC trends of the N-shaped and inverted N-shaped in Indonesia under the framework of the ARDL approach that accounts for both short and long-run dynamics of the interaction between economic growth, energy consumption, capital formation, and environmental quality.

3.6. Study Workflow

The research process will be organized into a sequential order that will start with descriptive statistical analysis, which will summarize the nature of all variables. This is succeeded by unit root testing and the cointegration test to determine the stationarity of time series data and the existence of long-run relationships between variables, respectively. After the data stability and cointegration, the optimum lag length is obtained to support the strong model of the Autoregressive Distributed Lag (ARDL) model estimation. After that, empirical evidence is interpreted, and findings are analyzed, which results in a more detailed discussion of the results in connection with the EKC hypothesis. The paper ends with an overall conclusion on the main findings, policy implications, and

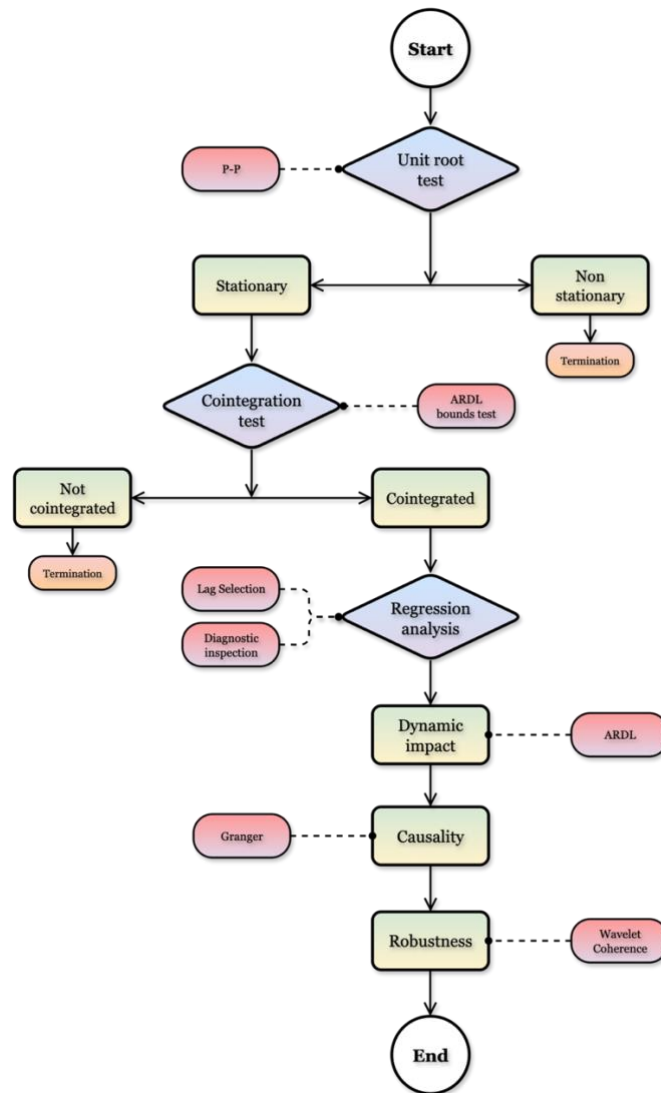


Figure 3. Study workflow.

recommendations on sustainable environmental and economic development, as shown in Figure 3.

4. Results and Discussion

4.1. Descriptive Statistics

The values provided in Table 4 are the descriptive statistics of all the variables in their natural logarithmic (LN) form, and this is to ensure that the values are consistent with the econometric estimates and further eliminate the possibility of heteroskedasticity. The median and the mean values of the majority of the variables, such as EFP, CO₂, and GDP are quite similar and suggest that data distributions are rather symmetric. The minimum and maximum values are separated by a wide range that indicates how much the economic and environmental conditions of Indonesia have varied significantly in the long term, considering the 1965-2023 period. NRE and GDP among the explanatory variables have higher averages and moderate dispersion in

relation to other variables and reflect their predominance in the growth path of Indonesia. RE, on the other hand, is more variable, implying that the adoption is not even over time. GFCF also presents moderate variations, which can be attributed to changes in the investment cycles and changes in the rate of infrastructure and industrial development. The standard deviations indicate that the environmental and energy-related indicators have varied, rather than the macroeconomic variables, which depict the structural changes in the energy and environmental policy in Indonesia. In general, the descriptive statistics give a good idea of the distributional nature of the data, as they give some preliminary information about the dynamic interaction of growth, energy structure, and environmental quality in Indonesia.

4.2. Unit Root Test

The unit root test results in Table 5 show that most of the variables are non-stationary at their levels but stationary after first differencing at all specifications- intercept,

Table 5. P-P unit root test results.

Variable	Intercept		Trend and Intercept		None	
	t-stat.	Prob.	t-stat.	Prob.	t-stat.	Prob.
<i>Level</i>						
EFP	1.6475	0.9995	-2.0293	0.5732	2.3030	0.9944
CO2	-3.4476**	0.0131	-1.8017	0.6912	-1.5879	0.1050
GDP	-0.6099	0.8600	-2.1503	0.5075	7.2487	1.0000
GDP ²	0.0242	0.9567	-2.3984	0.3765	7.1105	1.0000
GDP ³	0.5287	0.9864	-2.2594	0.4486	7.8237	1.0000
REC	0.0582	0.9597	-2.1236	0.5220	1.7563	0.9799
NRE	-1.5037	0.5248	-0.8100	0.9585	4.0805	1.0000
GFCF	-2.9821**	0.0425	-1.7626	0.7099	4.3513	1.0000
<i>1st Diff.</i>						
EFP	-7.1038***	0.0000	-18.5097***	0.0000	-6.8543***	0.0000
CO2	-8.2874***	0.0000	-9.5997***	0.0000	-6.3320***	0.0000
GDP	-5.9269***	0.0000	-5.8818***	0.0000	-3.1920***	0.0019
GDP ²	-5.9056***	0.0000	-5.8460***	0.0000	-3.2192***	0.0017
GDP ³	-5.8487***	0.0000	-5.8264***	0.0001	-3.2342***	0.0017
REC	-8.7502***	0.0000	-9.0403***	0.0000	-8.4426***	0.0000
NRE	-6.8662***	0.0000	-7.1745***	0.0000	-5.0987***	0.0000
GFCF	-5.2742***	0.0000	-5.5127***	0.0001	-4.0929***	0.0001

Note: *** denotes significance at the 1% level, and ** denotes significance at the 5% level.

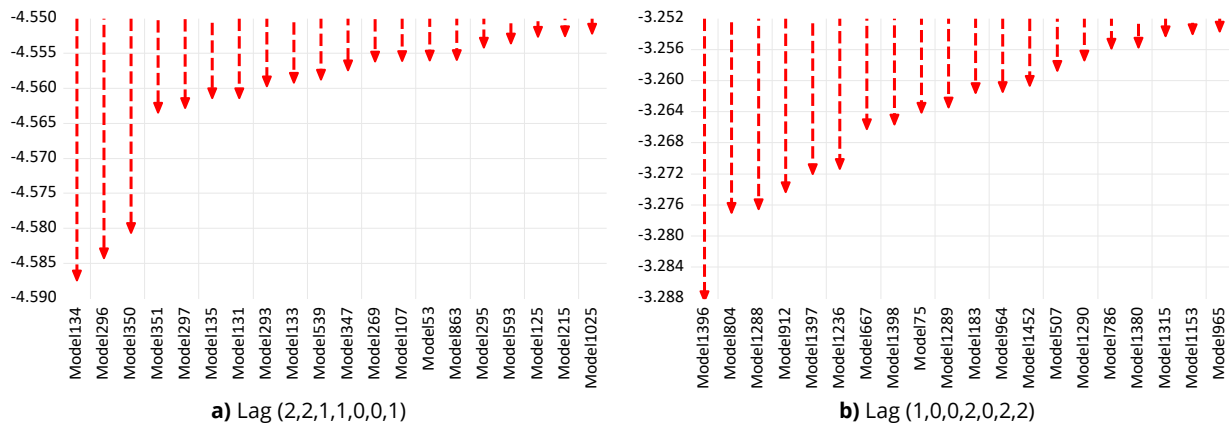


Figure 4. Optimal lag length selection for the ARDL models: a) EFP model and b) CO₂ model.

trend and intercept, none. This result indicates that the variables have long-term stochastic patterns, forcing the variables to be differenced in order to attain stationarity. In general, the findings substantiate the fact that the underlying data series can be further subjected to the econometric analysis, and the following estimates will not be influenced by the spurious relationships.

4.3. Optimal Lag Length Selection

The best choice of the lag length of the ARDL models used in the EFP and CO₂ emissions is presented in Figure 4. The graphs rely on the Akaike Information Criterion (AIC), with the lowest values of AIC representing the best-fitting models. Both panels (a) and (b) indicate the point at which the AIC reaches its lowest point, as indicated by the arrows, which indicate the most suitable lag structure of each model. In the case of the EFP model, the optimum lag is achieved sooner, and it is rather stable, whereas the CO₂ model indicates a slightly slower stabilization. The

choice of this guarantees that the dynamic behavior of every dependent variable is well represented without omitting the data and ensures improved reliability of the ARDL estimations. Choice of Shortening of Length of the ARDL Models:(a) EFP Model and (b) CO₂ Model.

4.4. Cointegration with ARDL Bounds Test

The outcome of the ARDL bounds test in Table 6 affirms that there is a long-run cointegrating relationship in both the EFP and CO₂ models. The F-statistic of EFP (6.0549) and CO₂ (6.0521) is higher than the upper critical values of the level 1, 5, and 10 percent significance, but the null hypothesis of no level relationship is rejected, and thus, ARDL estimation is suitable.

4.5. ARDL Estimation Results for EFP and CO₂ Models

4.5.1. ARDL Model for EFP

The ARDL estimation presented in Table 7 confirms the existence of an N-shaped EKC for Indonesia. The

Table 6. ARDL bound test results.

Model	F-Bounds Test		Null Hypothesis: No levels relationship		
	Test stat.	Value	Signif.	I(0)	I(1)
EFP	F-stat.	6.0549	10%	1.75	2.87
	K	6	5%	2.04	3.24
CO2	F-stat.	6.0521	1%	2.66	4.05
	K	6			

Table 7. ARDL results for the EFP model.

Variable	Coeff.	Std. Er.	t-stat.	Prob.
<i>Long-run</i>				
GDP	1.3503***	0.2238	6.0324	0.0000
GDP ²	-0.2319**	0.0983	-2.3590	0.0222
GDP ³	0.0155**	0.0071	2.1902	0.0331
REC	-0.0023	0.0119	-0.1920	0.8485
NRE	0.0099	0.0569	0.1736	0.8629
GFCF	-0.1368**	0.0577	-2.3712	0.0215
<i>Short-run (2,2,1,1,0,0,1)</i>				
ECT(-1)	-0.8011***	0.1154	-6.9400	0.0000
D(EFP (-1))	0.2247**	0.1092	2.0579	0.0448
D(GDP)	30.5599***	10.9801	2.7832	0.0076
D(GDP(-1))	-0.2789***	0.0823	-3.3863	0.0014
D(GDP ²)	-4.6147***	1.5075	-3.0612	0.0035
D(GDP ³)	0.2304***	0.0689	3.3454	0.0016
D(GFCF)	-0.0080	0.0481	-0.1670	0.8681
R ²	0.6547			
Adjusted R ²	0.6132			

Note: *** denotes significance at the 1% level, ** at the 5% level, and * at the 10% level.

coefficient of GDP per capita (GDP) is positive and highly significant at 1.3503, indicating that a 1% increase in GDP per capita raises the ecological footprint by about 1.35% in the long run. Conversely, the squared term of GDP (GDP²) is negative at -0.2319, showing that a 1% increase in GDP squared reduces ecological footprint by 0.23%, consistent with the notion that at higher levels of income, efficiency gains, cleaner technologies, and environmental awareness mitigate ecological pressures. However, the cubic term of GDP (GDP³) turns positive at 0.0155, meaning that a 1% increase in GDP cubed again raises the ecological footprint by 0.016%, confirming the N-shaped EKC trajectory. Among the control variables, gross fixed capital formation (GFCF) demonstrates a negative coefficient of -0.1368, suggesting that a 1% rise in investment reduces ecological footprint by about 0.14%, likely due to the role of modern infrastructure and technological upgrading in enhancing environmental efficiency. By contrast, renewable energy consumption (REC) and fossil energy consumption (NRE) are statistically insignificant, indicating that in the long run, energy use patterns have not yet delivered a measurable impact on ecological sustainability.

In the short run, the dynamic effects are even more pronounced. The immediate impact of GDP per capita (D(GDP)) is strongly positive at 30.5599, showing that a

1% increase in GDP sharply raises ecological footprint by 30.6%, reflecting the short-term environmental stress linked to rapid expansion. However, the lagged GDP term (D(GDP(-1))) is negative at -0.2789, meaning that a 1% rise in lagged GDP reduces ecological footprint by 0.28%, pointing to a correction mechanism from previous growth episodes. Similarly, GDP squared continues to mitigate footprint in the short run (D(GDP²) = -4.6147), while GDP cubed once again raises it (D(GDP³) = 0.2304), reinforcing the N-shaped EKC even in transitional dynamics. On the other hand, GFCF is insignificant in the short run (-0.0080), suggesting that investment does not produce immediate ecological benefits. Renewable and fossil energy consumption also remain insignificant, highlighting that short-term variations in energy use have not yet translated into noticeable effects on environmental sustainability. Importantly, the error correction term (-0.8011) is negative and highly significant, showing that around 80% of short-run disequilibrium is corrected each year, confirming the stability of the long-run relationship between growth, investment, and ecological footprint.

4.5.2. ARDL Model for CO₂

The ARDL estimation for the CO₂ model (Table 8) reveals the existence of an inverted N-shaped EKC for Indonesia. The coefficient of GDP per capita (GDP) is negative at

Table 8. ARDL results for the CO₂ model.

Variable	Coeff.	Std. Er.	t-stat.	Prob.
<i>Long-run</i>				
GDP	-2.0951***	0.4680	-4.4770	0.0000
GDP ²	0.8981***	0.3340	2.6885	0.0097
GDP ³	-0.0554**	0.0246	-2.2575	0.0283
REC	-0.1085***	0.0309	-3.5098	0.0009
NRE	0.2832	0.1760	1.6094	0.1137
GFCF	-0.5145***	0.2240	-2.2970	0.0258
<i>Short-run (1,0,0,2,0,2,2)</i>				
ECT(-1)	-0.6334***	0.0913	-6.9384	0.0000
D(GDP ³)	-0.0386***	0.0061	-6.2817	0.0000
D(GDP ³ (-1))	-0.0055***	0.0015	-3.5760	0.0008
D(NRE)	0.9168***	0.0977	9.3869	0.0000
D(NRE(-1))	0.4355***	0.1159	3.7569	0.0005
D(GFCF)	-0.1372*	0.0766	-1.7911	0.0793
D(GFCF(-1))	0.1545**	0.0746	2.0699	0.0436
R ²	0.7332			
Adjusted R ²	0.7011			

Note: *** denotes significance at the 1% level, ** at the 5% level, and * at the 10% level.

Table 9. Granger causality results.

Null Hypothesis of EFP	F-stat.	Prob.	Null Hypothesis of CO ₂	F-stat.	Prob.
GDP ≠ EFP	5.4403***	0.0072	GDP ≠ CO ₂	2.8137*	0.0991
EFP ≠ GDP	0.8155	0.4480	CO ₂ ≠ GDP	0.0655	0.7990
GDP ² ≠ EFP	5.8090***	0.0053	GDP ² ≠ CO ₂	2.0066	0.1623
EFP ≠ GDP ²	0.8710	0.4245	CO ₂ ≠ GDP ²	0.0432	0.8360
GDP ³ ≠ EFP	6.2097***	0.0038	GDP ³ ≠ CO ₂	1.4829	0.2285
EFP ≠ GDP ³	0.9300	0.4010	CO ₂ ≠ GDP ³	0.0302	0.8627
REC ≠ EFP	2.2971	0.1107	REC ≠ CO ₂	0.9178	0.3422
EFP ≠ REC	1.6666	0.1988	CO ₂ ≠ REC	3.2912*	0.0751
NRE ≠ EFP	3.0481*	0.0560	NRE ≠ CO ₂	0.0831	0.7742
EFP ≠ NRE	2.2970	0.1107	CO ₂ ≠ NRE	2.8428*	0.0975
GFCF ≠ EFP	4.7225**	0.0130	GFCF ≠ CO ₂	4.1779**	0.0458
EFP ≠ GFCF	2.6170*	0.0826	CO ₂ ≠ GFCF	1.4238	0.2379

Note: *** denotes significance at the 1% level, ** at the 5% level, and * at the 10% level.

2.0951, indicating that a 1% increase in GDP per capita reduces CO₂ emissions by around 2.1% in the long run. This suggests that at lower levels of income, growth is associated with improvements in efficiency and lower emissions. However, the squared term of GDP (GDP²) is positive at 0.8981, implying that a 1% rise in GDP squared increases CO₂ emissions by about 0.90%, reflecting the scale effects of industrial expansion and energy-intensive growth. Interestingly, the cubic GDP term (GDP³) turns negative again at 0.0554, suggesting that a 1% increase in GDP cubed reduces emissions by 0.055%, confirming an inverted N-shaped EKC where CO₂ emissions decline at very high-income levels. Among the control variables, renewable energy consumption (REC) significantly reduces emissions with a coefficient of 0.1085, showing that a 1% increase in renewable energy use lowers CO₂ by about 0.11%, while fossil energy consumption (NRE) is statistically insignificant in the long run. Gross fixed capital formation (GFCF) is negative at 0.5145, suggesting

that a 1% rise in investment reduces emissions by 0.51%, indicating that capital formation enhances environmental efficiency.

In the short run, the dynamic effects highlight strong transitional adjustments. The cubic GDP term (D(GDP³)) is negative both contemporaneously at 0.0386 and with a lag at 0.0055, reinforcing the inverted N-shaped trajectory even in the short-term dynamics. Fossil energy consumption plays a substantial role in the short run: D(NRE) shows that a 1% increase in fossil fuel use raises CO₂ emissions by 0.92% immediately, with lagged effects also positive at 0.436, confirming the dominance of fossil energy in driving short-term emissions. By contrast, renewable energy does not show significant short-run dynamics. Gross fixed capital formation has mixed effects: contemporaneously, D(GFCF) is negative at 0.1372, but its lagged effect is positive at 0.1545, suggesting that while immediate investments may reduce emissions through efficiency, the subsequent

Table 10. The diagnostic test results.

Diagnostic tests	EFP model		CO ₂ model		Conclusion
	Coeff.	Prob.	Coeff.	Prob.	
J-B	0.1919	0.9085	2.7052	0.2586	Residuals are normally distributed
CUSUM	-	< 0.05	-	< 0.05	The model is stable
CUSUMQ	-	< 0.05	-	< 0.05	The model is stable
B-G LM test	0.6439	0.5303	0.5624	0.5741	No serial correlation exists
B-P-G test	1.0027	0.4656	1.0412	0.4325	No heteroscedasticity exists
Harvey test	1.5823	0.1283	0.8330	0.6243	No heteroscedasticity exists
Glejser test	1.0937	0.3897	1.2480	0.2811	No heteroscedasticity exists
ARCH test	3.5396	0.0653	1.2889	0.2613	No heteroscedasticity exists
Ramsey test	0.3184	0.8640	0.2196	0.8272	The model is properly specified
R ²	0.6547	-	0.7332	-	The model is well fitted
R ² Adjusted	0.6132	-	0.7011	-	The model is well fitted

Note: J-B: Jarque-Bera; B-G: Breusch-Godfrey; B-P-G: Breusch-Pagan-Godfrey.

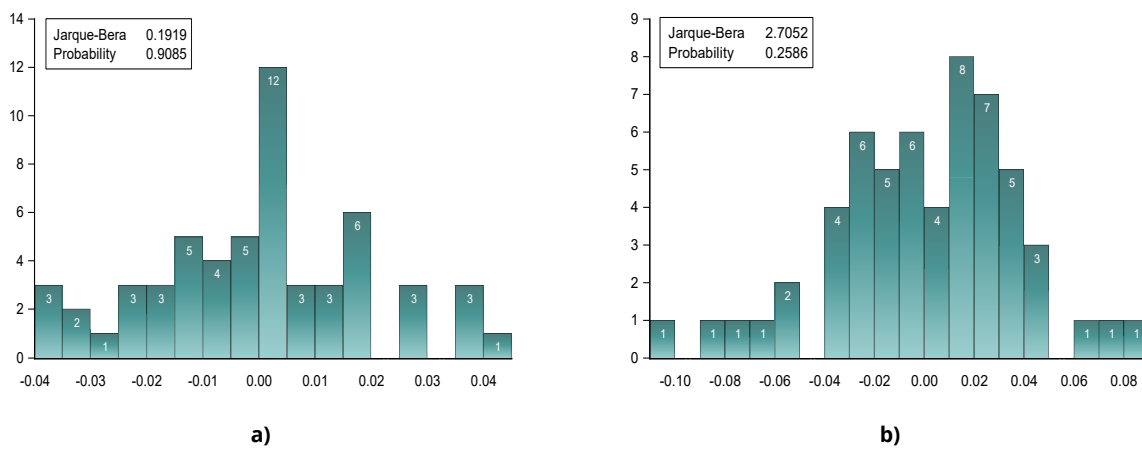


Figure 5. Jarque–Bera normality test results for a) the EFP model and b) the CO₂ model.

expansions can increase emissions. Importantly, the error correction term (0.6334) is negative and highly significant, indicating that about 63% of deviations from the long-run equilibrium are corrected within a year, ensuring the stability of the CO₂–income–energy–investment relationship.

4.6. Granger Causality Results

The Granger causality results in Table 9 (EFP) indicate unidirectional causality from GDP, GDP², GDP³ and NRE to the ecological footprint, showing that economic growth variables and non-renewable energy drive environmental pressure. In addition, GFCF exhibits a bidirectional causal relationship with EFP. In the CO₂ emissions model, GDP and GFCF exhibit unidirectional causality toward CO₂ emissions, while relationship is observed for REC and NRE, with unidirectional causality running from CO₂ emissions to REC and NRE.

4.7. Diagnostic Test

The diagnostic test results of the EFP and CO₂ models are shown in Table 10 and indicate that both models are well fitted, and the values of R² and adjusted R² are relatively large. The Jarque-Bera test shows that both models

follow a normal distribution of their residuals (shown in Figure 5), and the CUSUM and CUSUMQ tests show that the models are stable (shown in Figure 6 of the EFP model and Figure 7 of the CO₂ model). The results of the Breusch-Godfrey LM test indicate that there is no evidence of serial correlation, and all tests on heteroskedasticity problems (Breusch-Pagan-Godfrey, Harvey, Glejser, and ARCH) indicate that there are no heteroskedasticity problems. Lastly, the Ramsey RESET test ensures that both models are indeed specified properly. All in all, the diagnostic tests confirm that the models are statistically viable, stable, and robust, and can be used to make subsequent interpretations and policy analyses.

4.8. Wavelet Coherence Analysis Results

In the wavelet coherence plots, the color scale represents the degree of correlation between variables, with blue areas indicating weak coherence and red areas showing strong coherence. Thick black contours denote statistically significant regions at the 5% level, while the cone of influence (COI) marks the zone unaffected by edge distortions. The direction of arrows conveys both the phase relationship and the causal direction between



Figure 6. Stability Test Results for EFP Model: a) CUSUM; b) CUSUMQ.

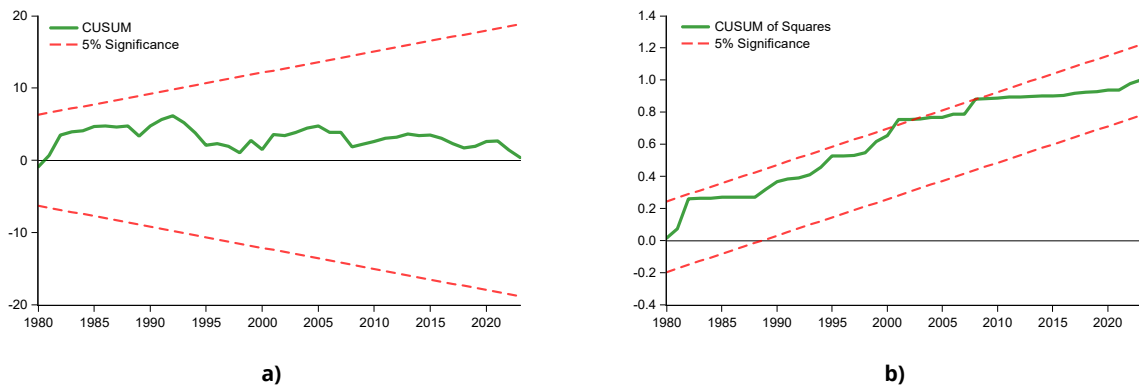


Figure 7. Stability test results for CO₂ model: a) CUSUM; b) CUSUMQ.

Table 11. Interpretation of wavelet coherence analysis.

Component	Description / Interpretation
Right arrows (→)	Positive correlation (in-phase) - both variables move together.
Left arrows (←)	Negative correlation (anti-phase) - variables move in opposite directions.
Right-up arrows (↗)	The second variable leads (causes) the first variable with a positive relationship.
Right-down arrows (↘)	The first variable leads (causes) the second variable with a positive relationship.
Left-up arrows (↖)	The second variable leads (causes) the first variable with a negative relationship.
Left-down arrows (↙)	The first variable leads (causes) the second variable with a negative relationship.
	Indicates the strength of the coherence between variables
Color scale (0 - 1)	Blue (0 - 0.3): weak coherence Green–Yellow (0.4 - 0.6): moderate coherence Orange–Red (0.7 - 1.0): strong coherence or high correlation
Short-term (period 0 - 4)	Represents high-frequency, short-run dynamics or immediate responses between variables.
Medium-term (period 4 - 8)	Represents medium-frequency cycles reflecting mid-run adjustments or interactions.
Long-term (period 8 - 32)	Represents low-frequency, long-run co-movements or equilibrium relationships between variables.

variables. Right-pointing arrows (→) indicate a positive, in-phase relationship, whereas left-pointing arrows (←) denote a negative, anti-phase relationship. Right-up arrows (↗) show that the second variable leads in a positive phase, while right-down arrows (↘) indicate that the first variable leads in a positive phase. Conversely, left-up arrows (↖) suggest that the first variable leads in a negative phase, and left-down arrows (↙) imply that the second variable leads in a negative phase. Short-term interactions are represented in high-frequency bands (period 0 - 4 years), medium-term in period 4 - 8 years, and long-term relationships in low-frequency bands (period 8 - 32 years). A detailed interpretation of color

intensity, arrow direction, and frequency band is presented in Table 11.

The wavelet coherence results between EFP and its main determinants (Figure 8a-d) reveal distinct temporal and frequency-dependent relationships that reflect Indonesia's evolving growth–environment dynamics over nearly six decades. Figure 8a (EFP vs GDP) displays a clear region of strong coherence between the late 1980s and early 2000s at medium-term periodicities (approximately 4 - 8 years), signifying a period when rapid economic growth and environmental degradation moved closely together. This synchronization corresponds with Indonesia's industrial expansion, urbanization, and

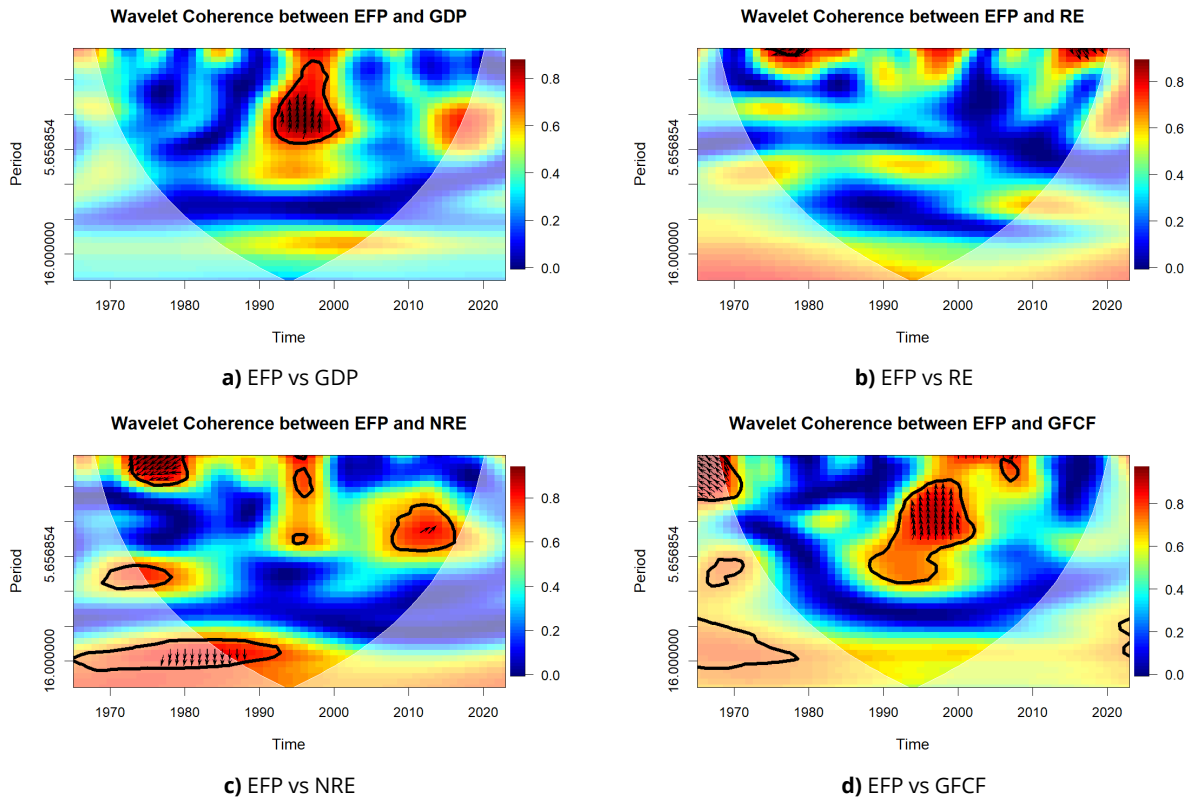


Figure 8. Wavelet coherence between EFP and selected independent variables.

resource exploitation during its high-growth era. The rightward-pointing arrows indicate a positive and in-phase relationship, where economic expansion directly amplified the ecological footprint, consistent with the upward phase of the EKC. After 2000, the coherence weakens, suggesting that while growth remains a major driver, its direct environmental impact has gradually lessened, possibly due to improved policy frameworks, economic diversification, and modest progress in cleaner production.

In [Figure 8b](#) (EFP vs RE), coherence is generally weak and fragmented, indicating that renewable energy adoption has played a limited and inconsistent role in influencing environmental quality throughout the observed period. Only small, localized patches of coherence appear after 2015, suggesting that recent policy shifts—such as renewable incentives and the gradual integration of solar and hydro power—may be starting to align with reductions in environmental degradation. Conversely, [Figure 8c](#) (EFP vs NRE) exhibits strong and sustained coherence during two key phases: the late 1970s–1980s and the post-2000 period. The positive correlation with EFP implies that increases in fossil fuel use, particularly coal and oil, have historically intensified ecological pressure. This confirms Indonesia’s structural dependence on non-renewables as a persistent environmental stressor despite global decarbonization

efforts. Lastly, [Figure 8d](#) (EFP vs GFCF) shows notable coherence during 1985 - 2000, reflecting how large-scale capital formation and infrastructure development contributed to higher ecological footprint levels. The relationship weakens after 2000, implying a gradual transition toward more sustainable or service-oriented investments. Overall, the four wavelet coherence plots collectively highlight that Indonesia’s environmental trajectory has been predominantly shaped by growth and fossil fuel consumption, with renewable energy and capital efficiency emerging only recently as potential moderating forces.

The wavelet coherence results between CO₂ and its main explanatory variables ([Figure 9a-d](#)) highlight how Indonesia’s emission dynamics evolved across different time scales and policy periods. [Figure 9a](#) (CO₂ vs GDP) shows moderate to strong coherence during the 1980s to early 2000s, corresponding with Indonesia’s rapid economic expansion and industrialization. The arrows in this period mostly point rightward, indicating a positive correlation—economic growth directly increased CO₂ emissions. After 2000, the coherence weakens, reflecting partial decoupling as Indonesia began introducing environmental management strategies and adopting cleaner production standards. This pattern supports the presence of an inverted N-shaped Environmental Kuznets Curve, where emissions decline temporarily at

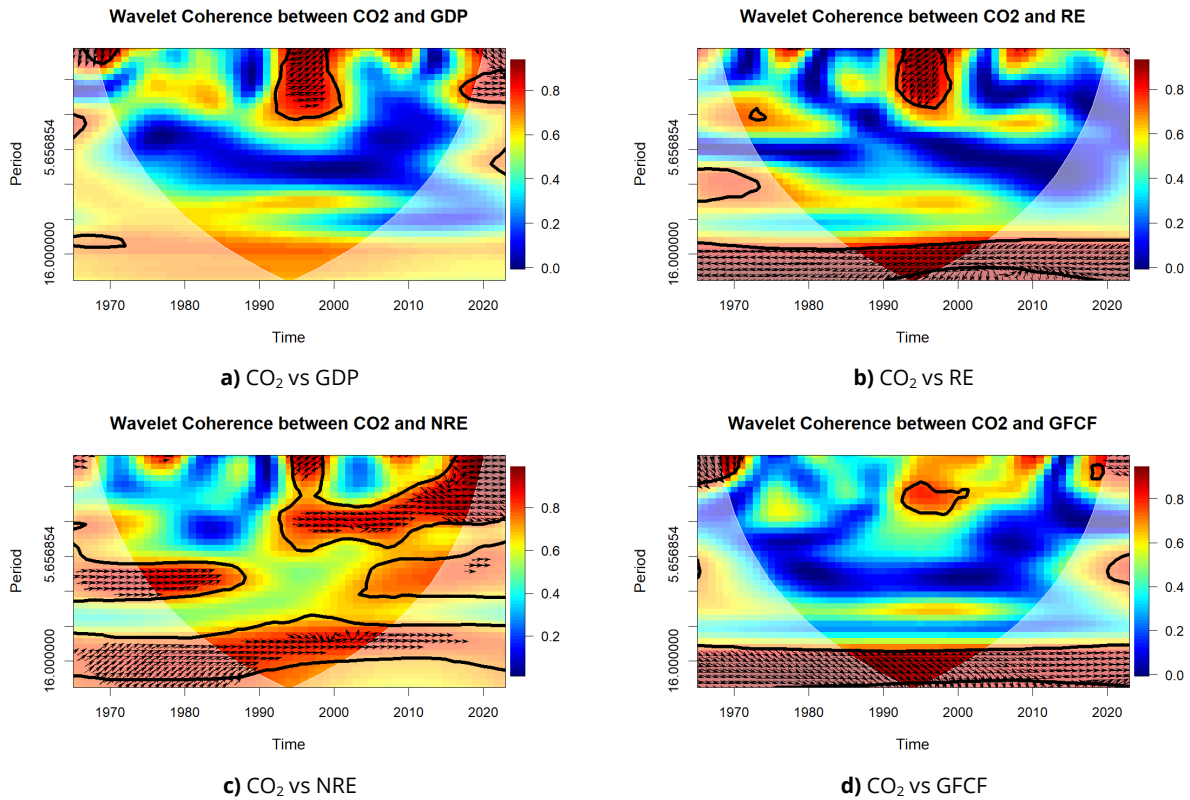


Figure 9. Wavelet coherence between CO₂ and selected independent variables

middle-income stages before stabilizing at higher growth levels.

In [Figure 9b](#) (CO₂ vs RE), localized but persistent coherence zones appear around 2000 - 2020, suggesting a strengthening negative relationship between renewable energy and CO₂ emissions, particularly at longer periods. This reflects the gradual impact of Indonesia's renewable energy policies, though the relatively small coherence areas confirm that renewables remain a minor share of the national energy mix. Conversely, [Figure 9c](#) (CO₂ vs NRE) displays the most pronounced and continuous coherence, particularly in the 1970s - 1980s and post-2000 phases, emphasizing that fossil fuel consumption remains the dominant driver of emissions. The arrows indicate a strong in-phase relationship, reinforcing the dependence of Indonesia's economic growth on carbon-intensive energy sources. Finally, [Figure 9d](#) (CO₂ vs GFCF) reveals notable coherence during the 1980s - 1990s and after 2010, indicating that capital investment has long-term effects on emissions. Initially, it amplifies CO₂ through infrastructure and industrial projects, but the coherence pattern has weakened in recent years, implying a gradual shift toward more efficient or greener capital utilization. Collectively, these results confirm that Indonesia's carbon trajectory is still closely linked to growth and fossil energy use, with

renewable expansion and investment efficiency showing emerging potential to moderate future emissions.

5. Discussion

The results of the ARDL estimations provide clear evidence of an EKC for Indonesia, with differing shapes across the EFP and CO₂ models. In the EFP model, the positive coefficient of GDP, the negative coefficient of GDP², and the positive coefficient of GDP³ confirm the presence of an N-shaped EKC, as shown in [Figure 10](#). This indicates that environmental degradation, measured by the ecological footprint, first rises with income, declines after reaching a certain turning point, and eventually increases again at higher levels of development. Such a trajectory reflects Indonesia's development path, where early industrialization and urban growth place heavy pressure on natural resources, followed by some improvements through efficiency gains and regulatory policies at middle-income levels. However, the resurgence of degradation at higher income levels points to the rebound effects of accelerated consumption, infrastructure expansion, and resource-intensive investment that again heighten ecological pressures. The finding of an N-shaped EKC for the ecological footprint in this study is supported by Tahir et al. [\[7\]](#) in 38 OECD countries, Jahanger et al. [\[87\]](#) in top nuclear energy-producing countries, Fakher et al. [\[92\]](#) in OPEC members, Huang et al. [\[93\]](#) in 199 districts and counties in the BTH

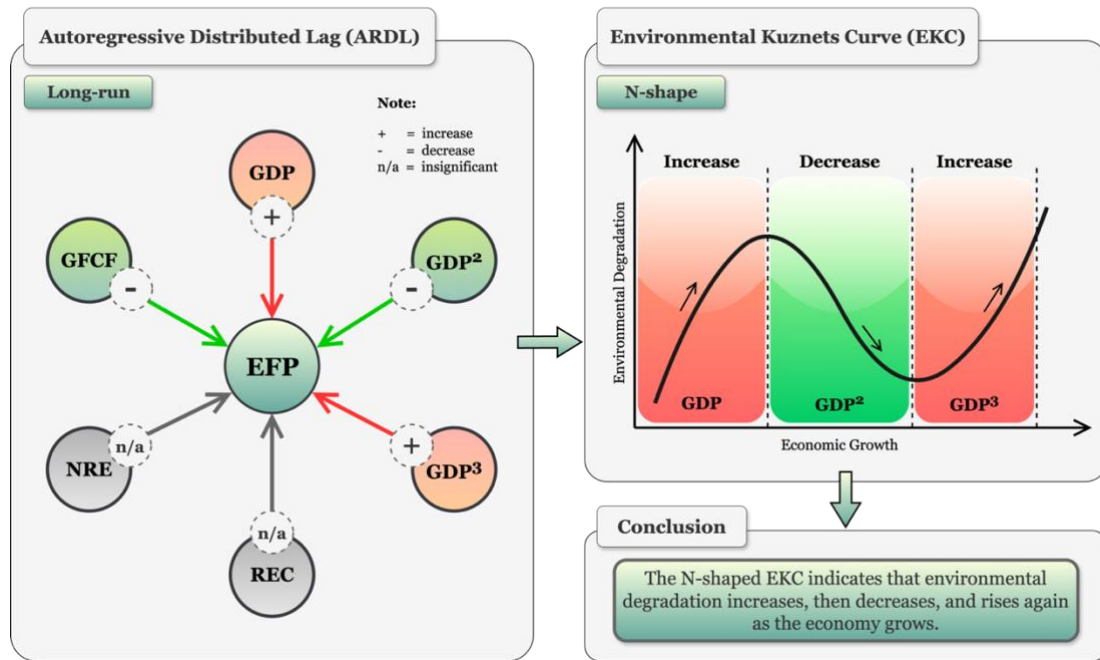


Figure 10. Graphical result of the EFP model.

region of China, Shehzad et al. [66] in Algeria, Farooq et al. [136] in India, and Sharma et al. [68] in eight developing countries in South and Southeast Asia. Furthermore, Malahayati [32] also supports this finding, reporting an N-shaped EKC in Indonesia with deforestation as the dependent variable.

In contrast, the CO₂ model exhibits an inverted N-shaped EKC, as reflected by the negative coefficient of GDP, the positive coefficient of GDP², and the negative coefficient of GDP³, displayed in Figure 11. This pattern suggests that CO₂ emissions initially decline as GDP rises, potentially due to efficiency gains and structural adjustments in early development phases. Emissions then increase during the middle-income stage, reflecting higher energy consumption and industrial expansion, before declining again at higher levels of income, where stricter regulations, technological progress, and the gradual integration of cleaner energy sources take effect. The inverted N-shape thus implies that while CO₂ emissions follow a more complex growth–environment path compared to the ecological footprint, Indonesia may eventually achieve some degree of long-term mitigation if cleaner energy transitions and strong environmental governance are sustained. Together, the differing EKC shapes highlight the multidimensional nature of Indonesia's environmental challenges, where pressures on ecological systems and CO₂ emissions do not always evolve in the same way, requiring tailored policy interventions for each dimension of sustainability. The finding of an inverted N-shaped EKC for CO₂ emissions in this study is supported by Ullah et al. [8] in 17 OECD countries, Hossain et al. [63] in India, Burki & Tahir [85] in

ASEAN, Tahir et al. [7] in 38 OECD countries, Allard et al. [60] in 74 countries, Narcisse et al. [88] Zeraibi et al. [95] Zhang [101] in China, Awan & Azam [89] in G-20 economies, Du et al. [64] in 35 OECD countries, Koc & Bulus [90] in Korea, Sinha et al. [91] in N-11 countries, Zeraibi et al. [65] in emerging economies countries, Özokcu & Özdemir [61] in 26 OECD and 53 emerging countries, Fakher et al. [92] in OPEC countries, Wang et al. [94] in 56 countries, Bekun et al. [96] in SSA, Bekun et al. [9] in SAC, Nica et al. [104] in BRICS, and Ali et al. [111] in Asian emerging economies. However, one finding from Indonesia by Ibrahim & Abbas [83] contrasts with our results, as their study reported an N-shaped EKC for CO₂ emissions in Indonesia.

Turning to the role of renewable energy and non-renewable energy, the results show contrasting outcomes between the ecological footprint model and the carbon dioxide emissions model, as presented in Figures 10 and 11. In the ecological footprint model, both renewable energy and non-renewable energy are statistically insignificant in the long run, indicating that neither energy source currently exerts a measurable effect on ecological sustainability. This suggests that Indonesia's energy structure, which remains dominated by fossil fuels and supported only by a relatively small share of renewable energy, is not yet capable of influencing resource-based environmental pressures in a significant way. In the CO₂ emissions model, the results are more conclusive. Renewable energy is found to significantly reduce carbon dioxide emissions in the long run, highlighting its central role in Indonesia's path toward a low-carbon economy. This finding suggests that

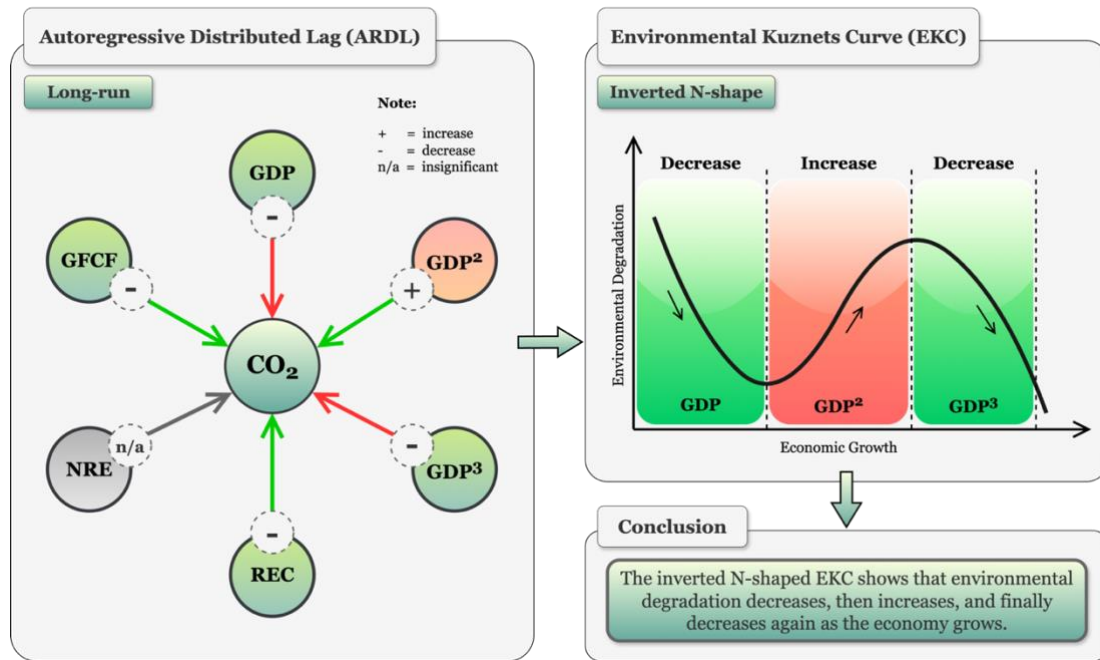


Figure 11. Graphical result of the CO₂ model.

even a gradual expansion of renewable energy capacity has already contributed to reducing CO₂ emissions, reflecting both the substitution of fossil fuels in electricity generation and the increasing efficiency of renewable technologies. The significance of this result emphasizes that scaling up renewable deployment through investment, supportive policy frameworks, and infrastructure development can deliver meaningful emission reductions. This result aligns with the findings of Abbasi et al. [69], Allard et al. [60], Koc & Bulus [90], Sinha et al. [91], Bulut & Tekdemir [70], Zeraibi et al. [65], Fakher et al. [92], Sun et al. [71], Bekun et al. [9], Qayoom & Altaf [74], Nica et al. [104], Nica et al. [106], Ali et al. [111], and Balsalobre-Lorente et al. [105], who reported that renewable energy has the ability to reduce CO₂ emissions in the long run. In contrast, non-renewable energy remains insignificant in the CO₂ model, which may reflect efficiency improvements in fossil fuel use or offsetting effects from technological advances. Taken together, these findings indicate that while renewable energy has begun to demonstrate tangible benefits in mitigating carbon emissions, its role in reducing broader ecological pressures remains limited. This underscores the urgency of accelerating Indonesia's clean energy transition in order to align economic growth with long-term environmental sustainability.

Finally, the role of gross fixed capital formation proves to be critical in both models, as shown in Figures 10 and 11. In both the ecological footprint and carbon dioxide emissions models, capital formation carries a negative and significant coefficient in the long run, indicating that

investment activity contributes to improvements in environmental quality rather than deterioration. This suggests that capital accumulation in Indonesia is increasingly directed toward modern infrastructure, cleaner technologies, and efficiency-enhancing assets that lower both resource intensity and emissions. Such a result contrasts with the conventional view that investment-driven growth is inherently resource-intensive and environmentally harmful, instead pointing to a structural shift in Indonesia's economy where new capital is more likely to incorporate environmentally friendly technologies and sustainable practices. This is especially relevant to Indonesia today, as the country is heavily investing in renewable energy projects, industrial upgrading, and transportation infrastructure to reduce reliance on coal and improve energy efficiency. Maintaining strong and sustainable capital formation is therefore essential to ensure that these investments continue to reduce ecological pressures while supporting economic growth. By prioritizing productive investment in sectors such as renewable energy, green industry, and sustainable urban development, Indonesia can preserve environmental gains and reinforce its commitment to achieving carbon neutrality by 2060. These findings are consistent with previous evidence, as Idroes et al. [13] and Idroes et al. [30] reported that capital formation reduces the ecological footprint in the long run, while Guevara-Segarra et al. [132], Södersten et al. [137], Maulidar et al. [138], Idroes et al. [139] and Anwar & Elfaki [140], found similar results for CO₂ emissions. Nonetheless, several studies, including Wang & Xu [141], Chekouri et al. [142], and Aderinto & Ogunro [143], argue

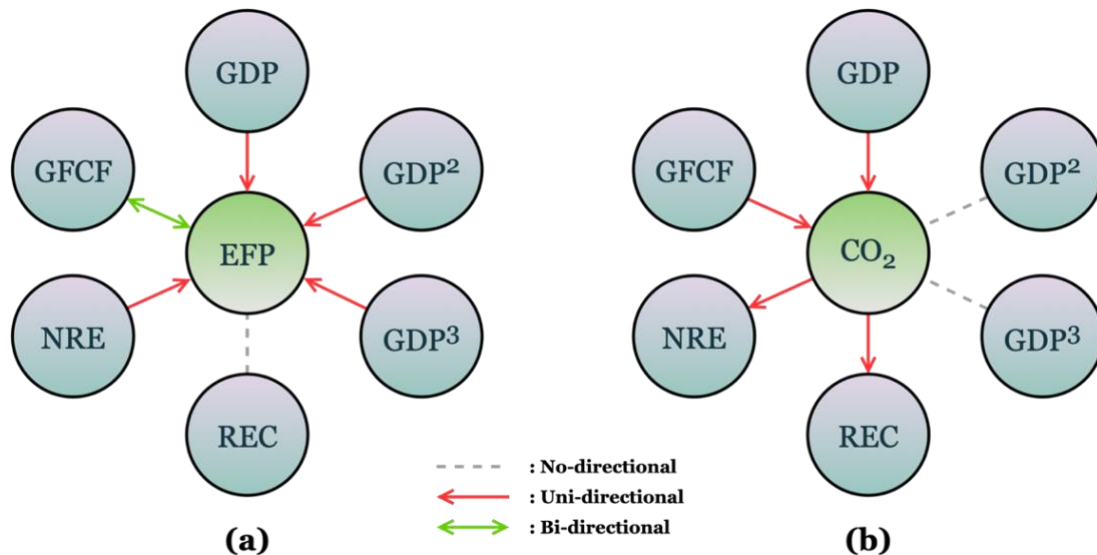


Figure 12. Overview of Granger causality results for (a) the EFP model and (b) the CO₂ model.

that capital formation can increase environmental degradation rather than improve environmental quality.

Turning to the Granger causality results presented in Figure 12, the EFP model shows that GDP, GDP², and GDP³ all exhibit a unidirectional causality toward EFP, meaning that changes in economic growth help predict variations in ecological pressure, but not vice versa. This finding is consistent with Sharma et al. [68]. In addition, non-renewable energy displays a unidirectional causality toward EFP, meaning that fossil fuel consumption helps predict changes in ecological degradation, in line with the results of Usman et al. [144], Saqib [145], and Dogan et al. [146]. Moreover, a bidirectional causality is observed between capital formation and EFP, meaning that capital formation helps predict changes in ecological footprint and vice versa, as reported by Idroes et al. [26]. In the CO₂ emissions model, only GDP is found to have a unidirectional causality toward CO₂ emissions, meaning that economic growth helps predict changes in emissions, while GDP² and GDP³ show no causal relationship, implying that nonlinear income terms do not predict emissions. This result aligns with the findings of Miyan et al. [50] and Ameyaw & Yao [147]. Furthermore, CO₂ emissions exhibit a unidirectional causality toward both non-renewable and renewable energy consumption, meaning that emissions help predict the pattern of energy use, as reported by Miyan et al. [50], Idroes et al. [13], Bekhet & Othman [77], and Idroes et al. [30]. Lastly, capital formation demonstrates a unidirectional causality toward CO₂ emissions, meaning that investment activity helps predict changes in emissions, as supported by Idroes et al. [139].

The wavelet coherence analysis for the EFP model (Figures 8a-d) provides a detailed view of Indonesia's

environmental dynamics over time. The EFP vs GDP relationship exhibits strong coherence during the late 1980s to early 2000s, coinciding with Indonesia's industrial expansion and urbanization, confirming that economic growth had a direct positive association with ecological pressure during this phase. This coherence weakens after 2000, suggesting early signs of decoupling as environmental regulations and efficiency improvements emerged. The EFP vs RE relationship shows limited but increasing coherence post-2010, reflecting the slow yet steady penetration of renewables. In contrast, EFP vs NRE demonstrates strong and persistent coherence throughout, underscoring the long-standing dependence on fossil fuels as a key driver of ecological stress. Lastly, the EFP vs GFCF interaction indicates that investment activities were initially emission-intensive but gradually became more efficient, particularly after the late 1990s, suggesting structural changes toward greener capital utilization. Collectively, these findings validate the ARDL results, confirming that while growth and fossil energy remain major contributors to environmental degradation, renewable expansion and investment efficiency are progressively influencing Indonesia's environmental footprint. For the CO₂ model (Figures 9a-d), the wavelet coherence patterns reveal distinct but complementary insights. The CO₂ vs GDP coherence is concentrated in the 1980 - 2000 period, aligning with rapid industrial growth and increased fossil fuel use, while the weakening coherence afterward implies partial decoupling of emissions from growth. The CO₂ vs RE relationship, though relatively weak, displays emerging negative coherence since 2000, indicating that renewable deployment has begun exerting downward pressure on emissions, albeit at a modest scale. The CO₂ vs NRE coherence remains the strongest and most

consistent, particularly before and after 2000, reaffirming fossil fuels' persistent influence on emission levels. Meanwhile, the CO₂ vs GFCF relationship shows notable coherence during the 1980s-1990s, reflecting infrastructure-driven emissions, but gradually diminishes in recent years, implying a shift toward cleaner or more efficient capital investments. Overall, the wavelet coherence results support the nonlinear and time-varying nature of Indonesia's growth-environment relationship, where policy and technological adaptation gradually moderate the environmental costs of development.

6. Summary of the Study

6.1. Conclusion

This study examined the relationship between economic growth, renewable and non-renewable energy, and capital formation on environmental quality in Indonesia during the period 1965-2023, using the Autoregressive Distributed Lag (ARDL) approach and Granger causality analysis. Environmental quality was measured through the ecological footprint and CO₂ emissions, providing a broad perspective on both resource use and emission dynamics. The results confirm the existence of nonlinear EKC patterns, with an N-shaped trajectory for the ecological footprint and an inverted N-shaped trajectory for carbon dioxide emissions. These findings indicate that while economic growth initially worsens environmental pressures and subsequently allows for improvements, degradation tends to reappear at higher income levels, reflecting renewed ecological and carbon challenges. At the same time, capital formation plays a constructive role by reducing both ecological footprint and emissions, suggesting that investment has been increasingly directed toward more efficient and environmentally friendly assets. Renewable energy significantly reduces carbon dioxide emissions but shows no effect on the ecological footprint, while non-renewable energy remains insignificant in both models. Taken together, the evidence highlights Indonesia's central challenge of reconciling sustained economic progress with long-term environmental sustainability.

The Granger causality analysis gives more information on the direction of the relationships between the two variables under examination. The findings indicate that economic growth (GDP, GDP² and GDP³) is statistically predictive of the changes in the ecological footprint and CO₂ emission and prove the presence of dynamic relationships between the income levels and the ecological quality. Renewable energy also exhibits a predictive correlation with the CO₂ emissions, which implies that changes in the renewable energy mix can

have a quantifiable effect on the reduction of emissions. In the meantime, the gross fixed capital formation and ecological footprint also exhibit a bidirectional causal relationship, indicating that investment activities and environmental outcomes affect each other in the long run. Wavelet coherence results indicate strong co-movement between economic growth and non-renewable energy with EFP and CO₂, confirming that fossil-fuel-driven expansion remains the main driver of degradation. In contrast, renewable energy and capital formation show negative coherence with environmental indicators, reflecting their growing role in mitigating ecological stress.

6.2. Policy Recommendations

Following the results of this research, the following policy recommendations are suggested, aiming to make Indonesia more sustainable in achieving economic growth and enhancing environmental quality:

6.2.1. Incorporate Environmental Sustainability in Economic Planning

The nonlinear EKC dynamics indicate that economic growth alone is not sufficient to ensure long-term environmental improvement. The RPJPN 2025 - 2045 and other national development plans should integrate clear environmental sustainability targets so that industrial, trade, and infrastructure policies are aligned with Indonesia's low-carbon growth agenda. Strengthening environmental considerations within the country's strategic development framework will help ensure that future economic expansion supports both productivity and ecological preservation.

6.2.2. Rapid Renewable Energy Development

As a country that emits high levels of CO₂, it is important to increase efforts to increase the renewable energy mix in Indonesia, given that renewable energy can do a great deal. These resources should be developed through emphasis on solar, hydro, geothermal, and wind development, especially in the eastern part of Indonesia, where they have not been utilized. Improvement of grid infrastructure, rural electrification using renewables and provision of feed-in tariffs or tax exemption will aid in attracting the interest of the private sector.

6.2.3. Decrease Reliance on Fossil Fuel slowly

The fact that non-renewable energy is insignificant in terms of the quality of the environment shows how much should be done to stop the use of coal and oil. Indonesia needs to introduce a gradual process of coal retirement, which would be in line with the Just Energy Transition Partnership (JETP), while being able to provide energy

security by diversifying. Short-term policies should be favorable to the clean coal technology and offer worker reskilling programs to those communities that depend on fossil fuel industries.

6.2.4. Encourage Green and Productive Capital Formation

This discovery that gross fixed capital formation decreases the ecological footprint and the level of CO₂ emission exemplifies why investment should be oriented towards environmentally friendly industries. Green infrastructure should be supported by the government, and there should also be development of industrial upgrading that is energy efficient and sustainable urban planning. Green technology can be financed by mobilizing public-private partnerships. Fiscal incentives should be used to reward those firms that adopt low-emission technologies and resource-efficient processes.

6.2.5. Enhance Institutional Capacity and Environmental Governance

Much effort should be made to coordinate various agencies in managing the environment. To enforce the emission standards, control the compliance of the industrial performance by the institutions, and enhance the transparency of data, it is important to strengthen institutions like the Ministry of Energy and Mineral Resources (ESDM) and the Ministry of Environment and Forestry (KLHK). The implementation of digital monitoring and community-based reporting of the environmental situation may increase accountability.

6.2.6. Promote Community Education and Behavior

The participation of society is also required in sustainable development. Campaigns and education of the government should be made to conserve energy, reduce wastage, and use renewable technologies at home and the local level. Partnerships with universities, non-governmental organizations, and local authorities can help to speed up community-based renewable initiatives and improve environmental awareness.

6.2.7 Make the National Policy consistent with the Global Commitments

The commitment of Indonesia to meet net-zero emissions by 2060 should have a regular domestic policy. A carbon pricing system, increased access to climate financing, and the incorporation of EKC knowledge into environmental planning will guarantee the compatibility of economic growth and the global climate goals.

6.3. Limitations and Future Research

While this study provides new evidence on the energy-growth-environment nexus in Indonesia, some

limitations remain. The use of aggregate national data may overlook important regional differences across provinces, which are likely to experience growth and environmental pressures unevenly. The study also distinguishes only between renewable and non-renewable energy, without exploring the heterogeneous impacts of specific energy sources such as coal, oil, hydropower, or solar. In addition, although the ARDL approach captures both short- and long-run dynamics, it does not fully account for structural changes or major policy interventions that may have influenced Indonesia's energy-environment relationship over the past five decades. Future research could extend this work by employing provincial panel data, testing for structural breaks, and incorporating additional explanatory variables such as trade openness, technological innovation, or institutional quality. Comparative studies with other Asian emerging economies would also enrich the understanding of how countries at similar stages of development manage the balance between economic growth and environmental sustainability.

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