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RESEARCH ARTICLE

Economic performance of Indonesia amidst CO_2 emissions and agriculture: a time series analysis

Tomiwa Sunday Adebayo[1] · **Gbenga Daniel Akinsola**[2] · **Dervis Kirikkaleli**[3] · **Festus Victor Bekun**[4,5] · **Sukru Umarbeyli**[6] · **Oseyenbhin Sunday Osemeahon**[7]

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Abstract

To minimize the awful situation confronting the entire globe, the global warming danger has raised the intensity of consciousness from all areas of life. Therefore, the research assesses the impact of CO_2 emissions and energy use on economic performance and considers trade openness, urbanization, and agriculture in Indonesia utilizing data covering the period from 1965 to 2019. The current research employed the dynamic ordinary least square (DOLS) and autoregressive distributed lag (ARDL) tests to capture the long-run association between these economic indicators. Furthermore, the gradual shift and wavelet coherence tests are utilized to capture the direction of causality. The ARDL bound test discloses a long-run interconnection among the variables of interest. The outcomes of the ARDL and DOLS depict that CO_2 emissions, agriculture, energy use, and urbanization trigger economic growth. Moreover, the wavelet coherence test findings revealed a positive correlation between economic growth and urbanization, CO_2 emissions, agriculture, and energy consumption. Furthermore, there is evidence of a weak and positive correlation between economic growth and trade openness. The gradual shift causality test outcomes disclosed that economic growth can predict urbanization and energy consumption, while agriculture can predict economic growth. These outcomes have far-reaching significance for economic growth and the selected variables in Indonesia.

Keywords Economic growth · Agriculture · Urbanization · CO_2 emissions · Energy use · Wavelet coherence · Indonesia

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✉ Tomiwa Sunday Adebayo
twaikline@gmail.com

Gbenga Daniel Akinsola
gbengadan@yahoo.com

Dervis Kirikkaleli
dkirikkaleli@eul.edu.tr

Festus Victor Bekun
fbekun@gelisim.edu.tr

Sukru Umarbeyli
sukru.umarbeyli@akun.edu.tr

Oseyenbhin Sunday Osemeahon
ose.sunday@gmail.com

1 Department of Business Administration, Faculty of Economics and Administrative Science, Cyprus International University, Nicosia, Mersin, Northern Cyprus TR-10, Turkey

2 Department of Business Management, Faculty of Economics and Administrative Sciences, Girne American University, Mersin, North Cyprus, Turkey

3 Department of Banking and Finance, Faculty of Economics and Administrative Sciences, European University of Lefke, Mersin, Lefke, Northern Cyprus TR-10, Turkey

4 Faculty of Economics Administrative and Social sciences, Istanbul Gelisim University, Istanbul, Turkey

5 Department of Accounting, Analysis and Audit, School of Economics and Management, South Ural State University, 76, Lenin Aven, Chelyabinsk, Russia 454080

6 University of Mediterranean Karpasia, TR-10 Mersin, Northern Cyprus, Turkey

7 Department of Management Information Systems, School of Applied Sciences, Cyprus International University, Nicosia, Mersin, Northern Cyprus TR-10, Turkey

Introduction

To minimize the awful situation confronting the entire globe, the global warming danger has raised the intensity of consciousness from all areas of life. The main root of climate change is human being's operations on the earth's surface, which leads to the destruction of the environment (Adebayo and Kirikkaleli 2021; Zafar et al. 2021). With global warming advent, both individual and global countries have been charged with planning and working towards mitigating global warming. Climate change is a huge problem that has raised domestic and international alertness to mitigate the growing trend (Alola et al. 2019; Ahmed et al. 2020a; Adedoyin et al. 2020; Kirikkaleli et al. 2021). The emissions from diverse sources of energy, particularly fossil fuels and other nonrenewable sources of energy, are spread as contaminant components into the air. They will adversely affect both the health of the masses and the environment. The air pollutants also have access to clean water sources and wetlands that poison or damage marine life and pollute clean water.

Economic growth has been described as causing the disastrous impact of pollution among several measures considered. Several economic practices, both directed at and based on economic growth, contribute to pollutants' emissions (Bekun and Agboola 2019; Khan et al. 2020b; Odugbesan and Adebayo 2020; Ahmed et al. 2020c). Such economic activity from multiple sectors (agriculture, petroleum, energy mining, and manufacturing sector), as summed up in economic growth, are all triggers for pollution (Udemba 2020). Moreover, it impacts public wellbeing with various forms of diseases, such as cancer, gaseous disease, and heart disease Pope III and Dockery (2006). The global prevailing expert viewpoint is that economic expansion is reliant on energy due to its position in improving income generation and development, stimulating employment, and accelerating productivity. Likewise, the literature on energy economics shows that the two major influences impacting the climate are economic growth and energy use. For instance, Khan et al. (2020a), Olanrewaju et al. (2021), Rjoub et al. (2021), and Akinsola and Adebayo (2021) establish that the main cause of environmental degradation in various countries and regions is energy usage and economic growth. The studies of Adebayo (2020), Kirikkaleli et al. (2020), Zhang et al. (2021), and Nathaniel et al. (2021) established that the use of energy from nonrenewable sources increases CO_2, which in turn decrease environmental sustainability. This stance is reinforced by the optimistic association between fossil fuel consumption and economic growth, which implies that GDP growth contributes to higher energy utilization and higher CO_2 emissions, respectively (Asongu et al. 2020; Khan et al. 2021; Adebayo 2021; Dogan et al. 2020). Also, emissions are created by agricultural activities, such as bush burning, herding activities, land reclamation, application of fertilizers, and other chemicals.

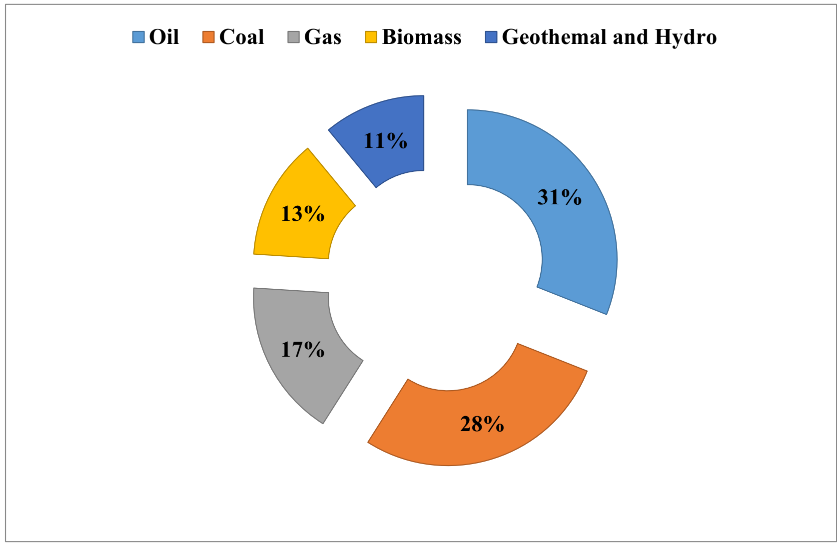
Indonesia's economy, dominated by the agriculture and energy sectors, is perceived to be an encouraging forum for dirty industrial activities. Minerals, electronic equipment, oil and gas, rubber goods, and crude palm oil are Indonesia's most essential export commodities. Nevertheless, as a percentage of GDP, Indonesia's exports of goods and services are comparatively low, at 20%. Indonesian exports in 2019 peaked at US$206 billion (World Bank 2020). Moreover, it should be remembered that most of the emerging economies (including Indonesia) that are expanding economic activity are increasing greenhouse gas (GHGs) emissions in the same way. In 2019, Indonesia is recognized as the 8th largest GHGs emitter EIA (2021). This illustrates that economic activity and GHGs emissions are rising at almost the same time.

If proper LCDIs[1] are not taken into account to make economic growth more eco-friendly, they will likely be in the same up-surging direction. No wonder this warning has encouraged the nation to peg its carbon reduction goal to 43% by 2030 whereas striving to produce GDP growth of 5.6 to 6.0% yearly over the next 25 years. Nonetheless, if the nation ever slacks in curbing the unnecessary use of coal, the nation's dream of transitioning to a low-carbon economy will lead to nothing. At present, to maintain its economy, the nation still depends on fossil fuels. The total energy consumption has increased by 3.1%/year since 2013 in Indonesia. As depicted in Fig. 1, oil is the country's dominant source of energy, providing 31% of the total (2019), but its market share is decreasing (35% in 2012). Coal comes second with 28%, while gas accounts for 17%, biomass for 13%, and geothermal and hydro for 11% (2019). The share of coal is increasing (+15% points since 2012), largely at the expense of oil (Enerdata 2020).

Over the years, numerous studies are done regarding the association between GDP and trade openness. However, mixed results have surfaced. For instance, some studies (Udemba 2019; Demet Kalmaz and Adebayo 2020; Bekun et al. 2020) found insignificant interaction between and GDP and trade openness, while the studies of Kong et al. (2020), Raghutla (2020), and Hdom and Fuinhas (2020) and Alam and Sumon (2020) found significant linkage between trade openness and economic growth. Also, Rahman and Vu (2020) and Amna Intisar et al. (2020) disclosed a negative association between trade and GDP. Recently, several scholars have assessed the association between urbanization and GDP growth. However, their outcomes are mixed, making it difficult to explore urbanization's exalt effect on economic growth. For instance, the study of Nathaniel and Bekun et al. (2020), Bekun and Agboola (2019), and Udemba et al. (2021) established that urbanization increase economic growth, while some studies (Nathaniel and Bekun 2020; Kong et al. 2020) found a negative connection between population and economic development. Thus, the present research

[1] Low-carbon development initiatives

Fig. 1 Total energy consumption in Indonesia in 2019



assesses the association between economic growth, energy usage, urbanization, agriculture, and CO_2 emissions in Indonesia between 1965 and 2019.

Given this progress, there has been limited emphasis on examining this pattern's importance in the midst of the Indonesian economy's optimistic and substantial growth. Despite this, the research is intended to explore the economic performance in Indonesia amidst CO_2 emissions. The current research is distinct from the existing studies because it accounts for other economic growth determinants such as urbanization, agriculture, energy usage, CO_2 emissions, and energy use. This report expands/complements the Indonesian economy discussion on the growth energy and pollution nexus and expands on the research of Udemba (2019). The research is inspired by the Sustainable Development Goals (SDGs-7, 8, 12, and 13). It discusses specific energy use concerns (SDG-7), emphasizing green and sustainable energy use (SDGs-7 and 12) to meet the 2020 Agenda. This is to avoid problems associated with economic growth (SDGs-8) and climate change (SDGs-13). The present research is especially timely and deserving of inquiry, particularly in the current age in which responsible energy use and environmental protection are increasingly being targeted.

This research is distinctive in its growth-based approach that is constructed following the EKC theory. This EKC is based merely on the trade-off between environmental degradation and economic performance. Most research on Indonesian emissions' involvement has considered an environmental paradigm that often gives a different understanding of the nation's emissions without any reference to its economic growth. Indonesia is anticipated to induce emissions through its economic growth operations as an emerging economy. That is why it is important to explore the growth-linked emissions of the nation with the growth-based framework. This research's importance can also be seen from Indonesia's stance in the world in geography, economics, politics, and agriculture. However, the nation's distinctiveness means that some of the ramifications in Indonesia's current analysis are relatively important to several nations in East Asia and the Pacific region. This research contributes to the literature by applying the novel wavelet coherence test to investigate the dynamics between the variables of interest. The advantage of the wavelet test is that it can capture correlation and causal interconnection between series. To the understanding of the investigators, prior studies did not utilize this technique to assess the connection between these economic indicators in the case of Indonesia. Thus, the present study fills the gap in the ongoing literature. Table 1 presents the summary of related studies.

The concluding part of this report is planned in the following ways: the "Data and methodology" section presents the methodology and data. The "Findings and discussions" section presents analytical outcomes. The "Conclusion" section concludes the research.

EC energy use, *CO_2* carbon emission; ⇨ (+), positive relationship; ⇨ (−), negative relationship; ⇨, one-way causality; ⇔, bidirectional causality; *URB* urbanization, *TO* trade openness, *AGRIC* agriculture, *GDP* economic growth, *TY* Toda-Yamamoto

Data and methodology

Data

The study examines the impact of agriculture (AGRIC) and CO_2 emissions (CO_2) on economic growth (GDP) and also consider the role of urbanization (URB), trade openness (TO), and energy use in Indonesia utilizing data stretching between 1965 and 2019. In Indonesia's case, the current paper was apprehended to assess the associations between GDP, CO_2

Table 1 Summary of related studies

Authors	Timeframe	Nation(s)	Methods	Findings
Economic growth and CO_2 emissions				
Bouznit and Pablo-Romero (2016)	1970–2010	Algeria	ARDL	CO_2 ⇨ GDP (+)
Adebayo (2020)	1971–2016	Mexico	ARDL and wavelet coherence	CO_2 ⇔ GDP
Gyamfi et al. (2020)	1990–2018	Emerging nations	Kao cointegration, panel DOLS, FMOLS, D-H causality	CO_2 ⇨ GDP (+) CO_2 ⇨ GDP
Akinsola and Adebayo (2020)	1971–2016	Thailand	ARDL and wavelet coherence, Granger and Toda-Yamamoto causality	CO_2 ⇨ GDP
Zhang et al. (2021)	1970–2016	Malaysia	ARDL, FMOLS, DOLS, wavelet, gradual shift causality	CO_2 ⇨ GDP (+) GDP ⇨ CO_2
Awosusi et al. (2021)	1980–2018	MINT Nations	Panel ARDL, D-H causality	CO_2 ≠ GDP GDP ⇨ CO_2
Adebayo (2021)	1980 to 2016	Thailand	ARDL, FMOLS, DOLS, wavelet	Positive comovement between CO2 and GDP
Udemba et al. (2021)	1981–2018	India	ARDL, Granger causality	CO_2 ⇨ GDP (+) CO_2 ⇨ GDP
Gao and Zhang (2021)	1980–2010	13 Asian developing countries	FMOLS and panel Granger causality tests	CO_2 ⇨ GDP
Economic growth and energy use				
Emir and Bekun (2019)	1990Q1–2014Q4	Romania	ARDL, Toda-Yamamoto causality	EC ⇨ GDP (+) EC ⇨ GDP
Balcilar et al. (2019)	1971–2014	Pakistan	ARDL, TY causality	EC ⇨ GDP (+) GDP ⇨ EC
Bekun and Agboola (2019)	1971–2014	Nigeria	Maki (2012) cointegration, DOLS, FMOLS	EC ⇨ GDP (+) EC ⇨ GDP
Saint Akadiri et al. (2019)	1973–2014	South Africa	ARDL, TY causality	EC ⇨ GDP
Udi et al. (2020)	1973–2014	South Africa	ARDL, TY causality	EC ⇨ GDP (+) EC ⇨ GDP
Nathaniel and Bekun et al. (2020)	1971–2014	Nigeria	DOLS, FMOLS, CCR, VECM	EC ≠ GDP
Sharma et al. (2020)	2000–2017	10 emerging and developing Asian countries	DOLS, FMOLS, panel D-H causality	EC ⇔ GDP EC ≠ GDP
Economic growth and urbanization				
Shahbaz et al. (2015)	1970–2011	Malaysia	ARDL, causality	URB ⇨ GDP (+)
Yang et al. (2017)	2000–2010	China	panel OLS	URB ⇨ GDP (+)
Nguyen (2018)	1971–2014	ASEAN	D-GMM and PMG	URB ⇨ GDP (+)
Nathaniel and Bekun et al. (2020)	1971–2014	Nigeria	FMOLS, DOLS, CCR, VECM Granger Causality	URB⇨ GDP (−) URB ⇔ GDP
Kong et al. (2020)	1981–2017	Top 10 mineral-rich countries	NARDL	Mixed findings
Talbi et al. (2020)	1980–2018	Tunisia	ARDL, Granger causality	URB ⇨ GDP (+) GDP ⇨ URB
Economic growth and trade openness				
Keho (2017)	1965–2015	Ivory Coast	ARDL, Toda and Yamamoto Granger causality	TO ⇨ GDP (+) TO ⇨ GDP
Elfaki et al. (2020)	1975–2014	Sudan	ARDL, Granger causality	TO ⇨ GDP (+)
Beton Kalmaz and Adebayo (2020)	1980-2018	Nigeria	ARDL, Granger causality	TO ≠ GDP TO ⇨ GDP (+)
Zheng and Walsh (2019)	2001–2012	China	GMM	TO ≠ GDP
Adebayo (2021)	1970–2015	Japan	ARDL, wavelet coherence	TO ≠ GDP
Economic growth and agriculture				
	1972–2012	Pakistan	ARDL, Granger causality	AGRIC ⇨ GDP (+)

Table 1 (continued)

Authors	Timeframe	Nation(s)	Methods	Findings
Awan and Aslam (2015)				
Matthew and Mordecai (2016)	1981–2014	Nigeria	Johansen cointegration, ECM	AGRIC ⇨ GDP (+)
Udemba (2020)	1981–2018	Nigeria	ARDL, Granger causality	AGRIC ⇨ GDP (+) AGRIC ⇨ GDP
Sertoglu et al. (2017)	1981–2013	Nigeria	Johansen cointegration, ECM	AGRIC ⇨ GDP (+)
Matandare (2017)	1980–2016	Zimbabwe	OLS	AGRIC ⇨ GDP (+)

pollution, urbanization, energy use, agriculture, and trade openness. The empirical modeling is based on the ARDL technique. This analysis is centered on Udemba et al. (2021) research by adjusting for further growth facilitators that have been overlooked in prior studies, including growth theory caused by the urban population. For Indonesia's case with the same economic characteristics, urban population is included in the present study. The parameters utilized are transmuted into a logarithm. This was conducted to ensure that data is normally distributed (Adedoyin et al. 2020; Wang et al. 2021). Table 2 portrays the data unit of measurement and source. Also, the flow of analysis is depicted in Fig. 2. The study function and econometric model are presented in Eqs. 1 and 2:

$$GDP_t = f(CO_{2t}, EC_t, TO_t, URB_t, AGRIC_t) \quad (1)$$

$$GDP_t = \vartheta_0 + \vartheta_1 CO_{2t} + \vartheta_2 EC_t + \vartheta_3 TO_t + \vartheta_4 URB_t + \vartheta_5 AGRIC_t + \varepsilon_t \quad (2)$$

In Eqs. 1 and 2, CO_2, EC, TO, AGRIC, GDP, and URB represent CO_2 emissions, energy use, trade openness, agriculture, economic growth, and urbanization. Also, "t" illustrate the period of study (1965–2019), the parameters are depicted by ϑ_1, ϑ_2, ϑ_3, ϑ_4, and ϑ_5, while the error term is represented by ε.

Constant expansion of the economy has contributed to an upsurge in GDP, leading to higher energy demand, contributing more to emissions (Adebayo 2021). Furthermore, output expansion and CO_2 emissions are positively linked with ecological footprint because of constant natural resource misuse. Thus, CO_2 is projected to lead to increased economic growth $\left(\beta_1 = \frac{\delta GDP}{\delta CO_2} > 0\right)$. Furthermore, energy use is projected to impact GDP positively, which indicates that an upsurge in EC will increase GDP $\left(\beta_2 = \frac{\delta GDP}{\delta EC} > 0\right)$. Moreover, following the research of Udemba (2020) and Beton Kalmaz and Adebayo (2020), we incorporate trade openness into our model. It is anticipated that trade openness will exert a positive impact on economic growth, which infers that an upsurge in trade openness will increase GDP $\left(\beta_3 = \frac{\delta GDP}{\delta TO} > 0\right)$. Following the study of Zhang et al. (2021) and Udemba et al. (2021), the investigators introduced urbanization into the model. Thus, an upsurge in urban population is projected to exert a positive impact on GDP, which infers that an upsurge in urban population will trigger GDP $\left(\beta_4 = \frac{\delta GDP}{\delta URB} > 0\right)$. Agriculture is anticipated to impact GDP positively, which infers that an upsurge in agriculture will lead to an increase in GDP $\left(\beta_5 = \frac{\delta GDP}{\delta AGRIC} > 0\right)$.

Methodology

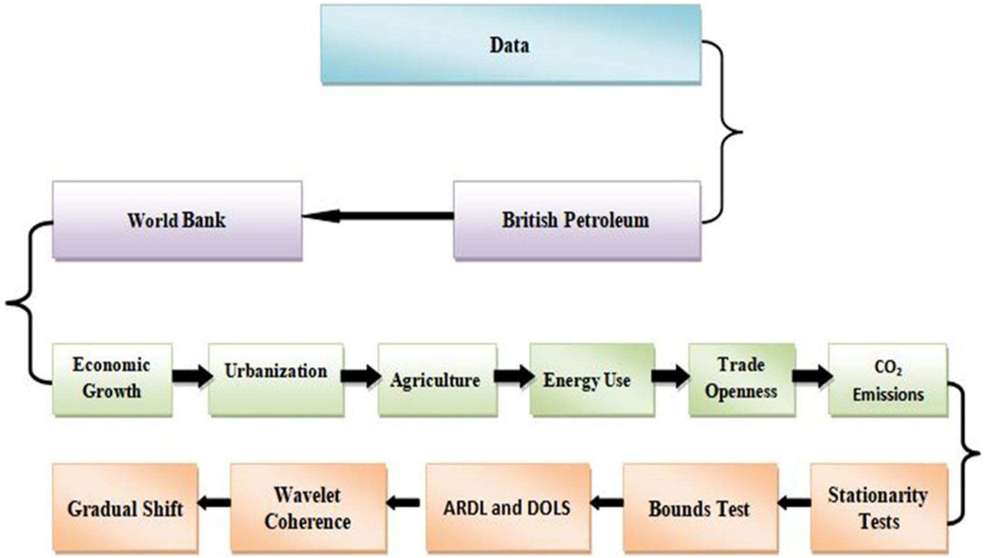
Stationarity test

This research's primary motive is to explore the impact of trade openness, CO_2 emissions, energy use, urbanization, and agriculture on economic growth in Indonesia. The study utilized both the PP and KPSS unit root tests initiated by Phillips and Perron (1988) and Kwiatkowski et al. (1992) to investigate the order of integration in which the parameters are

Table 2 Variables' units and sources

Variable	Description	Units	Sources
GDP	Economic growth	GDP per capita constant $US, 2010	WDI
TO	Trade openness	Trade % of GDP	WDI
URB	Urbanization	Urban population	WDI
AGRIC	Agriculture	Agriculture, fishing, and forestry, value-added	WDI
CO_2	CO_2 emissions	CO_2 emissions per capita	BP
EC	Energy use	Energy consumption per capita (kWh)	BP

Figure 2 Analysis flowchart



arranged. If the parameters are stationary at I(0) or I(1) or both I(0) and I(1), further analysis can be conducted. However, if the series is stationary at I(2), the ARDL test, which is the study analysis's core test, cannot be applied.

Correlation test

Analysis of correlation is used to verify the comovement between the two series. The correlation can be defined as follows:

$$\text{Corr (X, Y)} = \frac{Cov\ (X, Y)}{\sqrt{Var(X)Var(Y)}} \tag{3}$$

where the covariance between the two time series (X, Y) is denoted as Cov (X, Y), while Var (X) and Var (Y) represent the value of the two time series of X and Y, respectively.

ARDL approach

The autoregressive distribution lag (ARDL) model is applied to capture the long-run association between the dependent and independent variables. The benefits of the ARDL bounds model over the other traditional cointegration techniques are as follows: (i) it can be used when there is a mixed integration order; (ii) it incorporates both the short- and long-run coefficients concurrently; (iii) it is perfectly fit for small sample size (Odugbesan and Adebayo 2020); (iv) accommodating different lag length (Ahmed et al., 2021); and (v) autocorrelation problem is removed. The calculated F-statistics are compared to the lower and upper bound critical values. When the calculated F-statistics is below the critical value, the alternative hypothesis is rejected. However, when the calculated F-statistics is greater than the lower and upper critical values, the null hypothesis is rejected, showing evidence of a long-run interaction among the variable. Equation 3 explains the ARDL bounds model:

$$\begin{aligned}\Delta GDP_t = {} & \alpha_0 + \sum_{i=1}^{t} \alpha_1 \Delta GDP_{t-i} + \sum_{i=1}^{t} \alpha_2 \Delta C0_{2t-i} \\ & + \sum_{i=1}^{t} \alpha_3 \Delta EC_{t-i} + \sum_{i=1}^{t} \alpha_4 \Delta TO_{t-i} \\ & + \sum_{i=1}^{t} \alpha_5 \Delta URB_{t-i} + + \sum_{i=1}^{t} \alpha_6 \Delta AGRIC_{t-i} \\ & + \beta_1 GDP_{t-1} + \beta_2 CO_{2t-1} + \beta_3 EC_{t-1} \\ & + \beta_4 GCF_{t-1} + \beta_5 URB_{t-1} + \beta_6 AGRIC_{t-1} \\ & + \varepsilon_t \end{aligned} \tag{4}$$

Equations 5 and 6 illustrate the null and alternative hypotheses, respectively:

$$H_0 = \vartheta_1 = \vartheta_2 = \vartheta_3 = \vartheta_4 = \vartheta_5 \tag{5}$$

$$H_a \neq \vartheta_1 \neq \vartheta_2 \neq \vartheta_3 \neq \vartheta_4 \neq \vartheta_5 \tag{6}$$

where H_0 portrays the null hypothesis and H_a stand for the alternative hypothesis. After the long-run interaction is established, the ARDL model derives the ECM. It is derived by estimating the model's short-run parameters by applying ECM. Hence, the ARDL framework is transformed into as follows:

$$\begin{aligned}\Delta GDP_t = {} & \alpha_0 + \sum_{i=1}^{t} \alpha_1 \Delta GDP_{t-i} + \sum_{i=1}^{t} \alpha_2 \Delta C0_{2t-i} \\ & + \sum_{i=1}^{t} \alpha_3 \Delta EC_{t-i} + \sum_{i=1}^{t} \alpha_4 \Delta TO_{t-i} \\ & + \sum_{i=1}^{t} \alpha_5 \Delta URB_{t-i} + + \sum_{i=1}^{t} \alpha_6 \Delta AGRIC_{t-i} \\ & + \beta_1 GDP_{t-1} + \beta_2 CO_{2t-1} + \beta_3 EC_{t-1} \\ & + \beta_4 GCF_{t-1} + \beta_5 URB_{t-1} + \beta_6 AGRIC_{t-1} \\ & + \rho ECT_{t-i} + \varepsilon_t \end{aligned} \tag{7}$$

where $\theta_{i=5}$ denote coefficients in the short run, ε_t signifies the error term, $\beta_{i=5}$ denote coefficients in the long run, t denotes the lag lengths, ECT_{t-i} denotes error correction term. ρ denotes ECM coefficients, which will be negative and significant.

Long-run estimator (DOLS)

To ascertain the ARDL long-run outcomes, the present study utilized DOLS to catch the long-run linkage between CO_2 emissions and its regressors. Though several techniques can be utilized to catch the long-run interaction between parameters, the DOLS technique is used in this empirical analysis. This method enables asymptotic coherence to be collected by putting into account the serial correlation effect. Before conducting these techniques, it is essential to establish cointegration among the series. The DOLS estimator is depicted by Eq. 8 as follows:

$$GDP_t = \vartheta_0 + \vartheta_1 CO_{2t} + \vartheta_2 EC_t + \vartheta_3 TO_t + \vartheta_4 URB_t + \vartheta_5 AGRIC_t + \sum_{i=q}^{q} \beta_1 \Delta CO_{2t-i} + \sum_{i=q}^{q} \beta_2 \Delta EC_{t-i} + \sum_{i=q}^{q} \beta_3 \Delta TO_{t-i} + \sum_{i=q}^{q} \beta_4 \Delta URB_{t-i} + \sum_{i=q}^{q} \beta_5 \Delta AGRIC_{t-i} + \varepsilon_t \quad (8)$$

where the lag order is chosen by utilizing SIC and time trend is illustrated by t. DOLS has the benefit of addressing endogeneity, autoregression, and the bias arising from the prejudice of the sample Narayan (2016).

Wavelet approach

Wavelet coherence is employed to detect the time-frequency dependence of energy consumption, CO_2 emissions, urbanization, and agriculture on economic growth. Time-frequency dependence considers the changes over time and how the relationship varies from one frequency to another becomes essential (Adebayo 2020). The Morlet wavelet function was employed since it brings balance between phase and amplitude. Morlet wavelet function is defined as follows:

$$w(n) = \pi^{-\frac{1}{4}} e^{-iwn} e^{-\frac{1}{2}n^2} \quad (9)$$

where non-dimensional frequency was used by w and i denotes $\sqrt{-1}$ p(\ ). Using the time and space, with \ = 0, 1, 2, 3……N-1, the time series continuous wavelet transformation (CWT) is defined as:

$$w_{k,f}(n) = \frac{1}{\sqrt{h}} w\left(\frac{n-k}{f}\right), \quad k, f \in \mathbb{R}, f \neq 0 \quad (10)$$

Table 4 Traditional unit root tests

	At level I(0)	First difference I(1)	Decision
ADF unit root test			
GDP	−2.5260	−5.6531*	I(1)
CO_2	−2.2541	−7.6144*	I(1)
EC	−0.5753	−6.5170*	I(1)
AGRIC	−1.8105	−9.3066*	I(1)
TO	−5.0579*	−14.655*	I(0), I(1)
URB	−0.8968	−3.2010***	I(1)
KPSS unit root test			
GDP	0.1235***	0.0591	I(0)
CO_2	0.1565**	0.0253	I(0)
EC	0.4040*	0.1128	I(0)
AGRIC	0.1057	0.1581**	I(1)
TO	0.2048**	0.0952	I(0)
URB	0.2987*	0.1418***	I(0), I(1)

1% 5% and 10% level of significance are illustrated by *, ** and ** correspondingly

Table 3 Descriptive statistics

	GDP	CO_2	EC	AGRIC	TO	URB
Mean	3.2396	−0.0517	3.5018	10.788	1.6638	7.7474
Median	3.2739	0.0211	3.588	10.817	1.6909	7.7881
Maximum	3.6484	0.3582	3.9612	11.173	1.9831	8.1804
Minimum	2.8175	−0.6441	2.8912	10.402	1.0418	7.1995
Std. dev.	0.2414	0.2916	0.3478	0.2192	0.1395	0.3086
Skewness	−0.1339	−0.4858	−0.4540	−0.0536	−1.7455	−0.2646
Kurtosis	1.9457	2.1530	1.8373	1.9583	9.0199	1.7290
Jarque-Bera	2.7118	3.8071	4.9871	2.5173	110.98	4.3437
Probability	0.2577	0.1490	0.0826	0.2840	0.0000	0.1139
Observations	55	55	55	55	55	55

Table 5 Bound test

Kripfganz and Schneider (2018) critical and *P*-values						
	F-statistics		7.21*			
	T-statistics		−5.25*			
	10%		5%		1%	
F-statistics CV	2.204	3.320	2.615	3.891	3.572	5.112
T-statistics CV	−2.495	−3.798	−2.843	−4.207	−3.54	−5.021

Note * represents a 1% level of significance, and both F-stat and T-stat are greater than critical values

where k and f symbolize time and frequency, respectively. CWT helps the cross wavelet analysis to interrelate between two variables (Kirikkaleli 2019; Alola et al. 2019). The CWT is depicted in Eq. 11:

$$\mathfrak{w}_p(k,f) = \int_{-\infty}^{\infty} p(n)\frac{1}{\sqrt{f}}\,\mathcal{w}\left(\frac{n-k}{f}\right)dn, \tag{11}$$

The local variance was revealed using the wavelet power spectrum (WPS). Equation 12 illustrates the WPS as follows:

$$WPS_p(k,f) = \left|W_p(k,f)\right|^2 \tag{12}$$

The wavelet coherence approach (WTC) is defined in the equation below:

$$R^2(k,f) = \frac{\left|S\left(f^{-1}W_{pj}(k,f)\right)\right|^2}{S\left(f^{-1}\left|W_p(k,f)\right|^2\right)S\left(f^{-1}\left|W_j(k,f)\right|^2\right)} \tag{13}$$

where the time and scale smoothing operators with$0 \le R^2(k,f) \le 1$ is denoted as S. WTC can also detect the phase difference ϕ_{pq} of the two time series, and it is defined in this form:

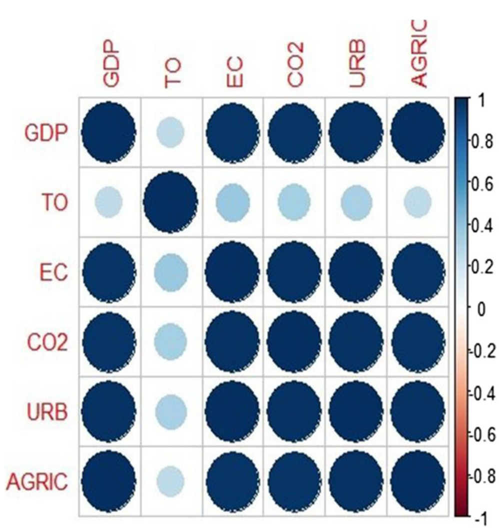


Fig. 3 Correlation box

Table 6 ARDL long-run and short-run results

Regressors	Coefficient	t-statistic	Prob
Short-run results			
ΔCO_2	0.1370*	4.0286	0.000
ΔEC	0.1560**	2.6527	0.012
ΔAGRIC	0.5705*	2.9061	0.006
ΔTO	0.0387	1.3253	0.195
ΔURB	3.4096***	1.8497	0.074
ECM(−)	−0.3317*	−5.4582	0.000
Long-run results			
CO_2	0.1370**	2.4709	0.019
EC	0.1560***	1.8770	0.070
AGRIC	0.5705**	2.4788	0.019
TO	−0.0453	−1.3558	0.185
URB	4.0669**	2.2662	0.031
R^2	0.98		
Adj R^2	0.97		
F-statistic	1737.4		
Prob (F-statistic)	0.0000		
DW	2.0578		
Post estimation tests			
χ^2 ARCH	0.23 (0.63)		
χ^2 RESET	0.15 (0.88)		
χ^2 normality	2.35 (0.30)		
χ^2 LM	0.22 (0.79)		

*, **, and *** signify 1%, 5%, and 10% level of significance

$$\phi_{pq}(k,f) = \tan^{-1}\left(\frac{L\left\{S\left(f^{-1}W_{pj}(k,f)\right)\right\}}{O\left\{S\left(f^{-1}W_{pj}(k,f)\right)\right\}}\right) \tag{14}$$

where L and O stand for the imaginary and real part operators.

Gradual shift test

Apart from the wavelet coherence approach, the present study utilized the gradual shift causality test developed by Nazlioglu et al. (2016) was utilized to establish the direction of causation between two variables. This technique helps to overcome the inaccuracies and inconsistencies associated with the VAR model. Using the modified VAR model stated in the equation below:

$$y_t = \sigma(\mathrm{t}) + \beta_1 y_{t-1} + \ldots + \beta_{p+dmax} y_{t-(p+dmax)} + \varepsilon_t \tag{15}$$

where y_t symbolizes variable used, σ symbolizes intercept, β symbolizes coefficient matrices, ε symbolizes the error term, and t symbolizes time function. The Fourier approximation with cumulative frequencies is defined as:

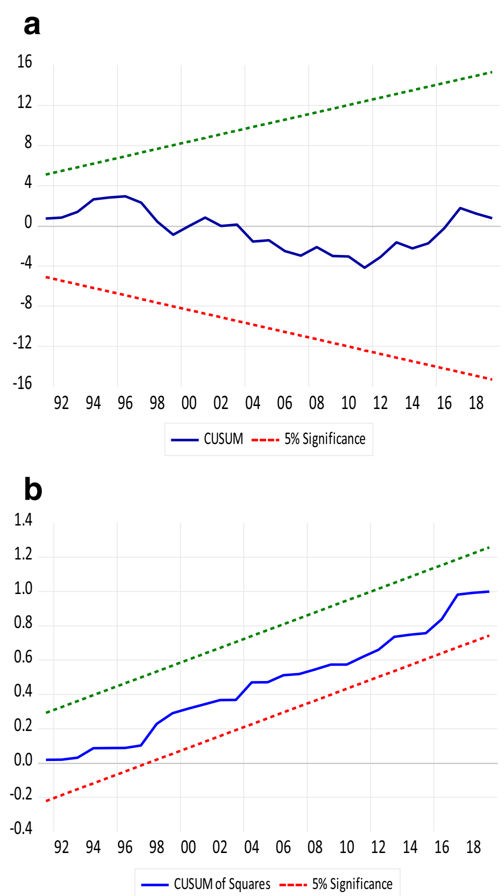


Fig. 4 **a** CUSUM and **b** CUSUM of square

$$\sigma(t) = \sigma_0 + \sum_{k=1}^{n} \gamma_{1k}\sin\left(\frac{2\pi kt}{T}\right) + \sum_{k=1}^{n} \gamma_{2k}\cos\left(\frac{2\pi kt}{T}\right) \quad (16)$$

where γ_{2k} and γ_{1k} measure the displacement and frequency amplitude, respectively; the number of frequencies is denoted as n. Fourier Toda-Yamamoto causality with cumulative frequencies (CF) is defined as follows:

$$y_t = \sigma_0 + \sum_{k=1}^{n} \gamma_{1k}\sin\left(\frac{2\pi kt}{T}\right) + \sum_{k=1}^{n} \gamma_{2k}\cos\left(\frac{2\pi kt}{T}\right) + \beta_1 y_{t-1} + \ldots + \beta_{p+dmax} y_{t-(p+dmax)} + \varepsilon_t \quad (17)$$

where approximation frequency is symbolized as k. For the Fourier Toda-Yamamoto causality with single frequencies, single-frequency components are defined in Eq. (18) as follows:

$$\sigma(t) = \sigma_0 + \gamma_1\sin\left(\frac{2\pi kt}{T}\right) + \gamma_2\cos\left(\frac{2\pi kt}{T}\right) \quad (18)$$

The Fourier Toda-Yamamoto causality with single frequencies (SF) is defined as follows:

$$y_t = \sigma_0 + \gamma_1\sin\left(\frac{2\pi kt}{T}\right) + \gamma_2\cos\left(\frac{2\pi kt}{T}\right) + \beta_1 y_{t-1} + \ldots + \beta_{p+d} y_{t-(p+d)} + \varepsilon_t \quad (19)$$

Findings and discussions

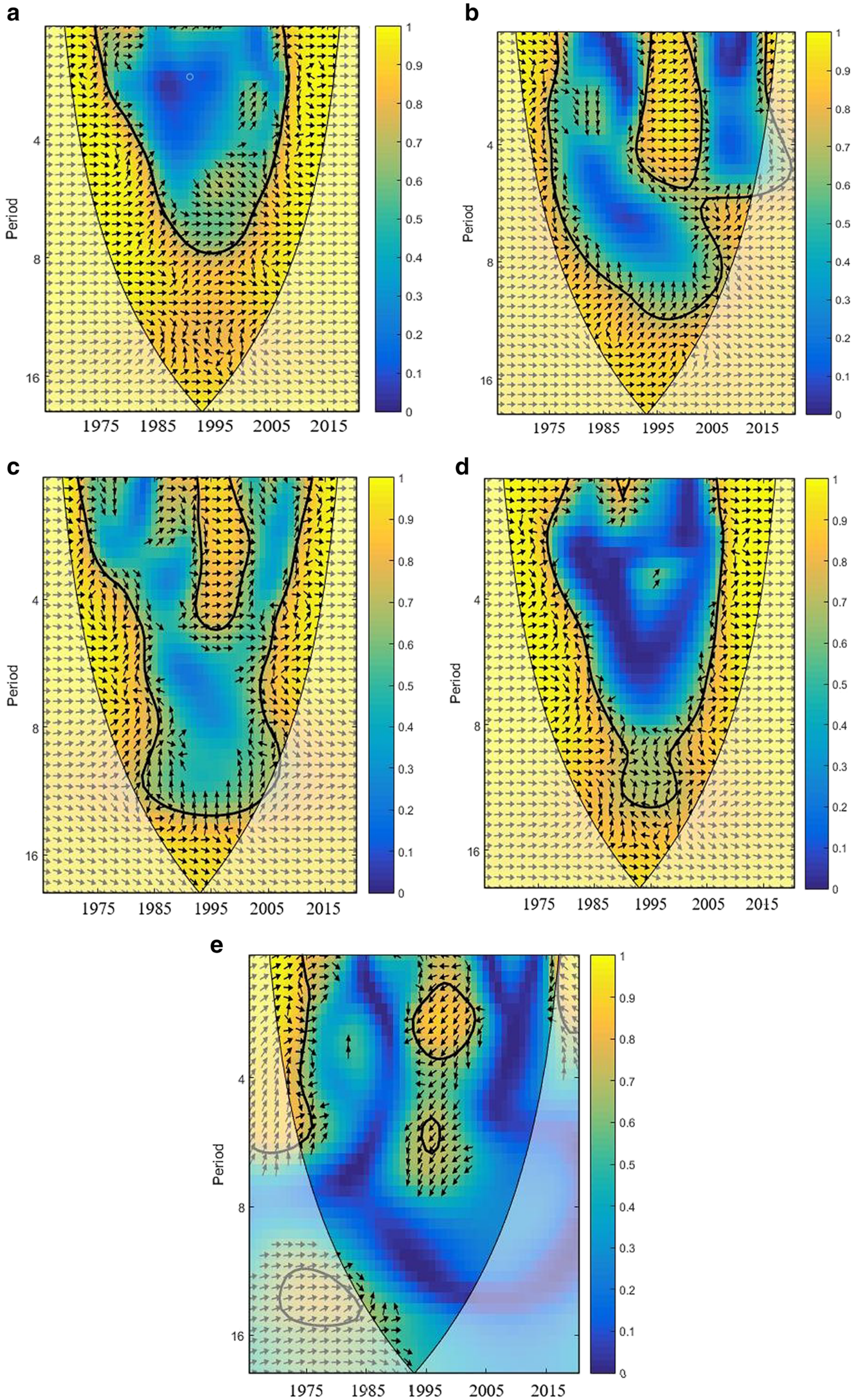
This segment of the study presents the discussion of the outcomes in a stylized manner. We set off with initial analysis by the investigation into the basic summary statistics properties. The basic summary statistical properties that report the measure of central tendencies and dispersion outlined in Table 3 show that agriculture has the highest average, followed by urbanization, energy consumption, GDP, trade openness, and CO_2. All series shows negative skewness with a light tail. Furthermore, all the series mirror normal distribution reported by the kurtosis, which is less than 3 for all examined series with the exemption of trade openness. Moreover, the outcomes of the Jarque-Bera (probability) show that all the series conform to normality with the exemption of both energy consumption and trade openness. Also, the correlation among the series is illustrated by the correlation box in Fig. 3. In Fig. 2, the blue color illustrates a positive correlation, while the red color illustrates a negative correlation between variables. Subsequently, we proceed to explore the unit root features of the series under analysis. Table 4 outlined the traditional unit root test of ADF and KPSS that shows the mix order of integration. This research proceeds to explore the long-run interaction between the study parameters as reported by the ARDL bound testing in Table 5 in conjunction with the Kripfganz and Schneider (2018) critical and P-values which confirm cointegration among variables under review. The bound test confirms a long-run association between these indicators. This is indicative that the explanatory variable converges to the dependent variable.

After the bound test confirms the cointegration, we proceed to estimate the ARDL model. The results of the ARDL model are portrayed in Table 6. The values of the R^2 and adj R^2 are 0.98 and 0.97 correspondingly. This outcome illustrates that the regressors (EC, CO_2, TO, AGRIC, and URB) can explain 98% variation in GDP, while the remaining 1% variation is attributed to the error term. The value of the DW is 2.04, which is within the anticipated range to affirm autocorrelation

Table 7 DOLS outcomes

	DOLS		
Regressors	Coefficient	t-Statistic	Prob.
CO_2	0.1370	2.7154**	0.011
EC	0.1560	2.0627**	0.048
AGRIC	0.5705	2.7241*	0.010
TO	−0.0453	−1.4899	0.147
URB	4.0669	2.4904**	0.018
R^2	0.98		
Adj R^2	0.98		

* and ** depict 1% 5% level of significance


a
b
c
d
e
Period
4
8
16
1975
1985
1995
2005
2015
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

◀ **Fig. 5** **a** WTC between GDP and AGRIC. **b** WTC between GDP and CO2. **c** WTC between GDP and EC. **d** WTC between GDP and URB. **e** WTC between GDP and TO

absence. This outcome shows that there is no issue of autocorrelation in the model. The serial correlation and heteroscedasticity results depicted in Table 6 show that the research framework is free from serial correlation and heteroscedasticity problems.

Furthermore, the RESET test reveals that there is no misspecification in the model. Also, both the CUSUM square and CUSUM outcomes in Fig. 4 a and b show that the model is stable and reliable. Appropriate lag selection is essential when applying the ARDL. Thus, we utilized the AIC criteria proposed by Akaike (1987). Akinsola and Adebayo (2021) stated that the AIC is ideal for selection lag due to its superior characteristics. The speed of adjustment is seen to facilitate long-term convergence between the parameters with a significant and negative error correction term (ECT) coefficient. The outcome of the ECT is 0.33, which illustrates evidence of cointegration among the parameters, and this signifies the capability of the model to witness 33% speed of adjustment to verify the alignment to equilibrium in the long run on GDP due to the effect of the regressors (URB, EC, CO_2, TO, and AGRIC). The outcomes of the ARDL model are as follows:

a. The study discloses that energy use exerts a positive and significant impact on GDP. Thus, energy consumption enhances economic growth as we observe that a 1% upsurge in energy consumption increases GDP growth by a magnitude of 0.15%. This outcome gives credibility to the energy-induced growth hypothesis, which resonates with the study of Adebayo et al. (2021) for Brazil, Ali et al. (2020) for Nigeria, Udemba (2019) for Indonesia, and Shahbaz et al. (2015) for Pakistan. This outcome implies that the Indonesian economy is energy-driven and cannot embark on conservative energy strategies, compromising GDP.
b. There is evidence of a positive (elasticity) and significant interaction between GDP growth and CO_2 emissions. This deduces that pollution is inducing GDP growth. This means that emissions cause economic growth. This may be the case because, with less care for environmental sustainability, the host nation is focused on pursuing economic growth. This may be found where the use of unsustainable nonrenewable energy in Indonesia's economic operations positively affects economic development while affecting the climate negatively. The result revealed that, according to the EKC postulation, Indonesian economic development is still at a scale-effect phase where both environmental degradation and economic growth are growing at the same time. This infers that a 0.13% increase in GDP growth is due to a 1% increase in CO_2 emissions. This outcome complies with the findings of Adebayo and Odugbesan (2020) for South Africa, He et al. (2021) for Mexico, Udemba et al. (2021) for India, and Kirikkaleli and Adebayo (2020) and Bekun and Agboola (2019) for Nigeria.
c. Moreover, we see that urbanization influences Indonesia's economic growth, which implies that a 1% increase in urbanization increases GDP growth by 3.40%. Based on the empirical revelation, we claim that the teaming growing population in Indonesia is productive to her economic trajectory. However, there is a need for caution on policymakers to match urban infrastructure and amenities in rural areas. This is to avoid the rush to urban cities, given that most government officials develop urban areas more than rural areas. Otherwise, the urban infrastructure might be overwhelmed and might impede economic growth in the long run.
d. Additionally, government officials need to encourage public-private partnerships (PPP) to build infrastructure

Table 8 Causality test

Causality path	Wald-stat	No of Fourier	*P*-value	Decision
GDP ⇨ CO_2	7.166269	3	0.411776	Do not reject Ho
CO_2⇨ GDP	4.772503	3	4.772503	Do not reject Ho
GDP ⇨ TO	1.586617	2	0.979159	Do not reject Ho
TO ⇨ GDP	4.878288	2	0.674813	Do not reject Ho
GDP ⇨ URB	54.02239	4	0.00000*	Reject Ho
URB ⇨ GDP	1.368549	4	0.986515	Do not reject Ho
GDP ⇨ EC	12.62092	3	0.081901***	Reject Ho
EC ⇨ GDP	2.834950	3	0.899839	Do not reject Ho
GDP ⇨ AGRIC	0.002475	2	0.153681	Do not reject Ho
AGRIC ⇨ GDP	22.06522	2	0.002475**	Reject Ho

*, **, and *** represent 1%, 5%, and 10% level of significance correspondingly

in other less urbanized regions to balance the infrastructural deficit in rural and urban areas. This alludes to the fact that small and medium enterprises (SME) are a key driver of any economy, which will have a ripple effect on the pace of other macroeconomic indicators and economic development at large. This outcome is in line with the findings of Udemba et al. (2021) and Bekun and Agboola (2019).

e. There is a negative and insignificant interaction between trade openness and GDP growth in Indonesia. Therefore, signifying that trade in Indonesia has an insignificant effect on economic growth, suggesting that the Indonesian economy's openness to the outside world does not promote economic growth. This explains the nature of Indonesia's trade pattern and the rest of the world due to Indonesia's economic size and structure.

f. A positive and significant interaction between GDP growth and agriculture infers that holding other indicators constant, a 0.57% increase in GDP growth is associated with a 1% increase in agriculture. This outcome is not surprising because the agricultural sector offered employments to roughly 49 million Indonesians in 2015. Presently, nearly 30% of land in Indonesia is utilized for agriculture. This result agrees with the study of Sertoglu et al. (2017), Udemba (2020), Matthew and Mordecai (2016), and Awan and Aslam (2015).

The current study utilized DOLS long-run estimator to check ARDL outcomes. The results of the DOLS estimators are represented in Table 7. The results show that energy use, CO_2 emissions, agriculture, and urbanization exert a positive and significant impact on GDP growth which implies that all the regressors with the exemption of trade openness enhance economic growth. These outcomes correspond with the results of the ARDL long run.

In addition, the present research further utilizes the wavelet coherence (WTC) test to catch the causality and correlation between economic growth and the regressors. This technique is created from physics to gather formerly unseen information. Thus, the research explores the connection in the short, medium, and long run between GDP and its regressors. The cone of influence (COI) is the white cone where discussion is carried out in the WTC. The thick black contour illustrates a level of significance based on simulations of Monte Carlo.

Furthermore, the vertical and horizontal axis in Fig. 5a–e depicts frequency and time, respectively. The blue and yellow colors represent low and high dependence between the series. In-phase and out-of-phase connections are depicted by rightward and leftward arrows correspondingly. Moreover, the rightward-down (leftward-up) illustrates that the first variable leads (cause) the second parameter, while the rightward-up (leftward-down) depicts that the second parameter leads (cause) the first parameter. Figure 5 a illustrates the WTC between AGRIC and GDP between 1965 and 2019. At various frequencies between 1970 and 2016, the arrows are rightward-up, showing the positive interconnection between the series with AGRIC leading. Figure 5 b depicts the WTC between CO_2 and GDP between 1965 and 2019 in Indonesia. The majority of the arrows are rightward-up, which illustrates a strong connection (dependency) at different frequencies with CO_2 leading. Figure 5 c illustrates the WTC between EC and GDP in Indonesia between 1965 and 2019. At different scales, from 1970 to 2016, the bulk of arrows are facing rightward-down, which show positive association (dependency) at different frequencies. Furthermore, the rightward-down arrows indicate that GDP lead (cause) EC. Figure 5 d illustrates the WTC between URB and GDP in Indonesia between 1965 and 2019. At different frequencies, from 1970 to 1993 and from 2000 to 2016, the bulk of arrows are facing rightward-down, which shows a positive association (dependency) between GDP and URB. Furthermore, the rightward-down arrows indicate that GDP leads (cause) URB. Figure 5 e shows the WTC between TO and GDP in Indonesia between 1965 and 2019. From 1970 to 1977, the bulk of arrows are facing rightward-up at different high and medium frequencies, which shows a positive association (dependency) with TO leading. However, between 1995 and 2005 at high frequency, most arrows are leftward-down, which indicates a negative connection (dependency) between GDP and TO with TO leading. The outcomes from the wavelet coherence test comply with the results of DOLS and ARDL.

In Table 8, the causality analysis of the gradual shift is reported. The causality test outcomes offer support for the results of the ARDL bound (long-run) and ECT (short-run) estimations in Table 5. The outcomes of the causality test revealed the following: (i) neutrality hypothesis between GDP and EC, this outcome is backed by the findings of Udemba (2019) for Indonesia; (ii) no evidence of causal linkage between GDP and TO in Indonesia between the period of study, this outcome is in line with the findings of Kalmaz and Adebayo (2020) for Nigeria and Udemba (2019) for Indonesia; (iii) unidirectional causality from AGRIC to GDP at a 1% significance level which implies that AGRIC can significantly predict GDP, this outcome resonates with the findings of Odetola and Etumnu (2013) for Nigeria but contradicts the conclusion of Raza et al. (2014) for Pakistan; (iv) one-way causality from GDP to URB at a significance level of 1%, which infers that GDP can predict significant variation in URB, this illustrates that economic reform in Indonesia promotes urbanization, and this finding resonates with the findings of Rahman and Vu (2020) for Canada and Narayan (2016) for India; and (v) unidirectional causality from GDP to EC, which illustrates that GDP can predict EC, this finding aligns with the results of Akinlo (2008) for 11 sub-Saharan African countries and Aqeel and Butt (2001) for Pakistan.

Conclusion

The present research adds to the existing studies by evaluating the impact of CO_2 emissions and agriculture on economic growth and taking into consideration the effect of urbanization, energy use, and trade openness in Indonesia utilizing data spanning between 1965 and 2019. The ARDL bounds, gradual shift causality, and novel wavelet coherence tests are utilized to accomplish the stated objectives. The outcomes show a mix (significant and insignificant) of interactions between economic growth and the regressors. The outcome of the bound test reveals that all the indicators have long-run interconnection. Furthermore, the outcomes of the ARDL long-run and short-run estimations show that agriculture and energy consumption promote the economic performance of Indonesia. The impetus behind this is attributable to the fact that Indonesia's economy primarily depends on two primary sectors that are regarded as pollution-induced sectors. These sectors (agricultural and petroleum sectors) are distinguished by the extreme usage of non-renewable energy sources in operations. As an emerging country, Indonesia is believed to be operating the economy to the detriment of the environment. As expected, CO_2 emissions and urbanization enhance economic growth of Indonesia. Furthermore, we applied the novel wavelet test to capture the correlation and causal association between economic growth and the regressors. The wavelet analysis findings revealed a positive correlation between GDP growth and the regressors with the exemption of trade openness, which has a weak connection with Indonesia's economic growth. Furthermore, the wavelet coherence test outcomes provide further support for the ARDL and DOLS tests. Moreover, the results of the Fourier Toda-Yamamoto causality test provide intuition and credibility for the linkage between economic growth and urbanization, energy usage, trade openness, and CO_2 emissions.

Based on the findings mentioned above, it is vital to explore policies that include a national sustainable development plan focused on social, economic, and environmental aspects. The goal should be to ensure best practice by combining the three dimensions to minimize trade-offs between economic growth and the environment's quality. There is a desire to understand the consequences of population change and the necessity for birth control in Indonesia. Besides, with the aid of modern agricultural technology and the availability of good seeds and other agricultural inputs, the productivity of agriculture and its value-added component can be increased at a higher level without harming the environment. Renewable sources, including hydropower, ocean power, geothermal, wind power, and solar, should be considered cleaner and substituted for non-renewable energy in economic activities.

In summary, as a nation, Indonesia has more opportunities to maintain sustainable growth in both economic and environmental operations. This study's outcome would positively impact neighboring countries willing to take the steps suggested in this paper to strengthen their sustainable growth. Conclusively, this study has examined the nexus between energy use, urbanization, trade openness, and Indonesia's economic growth using recent time series data. Additional research should be conducted for the other developing and advanced nations while considering asymmetric in the econometrics modeling or the use of micro disaggregated data.

Author contribution Gbenga Daniel Akinsola and Tomiwa Sunday Adebayo designed the experiment and collected the dataset. The introduction and literature review sections are written by Oseyenbhin Sunday Osemeahon and Sukru Umarbeyli. Tomiwa Sunday Adebayo and Festus Victor Bekun constructed the methodology section and empirical outcomes in the study. Festus Victor Bekun and Tomiwa Sunday Adebayo contributed to the interpretation of the outcomes. All the authors read and approved the final manuscript.

Data availability Data is readily available at https://data.worldbank.org/country/Indonesia.

Declarations

Ethics approval This study follows all ethical practices during writing.

Consent to participate Not applicable

Consent for publication Not applicable

Competing interests The authors declare no competing interests.

Transparency The authors confirm that the manuscript is an honest, accurate, and transparent account of the study reported; and that no vital features of the study have been omitted.

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