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Do renewable energy consumption and financial development matter for environmental sustainability? New global evidence

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Abstract

The present study aims to explore the long-run and causal effect of financial development and renewable energy consumption on environmental sustainability while controlling technological innovation and economic growth within the global framework. In line with the aim of the study, the fully modified OLS (FMOLS), dynamic OLS (DOLS), canonical cointegrating regression (CCR), Bayer and Hanck cointegration, and frequency-domain causality tests are employed. Empirical evidence confirms the existence of a long-run linkage among the variables. The present study also finds that in the long run, global financial development and global renewable energy consumption have a long-run significant positive effect on environmental sustainability, while economic growth increases carbon emission flaring around the world. Within the global framework, the study, therefore, recommends that in order to increase environmental quality, global policy-makers should further consider the roles of renewable energy and financial development by implementing reform energy policies in both developed and developing countries.

KEYWORDS

economic growth, environmental sustainability, financial development, renewable energy consumption, technological innovation

1 | INTRODUCTION

In recent years, an increasing discourse has developed among energy, environmental, and scientific researchers on the challenging consequences of climate change on future human well-being and environmental sustainability (Lanouar, Al-Malk, & Al Karbi, 2016). To avert the catastrophe of global warming, many scholars and decision-makers have emphasized the significance of reducing greenhouse gas (GHG) emissions, which are known to be the primary cause of climate change (Amran, Periasamy, & Zulkafli, 2014; Jaforullah & King, 2015). The increase in the production and consumption rates as well as the attempts of nations to attain rapid economic expansion have contributed to a dramatic rise in global CO_2 emissions. During this phase, governments have neglected the adverse environmental effects in order to promote growth in their countries' development, leading to a rise in CO_2 emissions over the years. According to research published by the Intergovernmental Panel on Climate Change (IPCC), global warming caused by human activities has caused average temperatures to increase by approximately 1°C compared to previous industrial eras.

The effects of the recent global warming of 1°C have also been witnessed as severe weather events, rising sea levels, the loss of Arctic sea ice, and other detrimental changes. If the rise in pollution persists in its current form, temperature increases caused by climate change will reach the 1.5°C mark between 2030 and 2050. Global warming over 1.5°C is expected to contribute to long-term and permanent shifts, including the loss of certain habitats (IPCC, 2018). GHG pollution, such as CO_2 emissions, is believed to be one of the factors causing climate change and global warming. Since the adverse impacts of environmental degradation have begun to be experienced on a global level, including climate change and global warming over time, this problem has motivated governments to pursue a collective remedy. According to Sathaye, Shukla, and Ravindranath (2006), the Kyoto Protocol and Paris agreement on climate change have continued to fail to adequately respond to climate change challenges. As a result, several analysts and academics have concluded that the implementation of new rules, legislation, and economic policies will help to enhance environmental efficiency (Cardenas, Franco, & Dyner, 2016). Nevertheless, many other researchers have indicated that enhancing environmental sustainability by conservative energy policies will contribute to a decline in economic growth (Apergis, Payne, Menyah, & Wolde-Rufael, 2010; Destek & Aslan, 2017). Therefore, the primary problem for policy-makers revolves around how economic growth can be enhanced without hampering environmental quality (Awosusi, Adeshola, & Adebayo, 2020; Shahbaz, 2020). Thus, policy-makers are obliged to utilize efficient and cheap sources of energy while also reducing GHG emissions.

This study proposes a range of critical policy alternatives aimed at facilitating the implementation of an environmental plan that will enhance environmental quality. In particular, from energy, environmental, and economic perspectives, three propositions are of particular interest: (i) the promotion of renewable energy, (ii) the development of the financial sector, and finally, (iii) impact of financial development and renewable energy on environmental quality. The first proposition consists of promoting and expanding renewable energy sources that are known to be clean, green energy, and environmentally friendly. By doing this, renewable energy sources can help to significantly reduce CO_2 emissions and other types of pollutants (Kahia, Aïssa, & Lanouar, 2017; Tiwari, 2011). Concerning the second proposition, several empirical studies have shown that the financial sector can perform an important role in curbing CO_2 emissions by encouraging technological advancements in the energy sector (Abbasi & Riaz, 2016).

Three initiatives are of specific concern from the environmental, economic, and energy viewpoints: (a) renewable energy promotion; (b) financial sector development; and (c) analyzing how renewable energy and financial development impact environmental sustainability. The first plan is to encourage and develop alternative energy options, considered to be efficient, safe, and environmentally sustainable. Through doing so, clean energy sources will lead to a substantial improvement in environmental quality by decreasing CO_2 emissions (Kahia, Kadria, Aissa, & Lanouar, 2017). With regard to the second argument, numerous studies have revealed that the financial sector will perform a significant role in lowering CO_2 emissions by promoting technological innovations in the energy sector (Kahia, Kadria, et al., 2017). Finally, with regard to the last proposal, empirical studies have demonstrated that both financial development and renewable energy can be used as instruments to curb environmental degradation (Brunnschweiler, 2010; Kim & Park, 2016). For example, as Brunnschweiler (2010) stated, commercial banking and credit markets can perform competitive roles in promoting the renewable energy sector. In addition, Kim and Park (2016) reported that the reliance of renewable sectors on debt and equity finance has led to relatively faster growth in nations with developed financial markets.

From an empirical point of view, most previous studies that have investigated the impact of renewable energy and financial development on CO_2 emissions have employed either time series or panel data analysis. In addition, only a few studies have concurrently included renewable energy consumption and financial development to assess their impact on CO_2 emissions. To the best of our knowledge, no studies in the empirical literature have examined this research question that accounts for both the concurrent effects of renewable energy consumption and financial development on CO_2 emissions within the global framework. In addition, from an observational perspective, several research studies conducted on the impact of financial development and renewable energy on environmental degradation have utilized either panel or a time-series data analysis. In comparison, only a few studies have concurrently incorporated a financial development index and renewable energy consumption to determine their effect on CO_2. Therefore, this research fills the gap in the existing research.

The contribution of this study to the extant literature is as follows: (i) the research seeks to fill the void in the literature on the effect of financial development and renewable energy on CO_2 emissions within the global context; (ii) the study utilizes the Zivot and Andrews (2012) unit-root test to verify the integration order and structural break simultaneously; (iii) the study employs the FMOLS, DOLS, and CCR estimators to ascertain the long-run interconnection; (iv) the paper uses the current Bayer and Hanck (2013) cointegration technique to ascertain the cointegration characteristics; (iv) the study utilizes the frequency-domain causality test suggested by Breitung and Candelon (2006), which enables the causality to be differentiated in the short term, medium term, and long term at different frequencies. Section 2 presents a synopsis of related studies. Section 3 discusses the data and methods utilized. Section 4 discusses the findings based on the methods adopted. Section 5 presents the conclusion and future policy directions.

2 | LITERATURE REVIEW

This section is dedicated to summarizing the studies conducted on the impact of renewable energy consumption, economic growth, financial development, and technological innovation on CO_2 emissions.

2.1 | Relationship between renewable energy consumption and CO_2 emissions

In the last two decades, there has been a vigorous discussion on the accelerated development of renewable energy and its effect on economic growth and environmental quality (Al-Mulali, Tang, & Ozturk, 2015; Doğan, Driha, Balsalobre Lorente, & Shahzad, 2020; Fotis & Polemis, 2018; Kahia, Aïssa, & Lanouar, 2017). From the viewpoint of climate change, the utilization of renewable energy sources has been considered to have a significant influence on environmental sustainability by decreasing the level of GHG pollution in the atmosphere (Bhattacharya, Churchill, & Paramati, 2017). Furthermore, as the OECD (2013) stated, investment in green energy sources is usually considered less carbon-intensive than conventional energy. Thus, by encouraging sustainable energy adoption, nations can boost environmental sustainability and create a globally sustainable and safe environment. Nevertheless, from an uneconomic viewpoint, the development of green energy sources offers several economic and environmental advantages (Dai, Xie, Xie, Liu, & Masui, 2016; Spiegel-Feld, Rudyk, & Philippidis, 2016). These economic advantages involve, but are not restricted to, addressing many concerns including portfolio diversification, energy mix, energy security, and employment opportunities, as the renewable energy market is more labor-intensive than the nonrenewable energy sector (Blazejczak, Braun, Edler, & Schill, 2014). In general, investment in renewable energy would allow oil-importers to decrease their reliance on foreign oil (Kahia, Aïssa, & Lanouar, 2017). Nevertheless, it would facilitate technological transitions and diversification of the economy for oil-exporting nations and sustain revenue from exports of hydrocarbon. Generally, empirical findings are mixed due to the techniques utilized, country/countries in focus, study period, and characteristics of economic variables (Adebayo and Demet, 2020; Shahbaz, 2018). Several studies have found support for the feedback causality between CO_2 emissions and renewable energy consumption. For example, Apergis et al. (2010) explored the causal link between renewable energy and CO_2 emissions in 19 developed and developing countries. The authors used the VECM and ARDL techniques to investigate the relationship. The empirical findings revealed a feedback causality between renewable energy and CO_2 emissions. Sebri and Ben-Salha (2014) conducted a study on the causal interconnection between renewable energy consumption and CO_2 emissions in the BRICS economies. The researchers used yearly data from 1971 to 2010 and the VECM to explore this causal relationship. The findings revealed a feedback causality between CO_2 emissions and renewable energy.

The findings of the study of Attiaoui, Toumi, Ammouri, and Gargouri (2017) corroborate those of Sebri and Ben-Salha (2014), who found a bidirectional causality between CO_2 emissions and renewable energy consumption. In addition, Aydoğan and Vardar (2020) investigated the linkage between renewable energy consumption and CO_2 emissions in the E7 nations. The authors used panel ARDL bounds testing and the Granger causality technique to explore this interaction. The outcomes revealed a bidirectional causality between renewable energy consumption and CO_2 emissions. However, in the case of Thailand, the study of Boontome, Therdyothin, and Chontanawat (2017) found no evidence of a causality between renewable energy consumption and CO_2 emissions. Some studies have found that renewable energy has a detrimental impact on CO_2 emissions. For instance, Zoundi (2017) examined the interaction between CO_2 emissions and renewable energy usage in 25 selected African economies by applying panel cointegration and ARDL techniques using data between 1980 and 2012. The findings revealed that renewable energy consumption enhances environmental quality. In the study conducted by Qi, Zhang, and Karplus (2014) on China for the period between 1090 and 2011, the authors found that renewable energy decreases environmental degradation. In addition, several studies have concurred that renewable energy consumption improves the quality of the environment (Salahuddin, Gow, & Ozturk, 2015; Saidi & Omri, 2020; Jebli, Farhani, & Guesmi, 2020; Ullah e al. 2020).

Ibrahim and Alola (2020) investigated the interconnection between energy efficiency nonrenewable energy, economic growth, and environmental sustainability in the MENA economies. The empirical outcomes from the study revealed that energy consumption causes environmental quality to deteriorate in the MENA nations. Using a dataset from the period between 1996 and 2014, Bekun, Alola, and Sarkodie (2019) explored the impact of nonrenewable energy consumption, economic growth, and energy usage on CO_2 emissions for the EU-16 countries. The researchers used recent panel techniques to establish this interconnection. The empirical outcomes showed that energy usage and natural resource rent hamper environmental quality in the long run, while renewable energy exerts a negative impact on CO_2 emissions. Furthermore, they found evidence of a feedback causality between renewable energy usage and CO_2 emissions. The study of Ike, Usman, Alola, and Sarkodie (2020) on the G-7 nations established that renewable energy and energy price improve environmental quality. Saint Akadiri, Alola, Akadiri, and Alola (2019) examined the drivers of economic growth using data from 28 EU-nations. The researcher established that CO_2 emissions and gross capital formation enhance economic growth.

2.2 | Relationship between financial development and CO_2 emissions

Theoretically, there is a general consensus among scholars regarding the important role that financial development plays in promoting growth in the economy (McKinnon, 1973). Presently, there is little question that financial development is an essential foundation of economic growth as it ensures capital creation via allocation, pooling, and savings, enhancing the necessary knowledge on investment activities and efficient allocations of resources. The financial sector also performs a critical role in controlling energy pollution by promoting technical developments in energy supply in order to reduce the level of emissions (Jensen, 1996). This indicates that financial development, which reflects the actual availability of financial assets by banks and stock markets for productive activities and financing networks for projects, can perform a positive and vital role in the fight against environmental degradation, primarily by decreasing CO_2 emissions. Therefore, financial development decreases environmental degradation. Furthermore, financial development will generally begin R&D, intensify economic activities, and attract foreign inflows (FDI) in order to have an effect on environmental sustainability through investment in renewable energy projects (Charfeddine, Al-Malk, & Al Korbi, 2018; Frankel & Romer, 1999). A well-established financial sector lowers funding rates, facilitates procurement practices, and curbs the spread of oil pollution by improving energy sector efficiency (Charfeddine, 2017). Nevertheless, financial development will worsen the condition of the environment by increasing industrial practices, thus triggering increased environmental degradation (Jensen, 1996). In the empirical literature, the findings regarding the linkage between financial development and CO_2 emissions are mixed.

In some recent studies, it has been found that financial development exerts a positive effect on CO_2 emissions, thereby increasing environmental degradation. For example, Shoaib, Rafique, Nadeem, and Huang (2020) found that financial development deteriorates environmental quality in eight developing countries. This finding was supported by the research conducted by Shahbaz, Haouas, Sohag, and Ozturk (2020), who used the United Arab Emirates as a case study. The researchers employed the Toda–Yamamoto causality and ARDL bounds test techniques to examine this interconnection. The findings revealed that financial development has a detrimental impact on the quality of the environment. Furthermore, financial development Granger causes CO_2 emissions in the United Arab Emirates. In addition, the study conducted by Wang, Mirza, Vasbieva, Abbas, and Xiong (2020) found that financial development has a detrimental impact on the quality of the environment. In contrast, some studies have found that financial development improves environmental quality. For instance, Shahbaz, Solarin, Mahmood, and Arouri (2013); Shahbaz, Tiwari, and Nasir (2013) conducted a research on the link between financial development and environmental degradation in South Africa. The researchers found that financial development diminishes environmental degradation. The study of Shahbaz, Solarin, et al. (2013); Shahbaz, Tiwari, and Nasir (2013) in Malaysia also found that financial development exerts a negative impact on environmental degradation. Furthermore, a two-way causality was found between financial development and CO_2 emissions in Malaysia.

2.3 | Relationship between economic growth and CO_2 emissions

Over the years, several studies have linked economic growth with CO_2 emissions (Kraft & Kraft, 1978; Grossman and Krueger 2002; Narayan & Smyth, 2008; Apergis & Payne, 2009). However, mixed findings have surfaced with regard to this interconnection. For instance, Appiah (2018) investigated the linkage between CO_2 emissions and economic growth in Ghana utilizing yearly data for the period between 1960 and 2015. The author employed the Granger causality and Toda–Yamamoto techniques, and the findings revealed a unidirectional causality from real growth to CO_2 emissions in the country. The study of Adebayo (2020) in Mexico found a positive linkage between CO_2 emissions and economic growth. In the study conducted by Gorus and Aydin (2019) on the link between environmental degradation and economic growth in the MENA countries, the researchers found no evidence of a causal link between CO_2 emissions and real growth. In Turkey, Kirikkaleli and Kalmaz (2020) conducted a study on the link between CO_2 emissions and economic growth. The investigators utilized the ARDL and wavelet coherence techniques to investigate this interconnection. The empirical findings revealed that economic growth exerts a positive impact on CO_2 emissions and the wavelet coherence technique revealed evidence of co-movement between CO_2 emissions and economic growth. The study of Odugbesan and Adebayo (2020b) using the ARDL and wavelet tools corroborated the findings of Kirikkaleli and Kalmaz (2020). Using yearly data for the period between 1971 and 2017, Chontanawat (2020) examined the nexus between economic growth and CO_2 emissions in the ASEAN economies utilizing the ARDL and Granger causality techniques. The researcher found that an increase in economic growth deteriorates the economy and a feedback causality was found between real growth and CO_2 emissions. Awosusi et al. (2020), in their study on the MINT economies, utilized panel data for the period between 1981 and 2018, and applied the Panel ARD and causality techniques to examine the linkage between CO_2 emissions and economic growth. The researchers found that economic growth does not exert any significant effect on CO_2 emissions in the MINT economies. Furthermore, they discovered evidence of a one-way causality from economic growth to CO_2 emissions.

2.4 | Relationship between technological innovation and CO_2 emissions

As a result of the significant importance of environmental challenges, an increasing amount of researchers are exploring the effects of technological innovation on CO_2 emissions. Technology advancements are known to have a major effect on the reduction of CO_2 emissions. Technological innovation, combined with environmental conservation initiatives, has reduced CO_2 pollution and enhanced the quality of the environment in host countries. Several studies have explored the connection between CO_2 emissions and technological innovation. For instance, utilizing data from provincial and district levels, Sun, Smith, and Anwar (2008) explored the connection between technological innovation and CO_2 emissions in China. The researchers indicated that technological advancement reduced CO_2 emissions significantly. Likewise, Lin and Wang (2015) explored the interconnection between technological innovation and CO_2 emissions in China. The findings revealed that technological innovation improves environmental quality. Using the United States, China, and European Union as a case study, Fernandez et al. (2018) explored the effect of technological advancement on CO_2 emissions. The empirical findings revealed that spending on technological innovation decreases environmental degradation. In addition, in the study conducted by Cho and Sohn (2018) on the interconnection between CO_2 emissions and technological innovation, the findings revealed that research and development enhances environmental quality in European Union's nations. Comparably, Kumar and Managi (2009) analyzed the connections between technological innovation and CO_2 emissions in 80 nations. They found that in industrialized economies, technological innovation decreased CO_2 emissions but raised carbon dioxide emissions in most emerging nations. Wang, Chen, and Zou (2005) utilized ARDL techniques to research the determinants of CO_2 emissions. The researchers found that technological innovation exerts a negative impact on CO_2 emissions. Also, using the ARDL techniques, Hammond and Norman (2012) explored the link between CO_2 emissions and technological innovation. The findings from this study established that technological innovation enhances environmental quality. In China, Zhao, Ma, and Yang (2013) conducted a research on the linkage between CO_2 emissions and technological innovation using data for the period between 1980 and 2011. The authors used the ARDL and Granger causality techniques to examine this interconnection. The empirical findings revealed that technological innovation improves the quality of the environment and a one-way causality was found from technological innovation to CO_2 emissions.

3 | EMPIRICAL METHODOLOGY

3.1 | Theoretical framework and description of data

The study aims to explore the impact of financial development (FIN) and renewable energy consumption (REN) on environmental sustainability from a global perspective. The study also incorporates the effect of economic growth (GDP) and technological innovation (TI) on environmental sustainability between 1985 and 2017 within the global framework. The study uses world CO_2 emissions, GDP, REN, TI, and FIN to investigate this interconnection. We used a dataset obtained from the databases of the World Bank (2020) and IMF (2020). Table 1 illustrates the data source and description of the variables. Furthermore, the GDP, TI, and CO_2 variables were transformed into their natural logarithm. In this study, the dependent variable is CO_2 emissions, which are a proxy for environmental degradation, and the independent variables are financial development index, renewable energy, gross domestic product, and TI.

The study framework is illustrated as follows:

$$LCO_{2t} = f(REN_t, FIN_t, LGDP_t, LTI_t) \tag{1}$$

In Equation (1), LCO_2, REN, FIN, LGDP, and LTI stand for CO_2 emissions, renewable energy usage, financial development index, real growth, and TI, respectively. All the variables utilized are sourced from the database of the World Bank. The study's economic model and econometric model are depicted in Equations (2) and (3), respectively;

$$LCO_{2t} = \vartheta_0 + \vartheta_1 REN_t + \vartheta_2 FIN_t + \vartheta_3 LGDP_t + \vartheta_4 LTI_t \tag{2}$$

$$LCO_{2t} = \vartheta_0 + \vartheta_1 REN_t + \vartheta_2 FIN_t + \vartheta_3 LGDP_t + \vartheta_4 LTI_t + \varepsilon_t \tag{3}$$

The reasons for utilizing LCO_2, REN, FIN, LGDP, and LTI in Equation (3) are stated as follows. Over the decades, several studies on these interconnections have been conducted (Hammond & Norman, 2012; Zhao et al., 2013; Sebri & Ben-Salha, 2014; Salahuddin et al., 2015; Dai et al., 2016; Attiaoui et al., 2017; Appiah, 2018; Fernandez et al. 2018; Gorus & Aydin, 2019; Kalmaz & Kirikkaleli, 2019; Alola & Kirikkaleli, 2019; Odugbesan & Adebayo, 2020a; Chontanawat, 2020; Ullah e al. 2020; Shoaib et al., 2020; Umar, Ji, Kirikkaleli, & Xu, 2020)). Nevertheless, these researchers did not explore these interconnections within the global framework. Therefore, making this current study relevant to ongoing studies in the literature. Based on prior outcomes, gross domestic product is projected to exert a positive impact on CO_2 (Adebayo & Akinsola, 2021; Awosusi et al., 2020; Kalmaz & Kirikkaleli, 2019; Salahuddin et al., 2015; Sebri & Ben-Salha, 2014; Shahbaz, Haouas, et al., 2020), while renewable energy negatively affects CO_2 emissions (Salahuddin et al., 2015; Saidi & Omri, 2020; Jebli et al., 2020; Ullah e al. 2020; Khan, Khan, & Rehan, 2020). In addition, it is anticipated that the interconnection between TI and CO_2 emissions is negative if it is ecologically friendly (Chandran & Tang, 2013; Khan et al., 2020; Shahbaz, Haouas, et al., 2020; Zhao et al., 2013); otherwise, a positive interconnection will surface. Lastly, financial development is anticipated to enhance the quality of the environment (Charfeddine, 2017; Charfeddine et al., 2018; Frankel & Romer, 1999).

Table 2 presents a brief description of the times-series variables employed in the current paper. CO_2 emissions range from 7.294 to 7.557, TI ranges from 5.836 to 6.475, GDP ranges from 13.500 to 13.904, renewable energy consumption ranges from 16.908 to 18.129, and financial development index ranges from 0.327 to 0.187. All the variables used are platykurtic, which illustrates a reduced potential for outliers. In addition, the skewness of the variables used is close to zero. The findings from both skewness and kurtosis show that our dataset is normally distributed. In addition, all the variables are close to zero, which is a sign of normal distribution. Furthermore,

TABLE 1 Data source and description

Sign	Description	Units	Sources
CO_2	CO_2 emissions	Kt	Word Development Indicators (WDI, 2020) https://data.worldbank.org/region/world
GDP	Gross domestic product	Constant U.S. Dollars, 2010	
TI	Technological innovation	Measured from both resident and nonresident patent applications	
REN	Renewable energy consumption	(% of total final energy consumption)	
FIN	Financial development index	Measured as financial institutions (financial institution depth, financial institution access, financial institution efficiency) and financial markets (financial market depth, financial market access, and financial market efficiency)	IMF, (2020) https://data.imf.org/?sk=f8032e80-b36c-43b1-ac26-493c5b1cd33b

TABLE 2 Descriptive statistics

Variable	CO_2 emissions (kt)	Technological innovation	GDP (constant 2010 US$)	Renewable energy consumption (% of total final energy consumption)	Financial development index
Code	LCO_2	LTI	LGDP	REN	FIN
Time	1985–2017				
Mean	7.429	6.117	13.707	17.491	0.270
Median	7.402	6.120	13.706	17.511	0.278
Maximum	7.557	6.475	13.904	18.129	0.327
Minimum	7.294	5.836	13.500	16.908	0.187
Std. dev.	0.088	0.196	0.121	0.340	0.049
Skewness	0.230	0.241	−0.023	0.100	−0.370
Kurtosis	1.559	1.912	1.745	1.787	1.645
Jarque–Bera	3.147	1.948	2.168	2.075	3.275
Probability	0.207	0.377	0.338	0.354	0.194

the Jarque–Bera test reveals that all variables are normally distributed as revealed by the associated p value.

3.2 | Econometrics methodology

3.2.1 | Unit-root test

As an initial step in the present study, the integration order of the time-series variables is explored. The traditional unit-root tests including Augmented Dickey–Fuller (ADF), Dickey–Fuller (DF) and Phillips and Perron (PP) cannot be utilized if a structural break(s) exists in the time-series data due to bias outcomes (Adebayo & Beton Kalmaz, 2020; Eminer, Awosusi, & Adebayo, 2020; Perron, 1997; Shahbaz, Solarin, et al., 2013; Shahbaz, Tiwari, & Nasir, 2013). Consequently, the study employs the Zivot–Andrews unit-root test suggested by Zivot and Andrews (2002) to capture a single structural break in the series. The Zivot–Andrew test not only tests the unit-root characteristics of each variable, but also considers one structural break. The Zivot and Andrews (2002) test equation is depicted as follows:

$$\Delta x_t = \varphi + \varphi x_{t-1} + \pi t + \delta DU_t + \sum_{j=1}^{k} d_j \Delta x_{t-j} + \mu_t \tag{4}$$

$$\Delta x_t = \varphi + \varphi x_{t-1} + \pi t + \gamma DT_t + \sum_{j=1}^{k} d_j \Delta x_{t-j} + \mu_t \tag{5}$$

$$\Delta x_t = \beta + \beta x_{t-1} + \beta t + \theta DU_t + \theta DT_t + \sum_{j=1}^{k} d_j \Delta x_{t-j} + \mu_t \tag{6}$$

There are three options when implementing the Zivot–Andrews unit-root test. They are: at intercept, trend and intercept, and trend. The preceding model can be captured, where the dummy variable is depicted by DU_t, which demonstrates that a shift occurred at a break point. The trend in shift is illustrated by DT_t. The empirical analysis utilizes model 6.

Therefore,

$$DU_t = \begin{cases} 1 \ldots\ldots if\ t > TB \\ 0 \ldots\ldots if\ t < TB \end{cases} \text{ and } DU_t = \begin{cases} t - TB \ldots.if\ t > TB \\ 0 \ldots.. \quad if\ t < TB \end{cases} \tag{7}$$

The null hypothesis of a unit-root break date is $\beta = 0$, which implies nonstationary with a drift that does not have structural breakpoint information, whereas the alternative hypothesis is $\beta < 0$, which demonstrates stationary with one unidentified time break.

3.2.2 | Bayer and Hanck cointegration

The study further utilizes the Bayer and Hanck (2013) as a robust cointegration test, which is a combination of the Banerjee, Dolado, and Mestre (1998), Boswijk (1995), Johansen (1991), and Engle and Granger (1987) cointegration tests. According to Kirikkaleli and Kalmaz (2020), the Bayer and Hanck (2013) cointegration test is focused on removing unnecessary multiple test techniques to give effective estimations of the typical problem created by other cointegration tests. Bayer and Hanck (2013) utilized the Fisher's formula in the construction of the cointegration test to strengthen the test. The Fisher's equation was illustrated by Bekun et al. (2019, p. 761) as follows:

$$EG - JOH = -2[ln\,(PEG) + ln(PJOH)] \tag{8}$$

$$\begin{aligned} EG - JOH - BO - BDM = -2[&\ln\,(PEG) + \ln\,(PJOH) + \ln(PBO) \\ &+ \ln\,(PBDM)] \end{aligned} \tag{9}$$

where the level of significance for the Engle and Granger (1987) is indicated by PEG and the level of significance of Johansen (1991) is represented by PJOH. The levels of significance for the Boswijk (1994) and Banerjee et al. (1998) cointegration tests are depicted by PBO and PBDM, respectively.

3.2.3 | FMOLS, DOLS, and CCR long-run estimators

To analyze the long-term interconnection, a single cointegrating vector will be estimated. In this respect, there are several econometric methods that can be utilized to explore the long-run interaction among the variables estimated. This analysis thus uses the fully modified OLS (FMOLS) developed by Phillips and Hansen (1990) and the dynamic OLS and canonical cointegrating regression (CCR) methods proposed by Stock and Watson (1993), respectively. These techniques allow asymptotic coherence to be obtained by considering the impact of serial correlation. The FMOLS, DOLS, and CCR tests can only be implemented if the criterion of cointegration among the variables is met. Thus, the long-term elasticity is estimated in this analysis by utilizing FMOLS, DOLS, and CCR estimators.

3.2.4 | Breitung and Candelon frequency-domain causality test

The current research also intends to capture the causal effects of TI, GDP, PPIE, and REN on C-CO_2 emissions at different frequencies within the global context. Thus, the frequency-domain causality test of Breitung and Candelon (2006) is utilized in this study. "The key distinction between the time-domain method and the frequency-domain method is: the 'time-domain' method informs us where a particular change arises inside a time series, while the 'frequency-domain' method evaluates the extent of a specific variation in time series" (Gokmenoglu, Eren, & Taspinar, 2019; Khan et al., 2020). The frequency-domain causality test enables the removal of seasonal fluctuations in the small sample data (Breitung & Candelon, 2006). In addition, nonlinearity and causality phases may be identified by the frequency domain test, while the test often facilitates the detection of a causality between variables at low, medium, and long frequencies (Breitung & Candelon, 2006; Guan et al., 2020). Furthermore, the Breitung and Candelon (2006) frequency-domain causality test enables us to differentiate long-term causalities from short-term causalities between time-series. The frequency-domain causality test is illustrated as follows:

$$Xt = [Ht, Ct, Dt]$$

where Xt is the three-dimensional vector of the endogenous and stationary variables observed at time t = 1, …, T. Xt is assumed to have a finite-order VAR illustration procedure as:

$$\Theta(L)X_t = \boldsymbol{\epsilon_t} \tag{10}$$

where the 3×3 polynomial lag order of p is denoted by $\Theta(L)$, which is illustrated as $\Theta(L) = I - \Theta_1 L^1 \ldots - \Theta_p L^p$ with $L^K X_t = X_{t-k}$. ϵ_t illustrates the error term that follows the process of white noise with zero expectancy and $\left(\epsilon_t \epsilon_t'\right) = \Sigma$. The positive and symmetric is denoted by Σ. For simplicity of analysis, in line with Breitung and Candelon's (2006) analysis, no deterministic terms are applied to Equation (11). $G'G = \Sigma^{-1}$ is the Cholesky decomposition, while G stands for the lower triangular matrix. Also, G' stands for the upper triangular matrix. $E\left(n_t n_t'\right) = I$ and $n_t = G\epsilon_t$. Utilizing the decomposition of Cholesky, the MA description of the framework is defined as follows:

$$X_t = \begin{bmatrix} H_t \\ C_t \\ D_t \end{bmatrix} = \Theta(L)\epsilon_t = \begin{bmatrix} \Theta_{11}(L) & \Theta_{12}(L) \\ \Theta_{21}(L) & \Theta_{22}(L) \\ \Theta_{31}(L) & \Theta_{32}(L) \end{bmatrix} \begin{bmatrix} \epsilon_t \\ \epsilon_t \\ \epsilon_t \end{bmatrix} \tag{11}$$

$$X_t = \begin{bmatrix} H_t \\ C_t \\ D_t \end{bmatrix} = \Phi(L)\Pi_t = \begin{bmatrix} \Phi_{11}(L) & \Phi_{12}(L) \\ \Phi_{21}(L) & \Phi_{22}(L) \\ \Phi_{31}(L) & \Phi_{32}(L) \end{bmatrix} \begin{bmatrix} \Pi_t \\ \Pi_t \\ \Pi_t \end{bmatrix} \tag{12}$$

where $\Theta(L) = \Theta(L)^{-1}$ and $\Phi(L) = \Phi L)G^{-1}$. By utilizing this depiction, the spectral density of H_t can be illustrated as follows:

$$f_H(\psi) = \frac{1}{2\pi}\left\{\left|\Phi_{11}\left(e^{-i\varphi}\right)\right|^2 + \left|\Phi_{12}\left(e^{-i\varphi}\right)\right|^2\right\} \tag{13}$$

In Equations (11) and (12), Ht can be defined as the sum of two uncorrelated MA procedures, which are: an integral part guided by previous Ht implementation, as well as an element containing the predictive ability of the Ct and Dt variables. The Ct and Dt variables' predictive power can be calculated regarding the predictive portion of the spectrum at each frequency of the Ct and Dt variables. The Granger causality null hypothesis is checked in the series. For example, Ct does not Granger cause H_t at the frequency ψ if the predictive factor of the H_t spectrum at the frequency ψ is 0. This is the explanation for the estimate of causality proposed by Hosoya (1991) and Geweke (1982) and is described as follows:

$$M_{x \longrightarrow y}(\psi) = ln\left[\frac{2\pi f_y(\psi)}{\left|\Phi_{11}\left(e^{-i\varphi}\right)\right|^2}\right] \tag{14}$$

$$= ln\left[+ \frac{\left|\Phi_{12}\left(e^{-i\varphi}\right)\right|^2}{\left|\Phi_{11}\left(e^{-i\varphi}\right)\right|^2}\right] \tag{15}$$

The above equations linked to Geweke's estimation would be zero (0) when $|\Phi_{11}(e^{-i\varphi})|^2 = 0$. A simple linear constraint is extended to the VAR Equation (1), which is described as follows:

$$\begin{aligned} CCO_{2t} = {} & \theta_1 GDP_{t-1} + \theta_\delta GDP_{t-\delta} + \gamma_1 PPIE_{t-1} + \gamma_\delta PPIE_{t-\delta} \\ & + \gamma_2 REN_{t-1} + \gamma_\delta REN_{t-\delta} + \gamma_3 TI_{t-1} + \gamma_\delta TI_{t-\delta} + \epsilon_t \end{aligned} \tag{16}$$

where the coefficients of the lag polynomials are illustrated by $\theta' s$ and $\gamma' s$. The null hypothesis $M_{x \to y}(\psi) = 0$ equal to the linear constraint,

$$H_O : R(\psi)\gamma = O \tag{17}$$

where $\gamma = [\gamma_1, \ldots . \gamma_\delta]'$ is the vector coefficient, whereas R(ψ) is explained below:

$$R(\psi) = \begin{bmatrix} \cos(\psi)\cos(2\psi)\ldots\cos(\delta\psi) \\ \sin(\psi)\sin(2\psi)\ldots\sin(\delta\psi) \end{bmatrix} \tag{18}$$

The standard F-stat is estimated as F (2, T− 2p) for $\psi\ \varepsilon(0, \pi)$, where 2 is the number of limitations and T is the number of observations utilized to calculate the VAR framework of order p (Gokmenoglu et al., 2019).

4 | DISCUSSION OF FINDINGS

The integration order of the variables is conveyed in the current study as an initial assessment. Although several traditional unit-root tests are utilized to ascertain the stationarity characteristics of variables, they are not included in this research because Shahbaz, Solarin, et al. (2013); Shahbaz, Tiwari, and Nasir (2013), Kalmaz and Kirikkaleli (2019), Adebayo and Beton Kalmaz (2020), Kirikkaleli, Adebayo, Khan, and Ali (2020) and Solarin, Al-Mulali, Musah, and Ozturk (2017) asserted that they yield ambiguity and erroneous outcomes due to structural break(s) in the variables. Consequently, the study utilized a unit-root test that can identify a single structural break in the series. In this regard, the study employed the Zivot–Andrews unit-root test to capture the series stationary features in the presence of a structural break. Table 3 illustrates the outcomes of the unit-root test, and the findings reveal that all the variables are not stationary at level. However, after taking the first difference, all the variables are stationary with LCO_2, REN, LFIN, LGDP, and TI having structural breaks in 2003, 2005, 2008, 2008, and 2011, respectively.

In order to verify the cointegration characteristics among the variables used, we employed the Bayer–Hanck combined cointegration test. Table 4 illustrates the results of the Bayer and Hanck (2013) combined cointegration test. The findings reveal that at a 5% level of significance, there is evidence of long-run cointegration among the variables used in this study.

After establishing the presence of cointegration among the variables, the present study examines the long-run impact of renewable energy, financial development index, gross domestic product, and TI on CO_2 emissions. The results of the FMOLS, DOLS, and CCR are illustrated in Table 5. As explicitly stated in the overview section of this research, TI is a significant factor in the reduction of carbon emissions. Surprisingly, the finding reveals that TI does not significantly affect CO_2 emissions within the global framework. Table 5 also illustrates that a 1% increase in gross domestic product increases CO_2 emissions by 0.637%, 0.771%, and 0.696% as revealed by the FMOLS, DOLS, and CCR long-run estimators, respectively. This illustrates that an increase in GDP is detrimental for the quality of the environment. It indicates that global growth leads to an increase in energy demand, which contributes to environmental degradation. The findings of the current paper are similar to the results of Salahuddin et al. (2015), Khan et al. (2020), Adebayo and Akinsola (2021) and Kalmaz and Kirikkaleli (2019), who established a positive link between GDP and CO_2 emissions. Furthermore, as anticipated, renewable energy consumption exerts a negative impact on CO_2 emissions within the global framework. This demonstrates that when other factors are kept constant, a 1% increase in renewable energy will decrease CO_2 emissions by 0.035%, 0.033%, and 0.034% as indicated by FMOLS, DOLS, and CCR, respectively. The likely reason for the negative link between

TABLE 3 ZA unit-root tests

	LCO_2	LTI	LGDP	REN	FIN
t-statistic	−2.288	−4.118	−4.305	−3.241	−4.397
SB	2010	2009	2004	2003	2006
	Δ CO_2	ΔLTI	ΔLGDP	Δ REN	Δ IN
t-statistic	−5.342 **	−5.793**	−5.090**	−9.677**	5.913**
SB	2003	2011	2008	2005	2008

Note: C and T denote constant and trend in the ZA unit-root test, respectively. ***, **, and * denote statistical significance at 0.01, 0.05, and 0.10 levels, respectively. The numbers in parenthesis () represent breakpoints.

TABLE 4 Bayer–Hanch cointegration test

Model specifications	Fisher statistics	Fisher statistics	Cointegration decision
	EG-JOH	EG-JOH-BAN-BOS	
LCO2 = *ƒ*(LTI, LGDP, REN, FIN)	55.472**	62.050**	Yes
	Critical value	Critical value	
	10.576	20.143	

Note: 5%, significance level is represented by **.
Abbreviation: CV, critical value.

TABLE 5 Long-run estimators

	FMOLS	DOLS	CCR
LTI	0.142 (1.280)	0.062 (0.465)	0.105 (1.158)
LGDP	0.637(2.728) **	0.771(2.667) **	0.696(3.710) **
REN	−0.035(−5.460) **	−0.033(−4.925) **	−0.034(−5.895) **
FIN	−0.356(−1.862) *	−0.356(−1.782) *	−0.362(−2.049) **
C	−1.464(−0.569)	−2.856 (−0.890)	−2.056(−0.994)
R-squared	0.984	0.998	0.983
S.E. of regression	0.011	0.005	0.011

Note: ** and * denote statistical significance at 0.05 and 0.10 levels, respectively.

TABLE 6 Frequency-domain causality test of Breitung and Candelon (2006)

	Long term		Medium term		Short term	
Direction of causality	$\omega_i = 0.01$	$\omega_i = 0.05$	$\omega_i = 1.00$	$\omega_i = 1.50$	$\omega_i = 2.00$	$\omega_i = 2.50$
LTI →LCO_2	<9.768>** (0.007)	<9.763>** (0.007)	<7.053>** (0.029)	<7.150>** (0.028)	<7.309>** (0.025)	<7.388>** (0.024)
LGDP →LCO_2	<19.518>** (0.000)	<19.407>** (0.000)	<13.837>** (0.001)	<15.705>** (0.001)	<16.358>** (0.000)	<16.624>** (0.000)
REN → LCO_2	<4.552>* (0.100)	<4.533> (0.103)	<4.997>* (0.082)	<4.832>* (0.089)	<6.729>** (0.034)	<2.942> (0.229)
FIN →LCO_2	<13.600>** (0.001)	<13.571>** (0.001)	<4.957>* (0.083)	<6.013>** (0.049)	<6.522>** (0.038)	<6.745>** (0.034)

Note: <> and () stands for Wald test statistic and *p* value respectively. The path of causality is represented by□. 10%, %5, and 1% levels of significance are illustrated by *, **, and ***, correspondingly. SIC is used to verify the lag lengths of the VAR models.

renewable energy usage and CO_2 emissions is because renewable technology uses cleaner and pure energy sources that are safe and satisfy present and future requirements, while it is also a source of CO_2 emissions reduction. This outcome corresponds with the findings of Sebri and Ben-Salha (2014), Spiegel-Feld et al. (2016), Aydoğan and Vardar (2020) and Khan et al. (2020), who established that renewable energy consumption improves environmental quality. In Table 5 it is shown that financial development exerts a negative impact on CO_2 emission globally. This shows that a 1% increase in financial development will result in a 0.356%, 0.356%, and 0.362% decrease in CO_2 emissions as shown by the FMOLS, DOLS, and CCR, respectively. This result is similar to the findings of Charfeddine et al. (2018), Frankel and Romer (1999) and Charfeddine (2017), who found that financial development improves environmental quality. This illustrates that financial development should be seen as a tool that can be used to keep the environment clean by implementing financial regulations.

After identifying the long-run effect, we have also used the Breitung and Candelon (2006) frequency-domain causality test to identify the causal impacts of LGDP, LTI, REN, and FIN on CO_2 emissions at various frequencies within the global framework. Table 6 illustrates that the null hypothesis that FIN Granger causes LCO_2 cannot be rejected in the short, medium, and long run. This implies that FIN is an important predictor of LCO_2 in the short term, medium term, and long term within the global framework. This is endorsed by the fact that FIN reduces environmental degradation. This empirical finding is similar to the findings of Shahbaz, Solarin, et al. (2013); Shahbaz, Tiwari, and Nasir (2013) for South Africa and Shoaib et al. (2020) for eight developing countries. As illustrated in Table 5, LTI Granger causes LCO_2 emissions in the short, medium, and long term. This shows that LTI is a predictor of LCO_2 emissions. This result aligns with past studies (Khan et al. 2020a; Shahbaz, Haouas, et al., 2020). Furthermore, in the long term, medium term, and short term, renewable energy consumption Granger causes LCO_2 emissions, which illustrate that REN is a predictor of LCO_2 emissions. In addition, in the short term, medium term, and long term, LGDP Granger causes LCO_2 emissions. This denotes that LGDP is a predictor of CO_2 emissions in the short term, medium term, and long term. The findings concur with past studies that found that LGDP Granger causes CO_2 emissions (Eminer, Awosusi, & Adebayo, 2020; Chontanawat, 2020; Kirikkaleli & Kalmaz, 2020).

5 | CONCLUSION

To the best of the authors' knowledge, within the global framework, the long-run and causal effects of financial development and renewable energy consumption on environmental sustainability while controlling TI and economic growth have not been investigated comprehensively using newly developed econometric techniques. This study attempts to fill this gap in the environmental literature using the FMOLS, DOLS, and CCR, Bayer and Hanck cointegration and frequency-domain causality tests. The outcomes of the Bayer and Hanck cointegration test revealed a long-run linkage between environmental sustainability and its possible determinants (namely financial development, renewable energy consumption, TI, and economic growth). The results of the FMOLS, DOLS, and CCR long-run estimators show that financial development exerts a negative impact on CO_2 emissions. As anticipated, renewable energy usage improves environmental quality around the world as economic growth increases carbon emission flaring. In addition, global economic growth deteriorates environmental quality. This is the result of various nations' attempts to expand their economies without considering the subsequent effects on environmental sustainability. Furthermore, the outcomes of the frequency-domain causality results revealed that financial development, renewable energy consumption, economic growth, and TI significantly cause environmental sustainability around the world. Thus, the current paper makes the following recommendations to global policy-makers:

a. Since financial development improves environmental quality, it can play a constructive and important role in improving environmental quality around the world, as increased development of the financial sector can encourage further borrowing at lower cost (as the nation's financial institution is controlled by commercial banks, whose main aim is to give loans to both the private and public sectors for various development projects), including for investment in environmental programs. In such situations, when considering potential CO_2 emission forecasts, they should consider the significance of financial development in addition to the position of conventional variables such as energy and income in order to improve environmental quality around the world, especially in relation to achieving Sustainable Development Goals (Feridun & Güngör, 2020) .
b. Policy-makers should also consider the role of renewable energy, which this study finds to be significant in reducing environmental degradation, by reforming the energy policies of both developed and developing countries to encourage the use of renewable energy sources and other energy-efficient technologies
c. In addition, financial resources should be efficiently allocated to environmentally friendly sectors of the economy around the world in order to minimize environmental degradation
d. Although some countries such as Libya, Turkey, Iran, Yemen, Iraq, etc., have not ratified the Paris Agreement, global policy-makers should encourage environmentally friendly technologies despite its cost.

Although the present study makes it possible to determine strong findings, further studies should be performed by employing different determinants of environmental sustainability, such as urbanization, FDI, trade, globalization, population, industrialization, and so on. In addition, this study used CO_2 as a proxy of environmental degradation, thus further studies should utilize other proxies of environmental degradation.

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