Role of Renewable Energy Consumption and Technological Innovation to Achieve Carbon Neutrality in Spain: Fresh Insights From Wavelet Coherence and Spectral Causality Approaches

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This research offers a new perceptive of the dynamic connection between CO_2 and globalization, technological innovation (TI), economic growth, and renewable energy (REN) consumption in Spain. The current research applied the wavelet tools to assess these interconnection utilizing data stretching from 1980 to 2018. The outcomes of these analyses disclose that the association among the series evolves over frequency and time. The current analysis uncovers notable wavelet coherence and strong lead and lag connections in the frequency domain, whereas the time domain indicates inconsistent correlations among the variables of interest. The outcomes of the wavelet analysis from the economic perspective affirm that in the short and medium term, globalization, economic growth, and TI contribute to environmental degradation; however, in the long term, globalization, economic growth, and TI do not contribute to the degradation of the environment. Moreover, at different frequencies, REN consumption helps mitigate environmental degradation in Spain. Furthermore, the spectral causality test unveiled that in the long term, REN utilization, globalization, TI, and economic growth can predict CO_2 emissions in Spain.

Keywords: CO_2 emissions, technological innovation, economic growth, wavelet tools, renewable energy consumption

INTRODUCTION

Energy is critical for economic activity and growth, but ecological impacts associated with fossil fuels (gas, coal, and oil) and the likelihood of their extinction has prompted a quest for alternative sources of energy (Nazir et al., 2018; Adebayo and Kirikkaleli, 2021; Rafique et al., 2022). Furthermore, the high cost of fossil fuels is a significant burden, particularly for energy importing nations. Climate change has presented new difficulties across the globe. Owing to climate change and global warming,

agricultural areas, several species of plants and animals, and water resources are at danger of disappearing (Ramzan et al., 2021; Wang et al., 2021). Following the Kyoto Protocol in 1997 and the Paris Agreement in 2015, several nations have begun to take significant environmental action. One of these initiatives is to use renewable energy (REN) to replace fossil fuels as much as possible. Technological innovation (TI) plays a critical role in reducing emissions while also assisting in the conservation of energy (Lin et al., 2021). TI is essential in lowering emissions while still aiding in the energy saving process (Ling et al., 2021). Additionally, TI is critical for the efficient use of both REN and conventional sources. TI can also help with the creation of new REN sources. TI further enhances REN capabilities, raising the overall amount of REN available to meet future energy demands. Because of the evident ever-increasing need for energy, it is acknowledged that REN will be the most important kind of energy in the future as well as an environmentally beneficial power source (Yuping et al., 2021). We identified a plethora of studies on the impact of REN on the deterioration of the environment. Previous studies suggest raising the amount of REN in the entire energy mix to reduce emissions (Shahzad et al., 2020; Shahzad et al., 2020b; Awosusi et al., 2021; He et al., 2021).

The significance of TI in reducing CO_2 emissions is clearly demonstrated in the existing studies, although it is not given adequate attention. There are just a few studies that look at the direct influence of TI on CO_2 emissions. For instance, Kihombo et al. (2021) reported that increasing TI mitigates CO_2 emissions in select developing nations. Similarly, Kirikkaleli and Adebayo (2020) established negative connection between TI and CO_2 emissions for the global economy. Likewise, Ullah et al. (2021) found that TI aids in improving environmental quality in OECD nations. Nonetheless, some studies (Lin and Zhu, 2019; Zhao et al., 2021) found positive TI-CO_2 connection whereas some studies (Garrone and Grilli, 2010; Dauda et al., 2021) established an insignificant T1-CO_2 connection. Despite the fact that the previous research revealed conflicting proof of the role of TI in CO_2 emissions, its significance for CO_2 emissions cannot be overlooked. We cannot dismiss the probability that TI performs an essential role in REN source growth globally. Studies have focused heavily on the interconnections between globalization, energy resources, and their usage. The theoretical basis for this link is straightforward: as countries become more globalized, so does their demand for energy. It is commonly accepted that as globalization develops, trade barriers disappear, leading to an upsurge in a country's output and level of income.

An increase in energy usage is associated with an upsurge in wealth and output. The effect of globalization on the environment has been examined. Nonetheless, considerable literature on this topic yields conflicting results. For instance, the studies by Haseeb et al. (2018) and Pata (2021) on Brazil and Chile established that globalization mitigates degradation of the environment. The rise in output and income caused by globalization is eventually reinforced by spillovers of technology in the exporting nations; thus, it is very likely that globalization can reduce the usage of energy and CO_2 emissions after a specific time period. We can examine the service sectors of advanced countries, such as the EU and the United States, where

employment is being moved to emerging nations, given that the utilization of energy in these sectors is lower than in the industrial sector. As a result, globalization has a positive ecological consequence in exporting nations. On the contrary, Kirikkaleli et al. (2021) in Turkey established a positive CO_2-GLO connection. According to these reasons, it is a well-known reality that the ecological consequences of globalization differ by nation or nations and areas. Globalization does not affect all nations in the same way or with the same severity. In the globalization process, there are many leaders and laggards. As a result, we can observe the most and least globalized nations on the global map. The same concept can be applied to energy and globalization connection; nonetheless, the linkage differs in the short and long terms correspondingly.

Why Spain? Spain is a developed nation with GDP and GDP per capita amounting to US$1.393 trillion US$29,600.38, respectively (World Bank, 2020). It is Europe's sixth largest energy consumer, after Germany, France, the United Kingdom, Turkey, and Italy, and has almost no domestic production of liquid fuel or natural gas. In recent years, Spain has considerably reduced CO_2 emissions, dropping from a peak of around 379 million metric tons of CO_2 in 2014 to approximately 278.5 million metric tons in 2019. As the globe witnesses the Arctic ice sheet melt and the weather gets more volatile, there is no denying that global warming is undeniably occurring. As a result, several nations have highly ambitious emission-cutting strategies in place for the forthcoming years. Spain has been notably effective in lowering CO_2 emissions caused by energy generation. Despite the fact that the energy sector continues to be responsible for the majority of GHG emissions, the nation has managed to reduce them to around 244 million tons of CO_2 equivalent in 2016, down from a record high of over 344 million tons in 2005. Furthermore, emissions from fuel combustion in industry and construction decreased by an astounding 30 million ton reduction, falling to around 41 million tons in 2016. Agriculture contributes to GHG emissions as well, and while not as significant as the manufacturing and construction industries, the sector decreased about 4 million tons of CO_2 equivalents with 34.4 million tons in 2016. Furthermore, **Figure 1** depicts the total energy supply (TES) by sources in Spain which is measured in ktoe (IEA, 2021).

The abovementioned factors make Spain an interesting case study. Thus, the current study objectives are highlighted as follows: First, we assess the connection between CO_2 emissions and globalization, TI, REN, and GDP at different frequencies. The second objective is to ascertain the causal effect of REN, GLO, TI, and GDP on CO_2 emissions at dissimilar frequencies. The current study adds to the previous literature in a variety of ways: 1) based on previous studies; we can conclude that this is the first research of its kind in Spain, which focuses on the association between CO_2 and REN, GLO, TI, and GDP at different time periods and frequencies. 2) The current research applied the wavelet tools to capture the connection between CO_2 and REN, GLO, TI, and GDP. The main benefit of this approach is that it distinguishes between short and long term over the sample period. Furthermore, this technique establishes a correlation and lead/
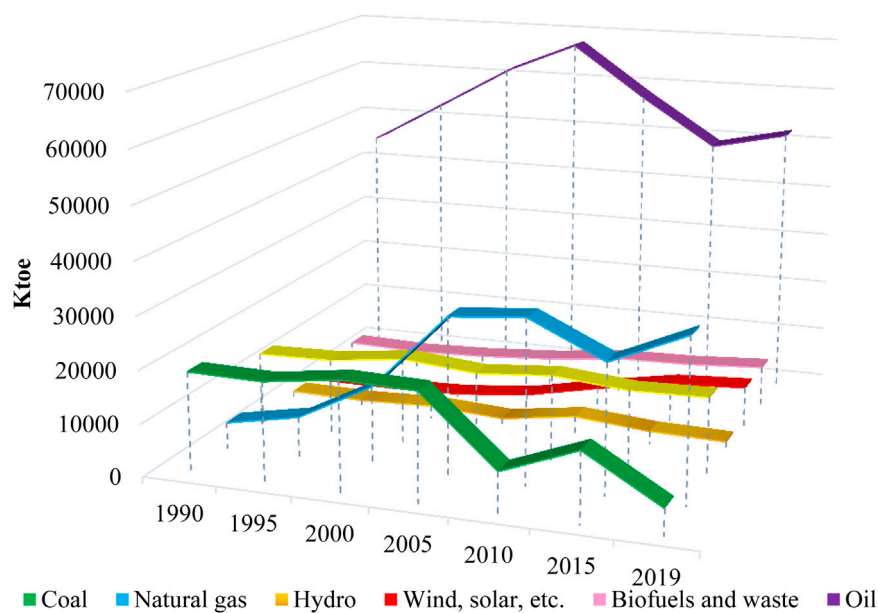
FIGURE 1 | Total energy supply (TES) by source, Spain 1990–2019.

lag association between the series. 3) We used spectral causality to capture the causal interrelation between CO_2 emissions and the independent variables at various frequencies. The benefit of this method is that it can detect causal interrelation between the series at different frequencies.

The remaining sections of this research are compiled as follows: a synopsis of previous studies is presented in *Literature Review*. *Theoretical Framework* presents the data and methods. *Data and Methodology* illustrates the findings and discussion, and the conclusion is presented in *Conclusion and Policy Direction*.

LITERATURE REVIEW

This portion of the current research tends to discuss previous studies conducted on the association between carbon emissions (CO_2) and TI, economic growth (GDP), REN usage, and globalization in Spain and the rest of the world. The objective of every nation is to achieve economic expansion; however, this has always come at the expense of environmental degradation. Thus, a plethora of studies has been conducted to assess the GDP-CO_2 association. For example, Shan et al. (2021) and Su et al. (2021) disclose that an upsurge in GDP triggers CO_2 emissions. Likewise, the study by Tufail et al. (2021) on highly decentralized economies uncovered a positive CO_2-GDP connection. In a bid to investigate the EKC hypothesis in Mexico, Adebayo (2020) employed the ARDL and wavelet tools. The empirical outcomes from this study disclosed that GDP impact CO_2 emissions negatively, and the EKC hypothesis is supported in Mexico. Similarly, the study by Kihombo et al. (2021) validates the EKC hypothesis. Furthermore, the study by Awosusi et al. (2021) on South Korea revealed positive coherency between GDP

and CO_2 emissions in the short, medium, and long term using the wavelet coherence. Similarly, the study by Akinsola et al. (2021) on the emission–growth nexus in Indonesia using wavelet tools reveals that an upsurge in GDP triggers CO_2 emissions. The positive relationship between GDP and economic growth is also validated by the studies of Sarwar and Alsaggaf (2021) on Saudi Arabia, Farooq et al. (2019) on China, Sarwar and Alsaggaf (2021) on 179 countries, Sarwar et al. (2019) on Chinese Provinces, Rauf et al. (2018) on belt and road initiative countries, Shahzad et al. (2020) on developed nations, Sarwar et al. (2019) on 161 countries, and Waheed et al. (2021) on six GCC economies.

Also, several studies have been conducted regarding the connection between TI and CO_2 emissions. For instance, using FMOLS and frequency domain causality (FDC) approaches, Kirikkaleli and Adebayo (2020) assessed the CO_2-TI connection with the global context utilizing quarterly data from 1980 to 2017. Their empirical outcomes disclosed a CO_2-TI negative association. Also, the FDC outcomes disclosed unidirectional causal linkage from TI to CO_2 emissions at different frequencies. In Brazil, Udemba et al. (2021) looked at the CO_2-TI association utilizing the NARDL from 1990 to 2018. The outcomes of the NARDL disclosed that positive shock in TI mitigates CO_2 emissions, whereas negative shock in TI exerts an insignificant influence on CO_2 emissions. Furthermore, the outcome of the asymmetric causality disclosed that increasing and decreasing TI can predict CO_2 emissions. Likewise, Kihombo et al. (2021) assessed the CO_2-TI connection in emerging markets within the STIRPAT framework from 1990 to 2017, and their findings unveiled a negative TI connection. Similarly, the study by Ahmad et al. (2021) on OECD nations disclosed a negative CO_2-TI interconnection. On the contrary, the study by Adebayo and Kirikkaleli (2021) on Japan utilizing wavelet tools established a positive CO_2-TI association, suggesting that an upsurge in TI

decreases CO_2 emissions. Likewise, Santra (2017) investigated the CO_2-TI association in BRICS economies utilizing dataset stretching from 2005 to 2012. The investigator applied the panel ARDL, and the study unveiled positive connection between TI and CO_2 emissions. Similarly, the study by Shaari et al. (2020) also reported that TI contributes to CO_2 emissions. Furthermore, Chen and Lee (2020) examined the influence of TI in reducing CO_2 emissions for a set of 96 nations. The research utilized spatial econometric frameworks by employing data from 1996 to 2018. The outcome revealed a significant interconnection between TI and CO_2 emissions in the overall sample, but when they separated the sample based on the levels of development, the outcomes gathered were found to be intriguing. In comparison to the other two categories of nations, the role of TI in mitigating CO_2 emissions is critical for high-income nations.

Due to its environmentally favorable qualities as compared to conventional energy sources, REN sources are getting a lot of support in the recent discussion on environmental sustainability. For instance, the study by Kirikkaleli and Adebayo (2021) on India using the FMOLS and DOLS discovered a negative CO_2-REN interconnection. Similarly, Altinoz and Dogan (2021) explored the connection between REN and CO_2 emissions in 82 nations applying the ARDL approach using data from 1990 to 2014. Their outcome revealed a negative CO_2-REN interconnection in the selected nations. The study by Mohsin et al. (2021) on the CO_2-REN connection in 25 developing Asian countries validated CO_2-REN association, which implies that REN significantly decreases the degradation of the environment. Likewise, Pata (2021) looked at the CO_2-GDP-REN interconnection in BRICS and developing countries, utilizing GMM and data stretching between 1990 and 2014. The authors applied the ARDL, and their outcome disclosed a negative CO_2-REN association whereas GDP deteriorates the quality of the environment. For the period 1990 to 2014, Sasana and Aminata (2019) assessed the impacts of energy-based economic development on CO_2 emissions in Indonesia. REN mitigates the degradation of the environment. Another interesting prospect is that, in the case of Indonesia, economic globalization has no effect on CO_2 emissions. In addition, there was no support of the EKC theory in Indonesia (Zandi and Haseeb, 2019), establishing the role of REN in mitigating CO_2 emissions in the selected African nations from 1995 to 2017. The research applied panel techniques, and their outcomes disclosed that green energy impacts environmental degradation negatively, and GDP impacts CO_2 emissions positively.

Scholars all across the globe are constantly interested in learning about the consequences of globalization on environmental sustainability. In this regard, the current literature yielded mixed results. For instance, Zaidi et al. (2019) explored the CO_2-GLO connection in APEC nations utilizing data stretching from 1960 to 2016. The investigators applied CUP and panel causality approaches, and their outcome disclosed a negative CO_2-GLO association. Similarly, the study by Haseeb et al. (2018) on BRICS nations was conducted from 1994 to 2014, and their findings show that GLO helps in decreasing the degradation of the environment. The study by He et al. (2021) on Mexico on the CO_2-GLO linkage between 1980 and 2016 unveiled a negative CO_2-GLO connection. Contrarily, the study by Muhammad and Khan (2021) on 155 emerging and advanced nations found a negative interconnection between GLO and CO_2 emissions. Similarly, Oluwajana et al. (2021) explored the CO_2-GLO connection in South Africa, utilizing data stretching from 1980 to 2018. The research applied ARDL and frequency domain causality approaches. The ARDL results disclosed a negative CO_2-GLO association whereas FDC unveiled unidirectional causal linkage from GLO to CO_2.

In summary, the majority of the existing studies have focused on the determinants of carbon emissions using time-domain techniques. Therefore, the present study contributes to the existing studies by assessing the influence of REN use, economic growth, and TI on carbon emissions using time–frequency and frequency-domain approaches. The current research applied the wavelet tools to capture the connection between CO_2 emissions and the independent variables. The main benefit of this approach is that it distinguishes between short and long term over the sample period. Furthermore, this technique establishes correlation and lead/lag association between variables. 3) We applied spectral causality test to detect the causal interrelation at various frequencies. The benefit of this method is that it can detect causal interrelation between the series at dissimilar frequencies. Exploring the combination of these methodologies helps to tap into the novelty of the approaches, thereby informing robust estimates that support proactive policy directions.

THEORETICAL FRAMEWORK

Over the past four decades, the world economy has seen enormous economic expansion, including increased energy utilization. Regrettably, strong economic development and rising energy demand have had environmental consequences. Kraft and Kraft (1978) were the first to demonstrate a link between the utilization of energy and economic development. According to Ozturk and Acaravci (2016), it is impossible to attain sustainable growth if concerns regarding the destruction of the environment such as climate change and global warming continue to worsen. Environmental economists including Panayotou (1997) and Grossman and Krueger (1991) used this approach to investigate the relationship between environmental deterioration and economic expansion. According to them, economic growth occurs in three separate phases: scale, structural, and composite effects. The ecosystems will suffer in the early stages of growth until a specific threshold (the turning point) is achieved; and growth will increase the degradation of the environment during this period. The initial phase is recognized as the scale effect phase, whereas the turning point and the time after the turning point are recognized as the composite and structural effect stages, respectively. The scale effect phase is linked with emerging economies where non-renewable sources of energy support economic performance and production activities. The composite and structural effect stages, on the other hand, are associated with developed nations, such as Spain, where technical innovation and services dominate economic prosperity.

Moreover, the theoretical basis for the linkage between CO_2 emissions and globalization is straightforward: as countries

| Indicators	Description	Units	Source
CO_2	CO_2 emissions	Metric tons per capita	BP
GDP	Economic growth	GDP per capita	WDI
REN	Renewable energy consumption	Renewable energy consumption per capita (kWh)	BP
TI	Technological innovation	Patent applications (resident + non-resident)	WDI
GLO	Globalization	Index based on FDI, trade, and portfolio investment	Gygli et al. (2019)
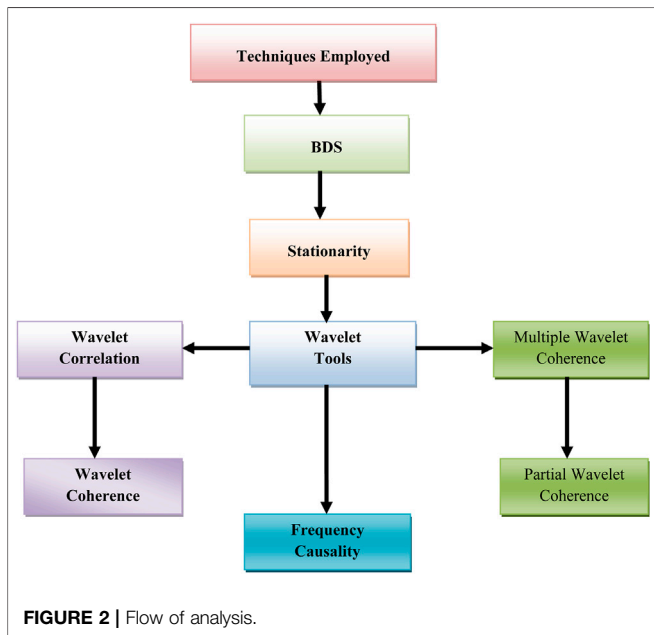
FIGURE 2 | Flow of analysis.

become more globalized, so does their need for energy. It is commonly assumed that as globalization advances, trade barriers would decrease, leading to an upsurge in a nation's output and revenue. An upsurge in the utilization of energy is associated with an upsurge in production and income. As it is generally believed that increasing globalization is associated with higher levels of economic growth, it is also commonly assumed that globalization aids to mitigate environmental degradation; otherwise, it would cause environmental degradation if not being eco-friendly. Finally, TI plays an essential part in lowering emissions while also aiding in energy conservation. Additionally, TI is critical to the efficient use of both REN and traditional sources. TI can also help with the creation of new REN sources. TI also improves REN capabilities, increasing the likelihood supply of REN to meet future energy demand. Because of the ever-increasing demand for energy, it is widely assumed that REN will be the most significant kind of energy in the future, and it is also an environmentally friendly energy source.

The research theoretical model is formulated based on the above discussions as follows:

$$CO_{2t} = f(GDP_t, GLO_t, REN_t, TI_t) \quad (1)$$

Here, GDP, REN, CO_2, GLO, and TI stand for economic growth, utilization of REN, CO_2 emissions, globalization, and TI, respectively. The period of study is depicted by t.

DATA AND METHODOLOGY

Data

The current article explores the effect of GDP-, GLO-, TI-, and REN-CO_2 in Spain. The research utilizes quarterly data stretching from 1980 to 2019. The time duration is limited by the availability of data. **Table 1** presents the variable's of interest description and source of data. Moreover, all variables are transformed into their natural log to guarantee normal distribution in the data and to resolve the issue of heteroscedasticity. In addition, the analysis flow is disclosed in **Figure 2**.

Methodology

In this empirical analysis, numerous econometric methods centered on time-series were utilized. First, the series stationarity features were tested by employing ZA introduced by Zivot and Andrews (2002). Furthermore, the research applied the BDS test initiated by Broock et al. (1996) to verify the nonlinearity features of the series of investigations.

Wavelet Coherence

Wavelet coherence is employed to detect the time–frequency dependence of TI, globalization, and economic growth on CO_2 emissions. Time–frequency dependence puts into account the changes overtime, and how the relationship varies from one frequency to another becomes essential and strategic in the formulation of policies (Mutascu, 2018; Adebayo, 2020). The Morlet wavelet function was employed since it brings balance between phase and amplitude. The Morlet wavelet function is defined as follows:

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

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

$$w_{k,f}(n) = \frac{1}{\sqrt{h}} w\left(\frac{n-k}{f}\right), \quad k, f \in \mathbb{R}, f \neq 0 \quad (3)$$

where k and f symbolize time and frequency, respectively. CWT helps the cross wavelet analysis to interrelate between the two variables. The CWT equation is written below as follows:

$$w_p(k, f) = \int_{-\infty}^{\infty} p(n) \frac{1}{\sqrt{f}} w\left(\frac{n-k}{f}\right) dn. \tag{4}$$

The local variance was revealed using the wavelet power spectrum (WPS). The equation defining the WPS is as follows:

$$WPS_p(k, f) = |W_p(k, f)|^2 \tag{5}$$

To examine the co-movement between two time series, the wavelet coherence approach (WTC) was used, which is defined in the equation given below:

$$R^2(k, f) = \frac{|S(f^{-1} W_{pj}(k, f))|^2}{S(f^{-1}|W_p(k, f)|^2) S(f^{-1}|W_j(k, f)|^2)} \tag{6}$$

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

$$\phi_{pq}(k, f) = \tan^{-1}\left(\frac{L\{S(f^{-1} W_{pj}(k, f))\}}{O\{S(f^{-1} W_{pj}(k, f))\}}\right), \tag{7}$$

where L denotes an imaginary operator whereas O stands for a real-part operator.

Partial Wavelet Coherence

PWC is a technique that is comparable to PC. The wavelet transfiguration approach is utilized to analyze PWC. The method catches WC for x1 and x2 series after canceling the x3 effect. The PWC is illustrated by the equations as follows:

$$R(x_1, x_2) = \frac{S[W(x_1, x_2)]}{\sqrt{S[W(x_1)], S[W(x_2)]}}; \tag{8}$$

$$R^2(x_1, x_2) = R(x_1, x_2).R(x_1, x_2); \tag{9}$$

$$R(x_1, x_3) = \frac{S[W(x_1, x_2)]}{\sqrt{S[W(x_1)], S[W(x_3)]}}; \tag{10}$$

$$R^2(x_1, x_3) = R(x_1, x_3).R(x_1, x_3); \tag{11}$$

$$R(x_2, x_3) = \frac{S[W(x_2, x_2)]}{\sqrt{S[W(x_2)], S[W(x_3)]}}; \tag{12}$$

$$R^2(x_2, x_3) = R(x_2, x_3).R(x_2, x_3); \tag{13}$$

The PWC is predicated on linear connection (by eradicating x3 impact). The PC is depicted as follows:

$$RP^2(x_1, x_2, x_3) = \frac{|R(x_1, x_2) - R(x_1, x_2).R(x_1, x_2)^*|}{[1 - R(x_{1-x3})]^2 [1 - (x_3 - x_2)]^2} \tag{14}$$

As stated by Sharif et al. (2019), when the effect of x3 is removed, a low PWC implies that series x2 has minimal influence on x1.

TABLE 2 | Descriptive statistics.

	CO_2	GDP	GLO	REN	TI
Mean	0.796265	4.403924	1.868733	0.456798	3.376555
Median	0.781438	4.433613	1.888811	0.407523	3.356217
Maximum	0.923965	4.518267	1.932782	0.797972	3.560146
Minimum	0.687074	4.239249	1.771246	0.140469	3.175512
Std. Dev	0.069109	0.093335	0.056253	0.198194	0.110602
Skewness	0.355507	−0.522701	−0.547909	0.388759	−0.033098
Kurtosis	2.020683	1.855983	1.726747	1.920159	1.959184
Jarque-Bera	2.379980	3.902664	4.585736	2.877208	1.767478
Probability	0.304224	0.142085	0.100976	0.237259	0.413235

Multiple Wavelet Coherence

The MWC technique is adequate for assessing the coherency of many variables with other control parameters (Adebayo and Kirikkaleli, 2021). The equation below depicts MWC as follows:

$$RM^2(x_1, x_2, x_3) = \frac{R^2(x_1, x_2) + R^2(x_1, x_3) - 2Re[R(x_1, x_3)*R(x_3, x_2)^*]}{1 - R^2(x_3, x_2)} \tag{15}$$

Frequency Domain Causality

The current research also intends to capture the causal effects of TI, economic growth, REN use, and globalization on CO_2 emissions at different frequencies. Thus, the frequency-domain causality test by Breitung and Candelon (2006) is utilized in this study. "The key distinction between the time-domain method and the frequency-domain method is such that the "time-domain" method informs us where a particular change arises inside a time series, whereas the "frequency-domain" method evaluates the extent of a specific variation in time-series" (Awosusi et al., 2021; Kirikkaleli and Adebayo, 2020). The frequency-domain causality test enables the removal of seasonal fluctuations in the small sample data. Additionally, non-linearity and causality phases may be identified by the frequency-domain test, whereas the test often facilitates the detection of causality between variables at low, medium and long frequencies. 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. The basis of the test is a recreated VAR between x and y, represented as follows:

$$x_t = \theta_1 x_{t-1} + \ldots + \theta_1 x_{t-1} + \beta_1 y_{t-1} + \ldots + \beta_l y_{t-1} + \varepsilon_t \tag{16}$$

The Akaike information criterion (AIC) is utilized in lag l selection. Centered on (Geweke, 1982) null hypothesis (M) that $M_{Y \to x}(\omega) = 0$, where the frequency $\omega \varepsilon (0, \pi)$, and adjusted null hypothesis (H) is formulated as follows:

$$H_0 : R(\omega)\beta = 0 \tag{17}$$

The vector linked to y coefficients is denoted by β

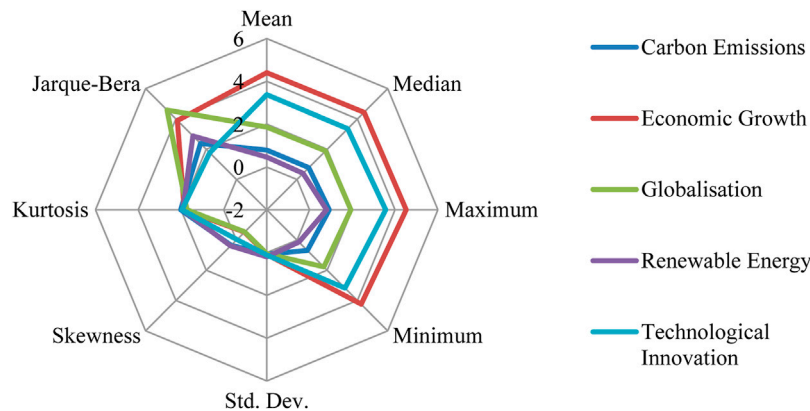$$R(\omega) = \frac{\cos(\omega) \cos(2\omega) \ldots \cos(l\omega)}{\sin(\omega) \sin(2\omega) \ldots \sin(l\omega)} \tag{18}$$

FIGURE 3 | RADAR chart.

TABLE 3 | BDS test.

	CO_2	GDP	REN	GLO	TI
M2	19.2091*	23.3176*	20.6860*	14.6472*	17.5940*
M3	19.3176*	24.2567*	21.6019*	16.0156*	19.9346*
M4	19.1785*	26.1772*	22.7767*	16.5159*	21.9580*
M5	19.3576*	28.8993*	24.5607*	17.0981*	24.5068*
M6	19.7247*	32.9134*	27.1143*	17.3026*	27.1247*

*, **, and *** stands for p < 1%, p < 5%, and p < 10%.

TABLE 4 | ZA outcomes.

Variables	I(0)	Break-Date	I(1)	Break-Date
CO_2	−3.5348	2007Q2	−5.3492**	2007Q2
GDP	−3.5242	2010Q2	−4.9000***	2007Q2
REN	−4.2337	1988Q2	−6.7721*	1992Q3
TI	−2.000	2013Q1	−5.8130**	2012Q4
GLO	−3.9450	1988Q4	−6.7982*	1988Q2

*, **, and *** stands for p < 1%, p < 5%, and p < 10%.

The null hypothesis pinpoint that at all frequencies, X does not cause Y. Moreover, Breitung and Candelon (2006) propose 5 and 10% significance levels for all frequencies in the interval (0,π). Frequency ω is linked to period t as **t = 2π/ω**.

FINDINGS AND DISCUSSION

We assess the effect of TI, economic growth (GDP), REN usage, and globalization (GLO) on carbon emissions (CO_2) in Spain utilizing the quarterly dataset from 1980 to 2018. Before further analyses are conducted, it is crucial to understand variables brief information. **Table 2** presents the research descriptive statistics. GDP has the highest mean which ranges from 4.2391 to 4.518267. This is followed by TI with a mean value of 3.376555 ranging from 3.175512 to 3.560146, GLO with a mean value of 1.868733 which ranges from 1.771246 to 1.932782, CO_2 with a mean value of 0.796265 which ranges from 0.687074 to 0.923965, and REN with a mean value of 0.456798 which ranges from 0.140469 to 0.797972. The value of standard deviation disclosed that CO_2 has consistent score which is followed by GLO, GDP TI, and REN respectively. The value of the skewness for the variables of interest uncovered that GDP, GLO, and TI are skewed negatively whereas CO_2 and REN are skewed positively. In addition, the kurtosis value disclosed that all series are platykurtic in nature. We also utilized the RADAR chat to present the variable's brief description which is illustrated in **Figure 3**. Furthermore, the current research applied the BDS test suggested by Brock et al.

(1996) to catch the nonlinearity features of the variables of concern. The outcomes of the BDS test are presented in **Table 3** which disclosed that all the variables are nonlinear. Based on this understanding, utilizing the linear techniques (e.g., FMOLS, ARDL, VECM, DOLS, and CCR) may produce outcomes that are misleading. **Table 4** also depicts the ZA unit root outcomes which illustrates that series are I(1).

The five-variables graph show that the pattern and movement are irregular, with surprising peaks and dips over time. As a result, it is difficult for the human eye to detect any discernible periodic patterns or cycles. As a result, the wavelet transform was employed in the research to investigate previously undiscovered patterns in these indicators. The wavelet transform's core multiresolution analysis allows concealed influences to be isolated and localized. The figures show the Morlet wavelet transform for each variable separately. **Figures 4A–E** depict the MRA of order j = 6 for GLO, CO_2, GDP, TI, and REN performed applying the maximum overlap discrete wavelet transform (MODWT). The orthogonal elements (D1, D2, , D6), which indicate distinct frequency parts of the initial variables, and also S6, which illustrates a smooth part, are displayed in the figures. The study evidences shown in **Figures 4A–E** show that each of the series display high frequencies in the short run before becoming stable in the long run. MODWT and DWT are used to decompose the time-series energy across scales. The motions are described using four periods, namely, D1 and D2-short term, D3 and D4-medium term, D5 and D6-long term, and S6-very long term.
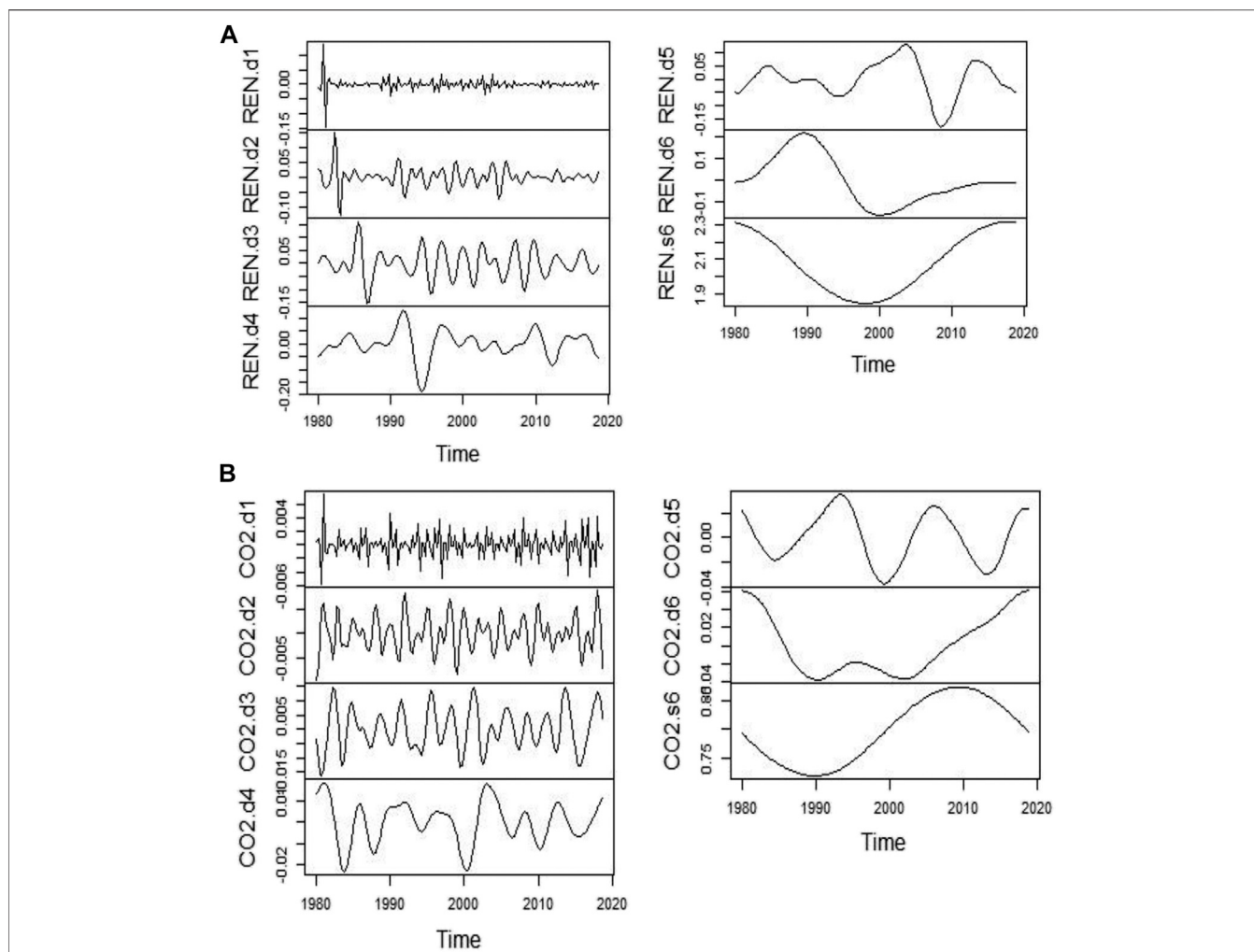
FIGURE 4 | (A) REN wavelet transfiguration. **(B)** CO_2 wavelet transfiguration. **(C)** GDP wavelet transfiguration. **(D)** GLO wavelet transfiguration. **(E)** TI wavelet transfiguration.

According to the discoveries shown in **Figures 4A–E**, the overwhelming of the changes in all series occurred in the short term, accompanied by the medium term. Nevertheless, when we move into the long term, the variance in CO_2, REN, GDP, TI, and GLO becomes more constant.

After, the wavelet transform of the variables is established, the present research explores the wavelet correlation (WC) between CO_2 and REN, GDP, TI, and REN at different scales which is depicted in **Figures 5A–D**, respectively. The Monte Carlo method is utilized to perform WC. The graphs show the correlation between CO_2 and REN, GDP, TI, and GLO at various levels. If the value of correlation between two variables is close to 0, it illustrates no dependency between the series. However, if the correlation coefficient is close to 1, it depicts dependency between series. In addition, a negative correlation denotes that two series move in different paths whereas a positive correlation means movement in the same direction. Thus, we applied WC to eliminate the fundamental concealed information

in the data associated with time-domain correlation technique. The outcomes from WC disclosed the following: 1) in the short and long run, there is positive correlation between CO_2 and GDP; though the coefficient is higher in the long term; 2) in the short and medium term, there is positive and weak connection between GLO and CO_2; however, in the long term, their strength of the correlation is stronger; 3) the correlation between CO_2 and REN is negative and significant in the short, medium, and long term; 4) in all scales, the correlation between TI and CO_2 is weak and positive.

The present research applied wavelet coherence (WTC) to catch the series co-movement and lead/lag association at different frequencies and period between series. This approach is crafted from mathematics and is utilized to acquire previously unnoticed information. As a result, the study looks at the association between the series at different frequencies. The white cone where discourse takes place in WTC is known as the cone of impact (COI). The black boundary depicts a significance level
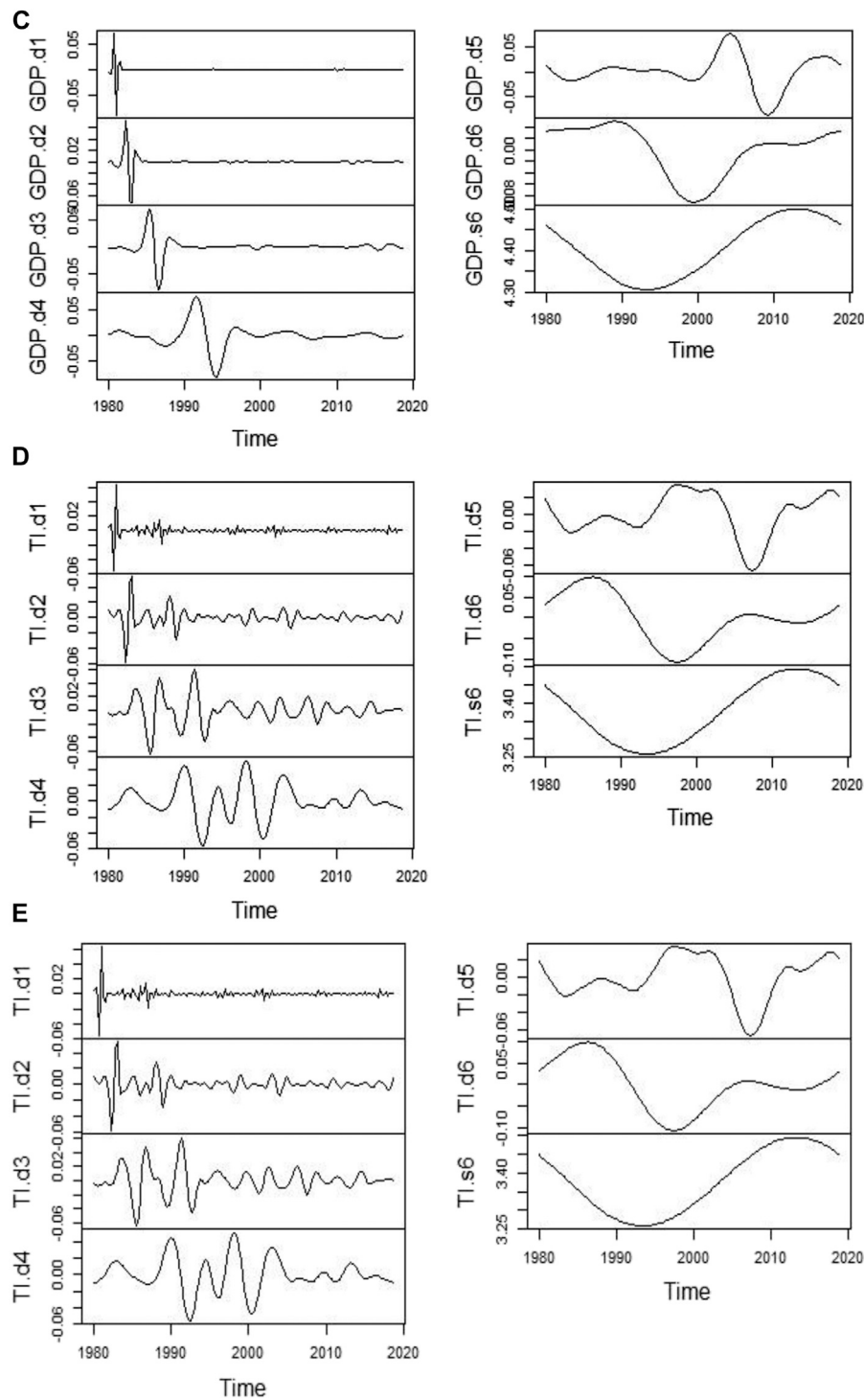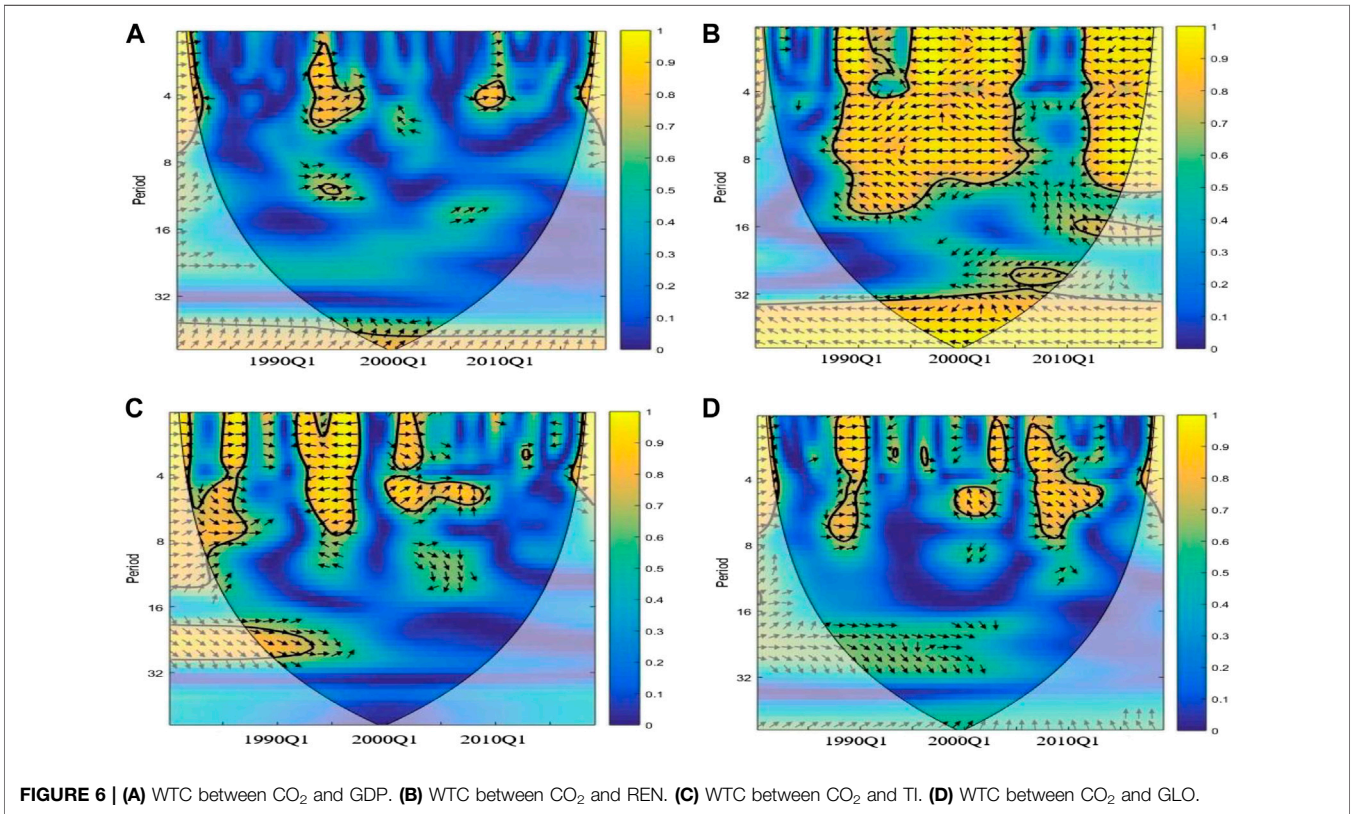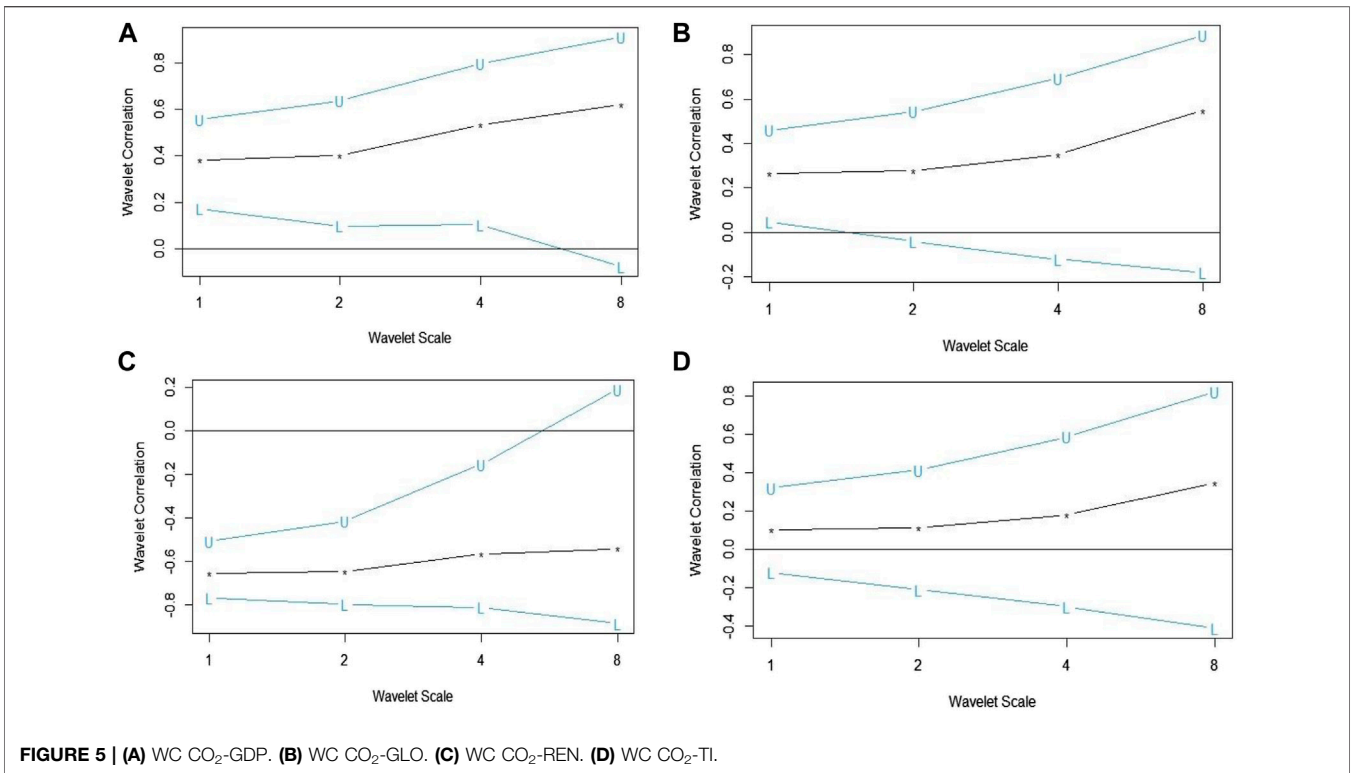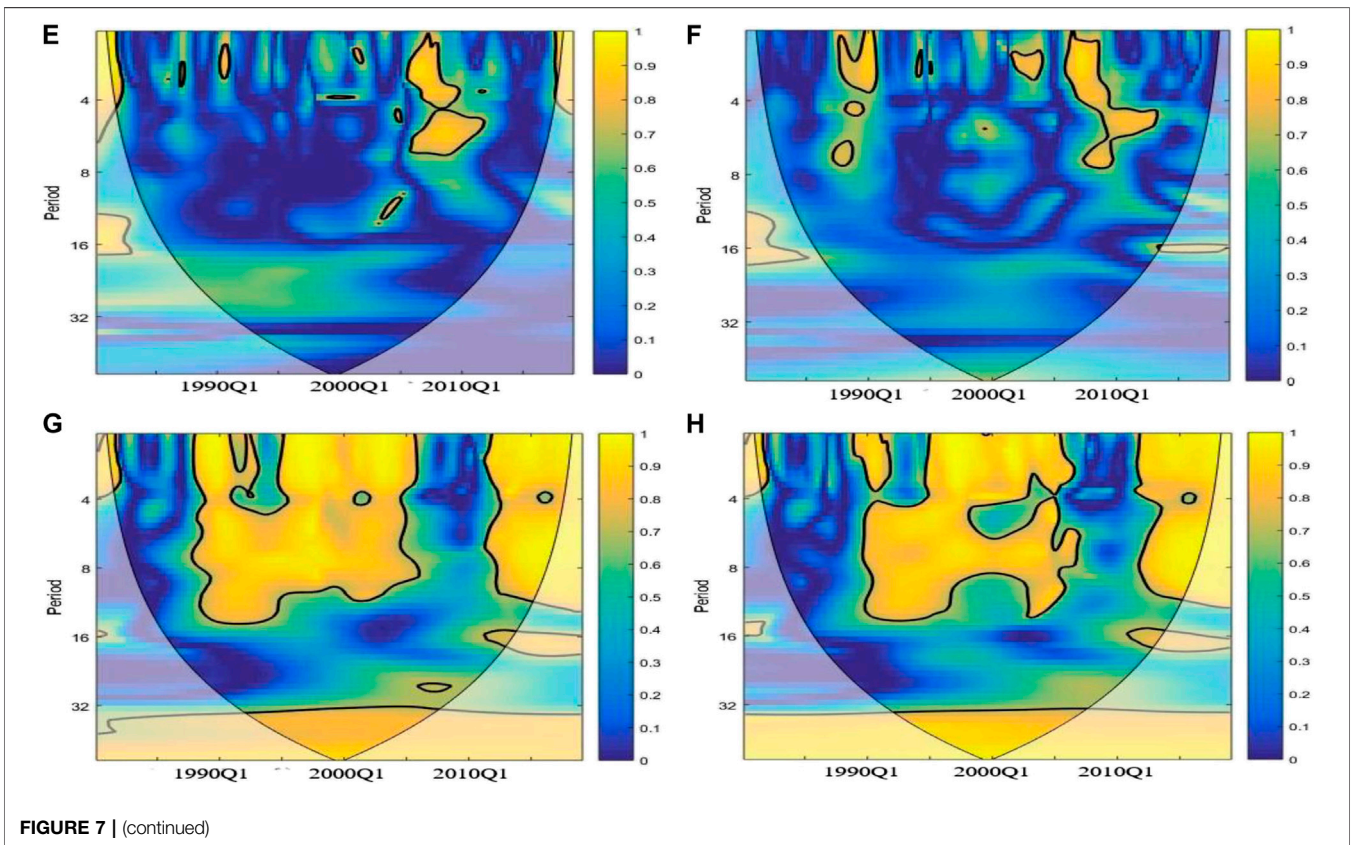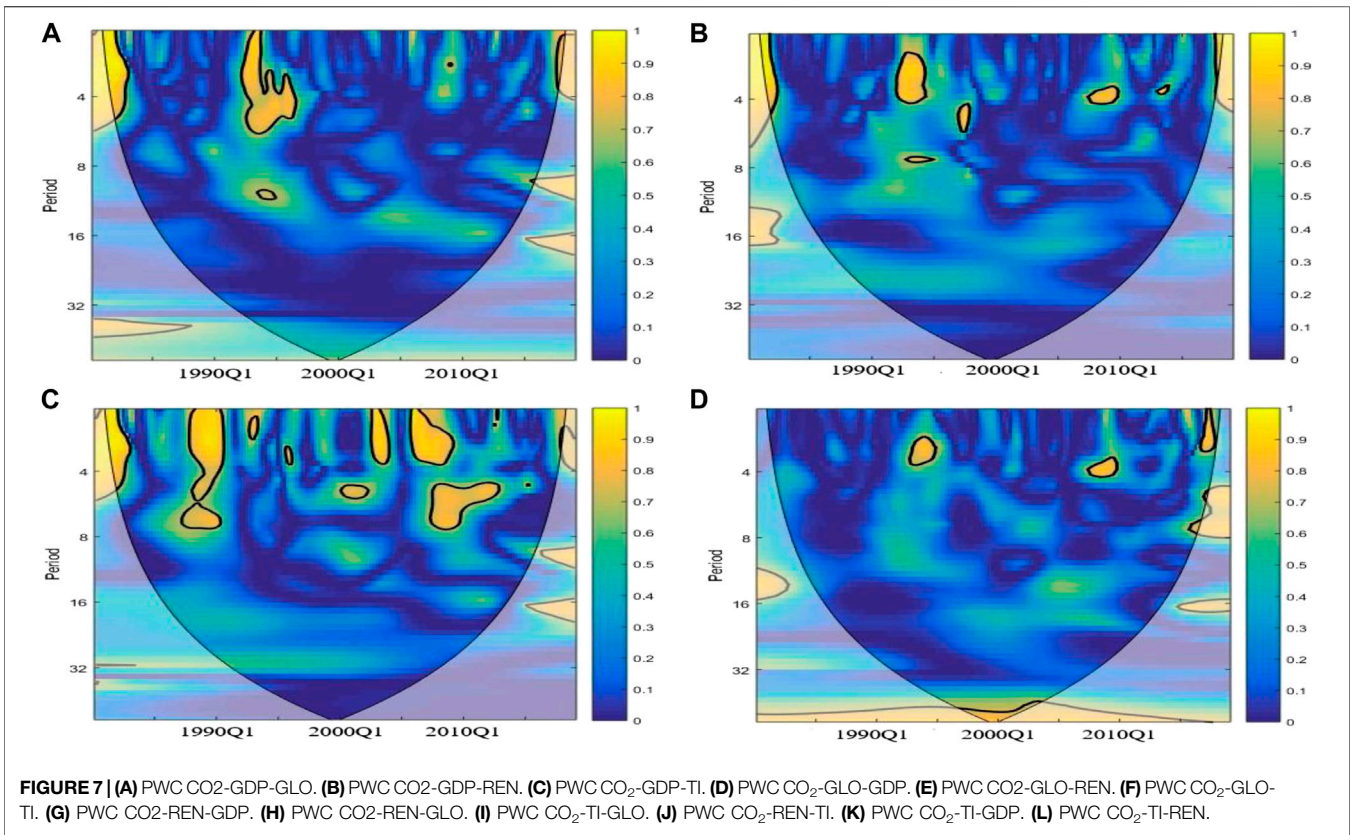
FIGURE 4 | (A) REN wavelet transfiguration. **(B)** CO_2 wavelet transfiguration. **(C)** GDP wavelet transfiguration. **(D)** GLO wavelet transfiguration. **(E)** TI wavelet transfiguration.

predicated on simulations. The short, medium, and long periods are illustrated by 0–4, 4–8, and 8–32, respectively, in **Figures 6A–D**. Furthermore, the figure's horizontal and vertical axes represent time and frequency, respectively. The colors blue and yellow represent low and high interdependence between the series, respectively. The leftward and rightward arrows represent out-of-phase and in-phase connections, respectively. Moreover, the rightward-down (leftward-up) signifies that the
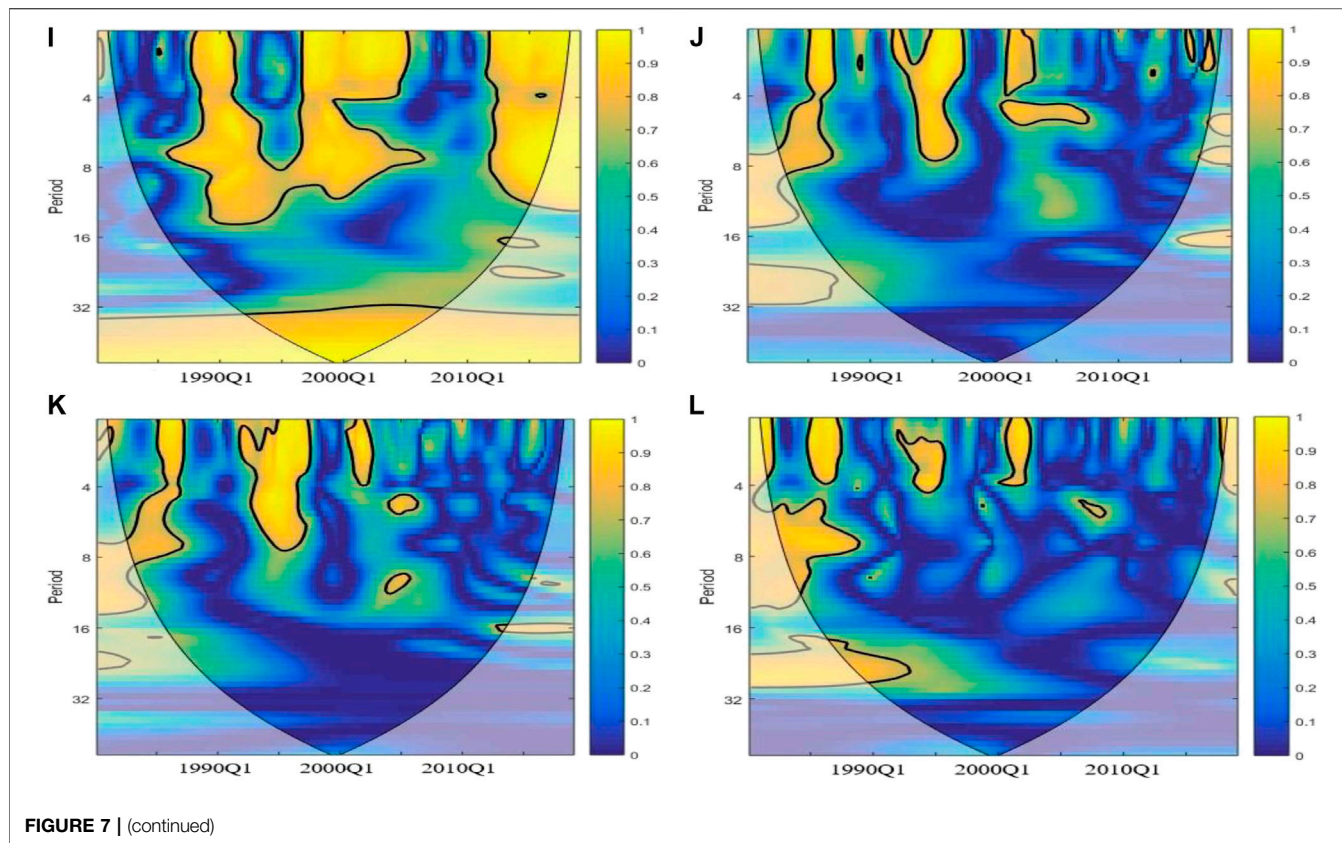
FIGURE 5 | (A) WC CO_2-GDP. (B) WC CO_2-GLO. (C) WC CO_2-REN. (D) WC CO_2-TI.

FIGURE 6 | (A) WTC between CO_2 and GDP. (B) WTC between CO_2 and REN. (C) WTC between CO_2 and TI. (D) WTC between CO_2 and GLO.

FIGURE 7 | (A) PWC CO2-GDP-GLO. **(B)** PWC CO2-GDP-REN. **(C)** PWC CO$_2$-GDP-TI. **(D)** PWC CO$_2$-GLO-GDP. **(E)** PWC CO2-GLO-REN. **(F)** PWC CO$_2$-GLO-TI. **(G)** PWC CO2-REN-GDP. **(H)** PWC CO2-REN-GLO. **(I)** PWC CO$_2$-TI-GLO. **(J)** PWC CO$_2$-REN-TI. **(K)** PWC CO$_2$-TI-GDP. **(L)** PWC CO$_2$-TI-REN.

FIGURE 7 | (continued)
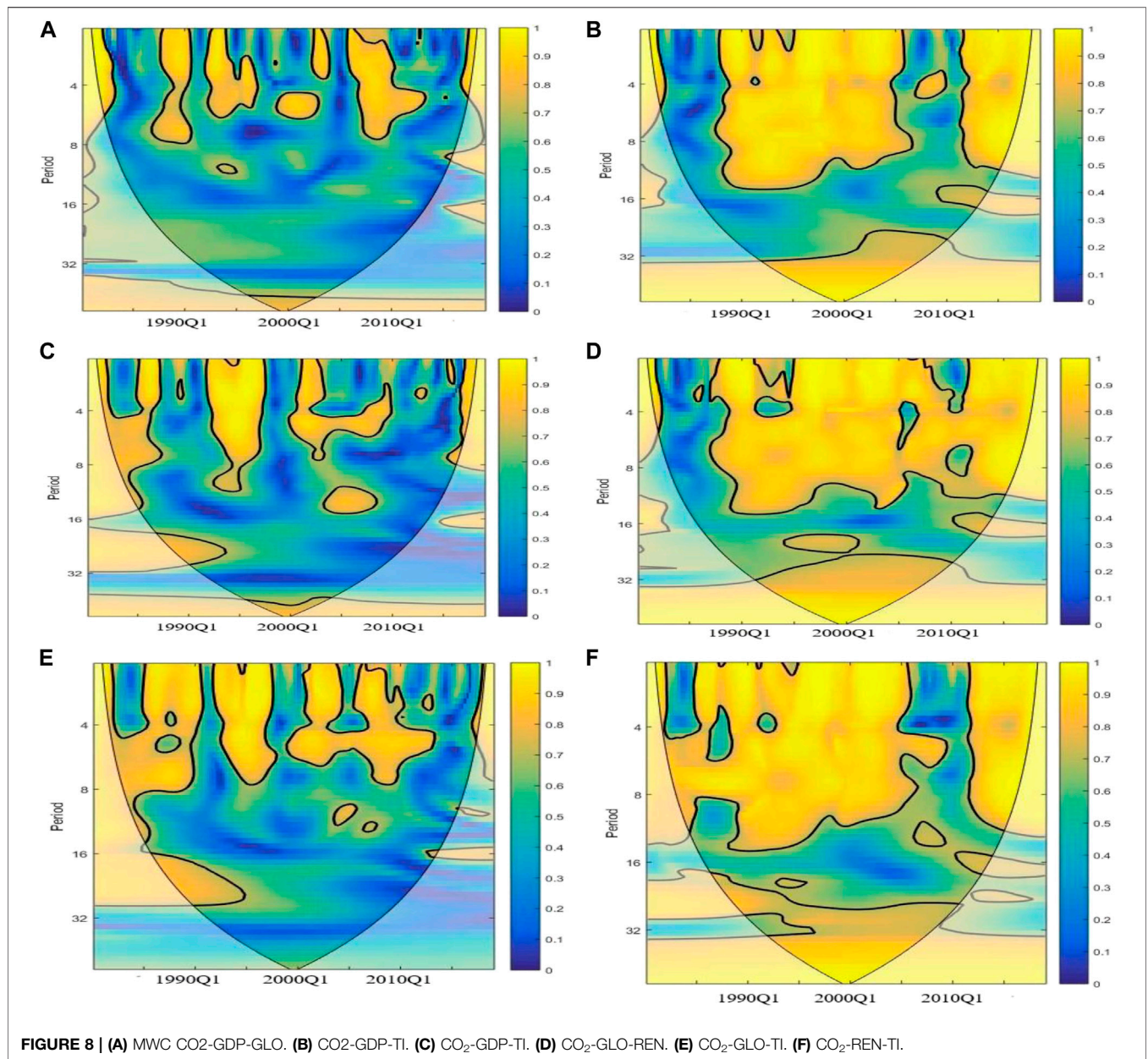
FIGURE 7 | (continued)

first series leads (cause) the second series, whereas the rightward-up (leftward-down) signifies that the second series leads (cause) the first series. The outcomes of WTC are illustrated as follows.

Figure 6A depicts WTC between GPD and CO_2 emissions in Spain from 1980 Q1 and 2018 Q1. WCT identifies regions in which there is coherence between GDP and CO_2 in the time and frequency domains. The results of **Figure 6A** show impressive outcomes. The outcomes of WTC for CO_2-GDP displays that at period of scale 0–4, the coherence between CO_2 and GDP is positive (in-phase) from 1980 Q1–1982 Q1 with the arrows pointing rightward-up, suggesting that GDP leads CO_2 (GDP has a positive causal influence on CO_2). Also, at high frequency at a period of scale 0–8, from 1995 to 1998, the bulk of the arrows are facing right which implies positive coherence between GDP and CO_2 with GDP leading (GDP has a positive causal influence on CO_2. Furthermore, between 2009 and 2010, the CO_2 and GDP are in-phase (positive connection) as disclosed by the rightward arrows. The possible explanation for the weak in-phase connection between CO_2 and GDP is that economic expansion contributes to the degradation of the environment in Spain; however, the co-movement between GDP and CO_2 is not significant. This outcome further supports the EKC hypothesis where in developed nations, such as Spain, services and TI dominates the economic expansion. Another notable outcome from our empirical analysis is that there is no coherency between CO_2 and GDP at low frequencies, implying that in the long term; increase in economic growth does not trigger CO_2 This outcome

complies with the studies by Shan et al. (2021), Orhan et al. (2021), and Zhang et al. (2021).

Figure 6B presents WTC between CO_2 and REN from 1980 Q1 and 2018 Q1. At period of scale 0–32, from 1990 Q1 to 2018 Q1, all the arrows point leftward which illustrates that the series are out-of-phase (negative coherence) with REN leading (REN has a negative causal influence on CO_2). This further implies that an upsurge in REN is accompanied by a decrease in CO_2 in Spain. Another notable outcome from our empirical analysis is that there is strong coherency between CO_2 and REN at low frequencies, implying that in the long term; increase in REN consumption in Spain mitigates the degradation of the environment. This is hardly unexpected, given that renewables provided 44% of total energy in Spain in 2020, making it the cleanest year on record in the country's history since 2007. Inexhaustible and natural resources including Sun, water, and wind produced a total of 110,450 GWh, an upsurge of 12.8 percent over the previous year's figures. This is the highest percentage of renewables in Spain's energy mix since records began in 2007. Coal-fired power plants, on the flipside, decreased production by 60% compared to 2019 and 2% in the total generation which is a record low. This outcome is consistent with the studies by Pata (2021), Shahzad et al. (2020), and Soylu et al. (2021).
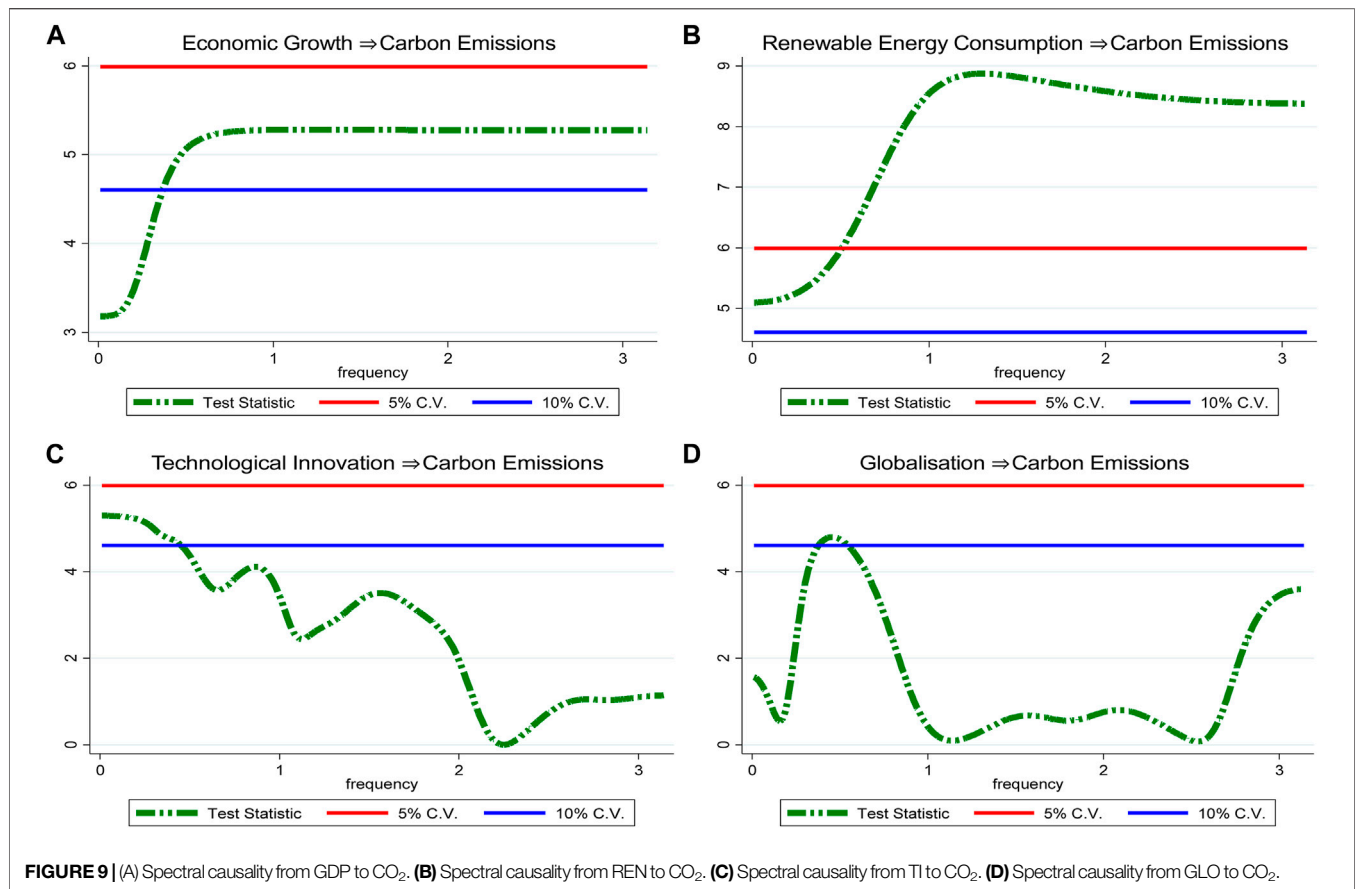
Figure 6C presents WTC between CO_2 and TI from 1980 Q1 and 2018 Q1. At period of scale 0–8, 1983–1995, the arrows are rightward which demonstrates an in-phase (positive) association between CO_2 and TI with TI leading CO_2 (TI Granger cause CO_2 positively). However, between 1995 and

FIGURE 8 | (A) MWC CO2-GDP-GLO. **(B)** CO2-GDP-TI. **(C)** CO_2-GDP-TI. **(D)** CO_2-GLO-REN. **(E)** CO_2-GLO-TI. **(F)** CO_2-REN-TI.

2000, at high and medium frequencies, CO_2 and TI are out-of-phase (negative connection) with the leftward down arrow suggesting that TI leads CO_2 (TI Granger cause CO_2 negatively). Furthermore, at scale 0–8, between 2002 and 2008, the arrows are rightward suggesting positive coherency between CO_2 and TI with TI leading (TI Granger cause CO_2 positively). The main explanation from this findings disclosed that in the short and medium term, from 1983 to 1995 and from 2002 to 2008, TI in Spain is not eco-friendly. This result complies with the works of Zhao et al. (2021) and Coelho et al. (2021). However, in the short and medium term from the period 1995 to 2000, there is negative coherence between TI and CO_2. This illustrates that during this period TI

in Spain is eco-friendly. This outcome concurs with the works of Ikram et al. (2021) and Kihombo et al. (2021b), Lin and Zhu (2019) established a negative CO_2-TI association.

Figure 6D portrays WTC between CO_2 and GLO in Spain between 1980 and 2018. At period of scale 0–8 quarters, from 1988 to 1990 and 2009–2012, majority of the arrows point right, suggesting positive coherence between GLO and CO_2 with majority of the arrows pointing rightward-down (CO_2 Granger cause GLO). The most likely explanation for this connection is that *via* increased trade, globalization also improves total factor productivity. It boosts economic activity by attracting the FDI and facilitating the transfer of superior technology between developed and developing countries. This process triggers

FIGURE 9 | (A) Spectral causality from GDP to CO$_2$. **(B)** Spectral causality from REN to CO$_2$. **(C)** Spectral causality from TI to CO$_2$. **(D)** Spectral causality from GLO to CO$_2$.

economic growth, financial markets, and commerce as well as the utilization of energy. However, the process of globalization triggers emissions of CO$_2$ as a result of generation and utilization of energy for the production of activities in developing and advanced nations. Another notable outcome from our empirical analysis is that there is no coherency between CO$_2$ and GLO at low frequencies, implying that in the long term; increase in globalization does not trigger CO$_2$ emissions This outcome corroborates the studies by Kirikkaleli et al. (2021) and Adebayo and Kirikkaleli (2021) who established a positive CO$_2$-GLO connection.

As a robustness check for WTC, the research applied PWC to identify the effect of the second variable (x2) on the first variable (x1) after removing the third serie's (x3) effect. **Figure 7A** presents PWC between CO$_2$ and GDP after GLO effect is annulled. In the period of scale 0–8 quarters, from 1981 to 1983 and from 1993 to 1995, GLO has significant effect on CO$_2$ with the GLO effect being cancelled. **Figure 7B** displays PWC between GDP and CO$_2$ after REN impact has been eliminated. At period of scale 0–4 quarters, between 1994 and 1995, the impact of GDP on CO$_2$ is significant with the REN effect being eliminated. **Figure 7C** shows PWC between CO$_2$ and GDP with TI impact being eradicated. Moreover, from 1987 to 1990, 2005 to 2005, and 2006 to 2010, at higher frequency and period of scale 0–8 quarters, the coherency between CO$_2$ and GDP is strong after the influence of TI is removed. The impact of GLO on CO$_2$ after annulling the effect

of GDP is presented in **Figure 7D**, and the outcome displays no significant coherence between CO$_2$ and GLO after eliminating the GDP effect. Also, the impact of GLO on CO$_2$ after annulling the effect of REN is presented in **Figure 7E**. In the short and medium frequencies, GLO's impact on CO$_2$ is strong between 2005 and 2010 with the REN influence being neglected. **Figure 7F** presents the GLO effect on CO$_2$ after TI impact is eradicated. At short and medium term, from 1997 to 1990 and 2005 to 2010, there is strong coherency between GLO and CO$_2$ after TI impact is cancelled. The impact of REN on CO$_2$ after annulling the effect of GDP is portrayed in **Figure 7G**. At different frequencies, between 1990 and 2017, the effect of REN on CO$_2$ is significant with GDP impact dismissed.

Figure 7H depicts PWC between CO$_2$ and REN with the GLO impact removed. At different frequencies (short, medium, and long term), between 1990 and 2017, the effect of REN on CO$_2$ is significant with GLO impact dismissed. **Figure 7I** depicts PWC between REN and CO$_2$ with TI influence annulled. At different frequencies between 1995 and 2017, the effect of REN on CO$_2$ is significant with TI impact dismissed. Also, the impact of TI on CO$_2$ after annulling the effect of GLO is presented in **Figure 7J** with significant coherence observed in the middle and high frequencies from 1985–1987, 1996–1999, and 2003–2006. The impact of TI on CO$_2$ after annulling the effect of GDP is presented in **Figure 7K**. There is a strong coherency between CO$_2$ and TI after the impact of GDP is eradicated in the high and

medium frequencies from 1985–1987 and 1996–1999. The effect of TI on CO_2 after annulling the effect of REN is presented in **Figure 7L**. There is a strong coherency between CO_2 and TI after the REN effect is removed at various frequencies from 1981 to 1990. Also, at the short term, from 1994 to 1995 and from 2001 to 2002, there is significant co-movement between CO_2 and TI with the influence of REN removed.

The current research also assesses the influence of the second variable (x1) and third variable (x3) on the first variable (x1) by applying multiple wavelet coherence (MWC). **Figures 8A–F** present MWC for Spain for the period from 1980 to 2018. **Figure 8A** presents MWC depicting the effect of GDP on CO_2 without eradicating GLO impact. At high frequency, from 1988 to 2012, GDP has strong influence on CO_2 by taking into account the impact of GLO. **Figure 8B** signifies MWC depicting the effect of GDP on CO_2, considering GLO impact. At different frequencies, from 1988 to 2018, GDP has strong influence on CO_2 when GLO is considered. **Figure 8C** illustrates MWC depicting the effect of GDP on CO_2 considering TI influence. At different frequencies from 1983 to 1990, 1993 to 1999, and 2000 to 2010, there is strong coherency between GDP and CO_2 with TI impact considered. **Figure 8D** depicts MWC illustrating the effect of GLO on CO_2 considering REN impact. At various frequencies, the GLO effect on CO_2 considering REN influence is strong from 1990 to 2018. MWC between CO_2 and GLO considering TI influence is depicted in **Figure 8E**. At high and medium frequencies, the influence of GLO on CO_2 is significant, considering the effect of TI from 1982 to 2011. MWC between CO_2 and REN considering TI influence is depicted in **Figure 8F**. At different frequencies, the influence of REN on CO_2 is significant considering the effect of TI from 1982 to 2018.

The present study also applied the causality test suggested by Breitung and Candelon (2006) to capture the causal connection between economic growth and CO_2, technological innovation, globalization, and renewable energy consumption in Spain between 1980 and 2018. The outcomes of this test are shown in **Figures 9A–D**. The causal interrelation between GDP and the regressors at various frequencies (0–1, 1–2, and 2–3) discloses long-, medium-, and short-term connections. The permanent causality is defined as a frequency from 0 to 1, whereas temporary causality is defined as a frequency from 2 to 3. In **Figures 9A–D**, the upper line (red) represents a significance level of 5%, and the bottom line (blue) represents a 10% level of significance. The statistical tests between the (0, π) intervals at different frequencies are depicted by the (green) curve.

Figure 9A depicts the presence of causality from CO_2 to GDP in the long term. Thus, the Ho of "no causality" from CO_2 to GDP for frequencies 0.01–3.00 is rejected at a level of significance of 10%. **Figure 9B** depicts the presence of causality from REN to CO_2. Thus, the Ho of "no causality" from REN to CO_2 for frequencies 0.01–3.00 is rejected at a level of significance of 5% and 10%, respectively. This implies that the REN use can predict CO_2 in Spain at all frequencies. This is not surprising, given the fact the REN constitutes a chunk of energy mix of Spain. **Figure 9C** shows the presence of causality from TI to CO_2 in the long term. Therefore, the Ho of no causality from to TI to CO_2 is

rejected at a 5% level of significance. Finally **Figure 9D** shows presence of causality from GLO to CO_2 in the long term. Therefore, the Ho of "no causality" from GLO to CO_2 is rejected at 10% level of significance.

CONCLUSION AND POLICY DIRECTION

The present research assesses the influence of REN consumption and TI on carbon emissions (CO_2) in Spain employing the quarterly dataset covering between 1980 and 2018. The study applied a series of wavelet tools to investigate these associations. The main contribution of the research to the existing studies is the application of wavelet transform approach to assess the temporal and frequential activity of the discussed variables impacting Spain's environmental condition, as well as their interconnection and evolution over time. Economic growth, globalization, TI, and REN consumption trends disclosed unexpected trends. The trend had localized cyclic peaks and dips. The outcomes of the wavelet transform disclosed overwhelming of the changes in all series that occurred in the short term, accompanied by the medium term. Nevertheless, when we move into the long term, the variance in CO_2 emissions, economic growth, globalization, TI, and REN consumption becomes more constant. The wavelet coherence test outcomes disclosed positive co-movement between CO_2 and economic growth, TI, and globalization at low and medium frequencies. This suggests that in the long term, there is no substantial connection between CO_2 and economic growth, TI, and globalization. Furthermore, at all frequencies, there is a negative connection between REN consumption and CO_2 at all frequencies. The outcomes of wavelet correlation also validate these findings. Regarding PWC, the results revealed that eliminating the third serie's effect had no strong effect on the interconnectivity between the two series except when REN use is the second variable. MWC findings indicate that the third series has a substantial impact on the connection between the first and second series, especially in the high and medium frequencies. Last, we utilized the FDC test, and the outcomes unveiled causal linkage from economic growth, TI, REN and globalization to CO_2 in the long term.

The following suggestions are proposed based on the findings. Our empirical research also shows that the consumption of REN is an essential approach to minimize CO_2 emissions. It is generally known that REN is less carbon-intensive than conventional energy sources such as fossil fuels. Furthermore, REN sources are cost-effective. It has become a crucial step for the government to increase the total percentage of REN in Spain's energy mix in order to fulfill the country's excessive energy consumption. It is critical to understand the innovative and new energy sources in order to enhance environmental sustainability. The government should prioritize the development of new REN projects. It is critical to address the major points of rising CO_2 for policy consideration. The following are proposed: 1) shifting to a low-carbon economy based on REN consumption, 2) improving the efficiency and energy conservation of the existing fossil fuel energy production; and 3) using carbon capture storage technology to minimize CO_2 emissions in order to transition from present fossil fuel reliance to a low-carbon

future. Furthermore, the positive connection between CO_2 and globalization implies that globalization is a major contributor to the increase in CO_2 emission. Furthermore, special emphasis should be given to raising public environmental consciousness while enhancing social welfare via globalization in order to remove the negative effects of globalization on reducing emissions. Otherwise, the Spanish economy will be subjected to environmental repercussions of globalization. As a result, policymakers must thoroughly examine the social, environmental, and economic domains to determine which of the three is most directly connected to an upsurge in emissions.

Although the present research assesses the interconnection between CO_2 emissions and the regressors utilizing novel techniques, there are still several limitations to this study that can be addressed in future investigations. Since the wavelet transform is a bivariate method, future researchers can re-assess these connections utilizing multivariate techniques. In addition, further studies can be conducted by incorporating other economic indicators, such as financial development and foreign direct investment.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Materials, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct, and intellectual contribution to the study and approved it for publication.

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