Persistence of CO₂ emissions in G7 countries: a different outlook from wavelet-based linear and nonlinear unit root tests

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Abstract
Today, environmental issues such as the inability to control rising carbon dioxide (CO₂) emissions, climate change, and global warming are on the agenda of policy-makers and various organizations. The Paris Agreement, signed in 2016 and rejoined by the USA in 2021, emphasizes the need for decarbonization and the importance of CO₂ reduction for sustainable development. Since environmental policies can have long-term effects on variables containing unit roots, it is important for policy-makers to understand the stochastic properties of CO₂ emissions. In this context, we propose a new wavelet-based nonlinear unit root test to investigate the stationary properties of the per capita CO₂ emissions for the G7 countries during the period 1868–2014. To compare results, we use eight different tests that take into account both the time–frequency domain difference, the nonlinear-linear difference, and smooth structural breaks. The results of the different linear tests illustrate that CO₂ emissions have a unit root in the frequency domain for all countries. Moreover, nonlinear unit root test results indicate that the CO₂ emissions for the UK are stationary in the time domain. Overall, we consider frequency domain test results, and conclude that CO₂ emission policies have permanent effects for G7 countries. Based on the findings, we recommend that the G7 countries take long-term measures to reduce CO₂ emissions, such as joint actions to improve environmental quality through fossil fuel conservation, renewable energy improvement, and environmental awareness programs.

Keywords CO₂ emissions · Fourier function · Frequency domain · G7 countries · Wavelet unit root test

Introduction
Many researchers have long studied the harmful effects of greenhouse gases on the environment for a long time. A common conclusion of these studies is that CO₂, the most common greenhouse gas, contribute to global warming. Global CO₂ emissions increased 150 times from 1850 to the early 2000s (Gil-Alana et al. 2017). According to the World Bank data (2020), CO₂ emissions have experienced a rapid rise from 9 million kilotons in 1960 to 36 million kilotons in 2014. It is known that the main cause of this increase is fossil fuel–based energy consumption.

Although the use of natural gas and renewable energy sources grew rapidly in 2018, CO₂ emissions reached their highest level this year (BP 2019). This shows that renewable energy consumption is still not at a level to reduce CO₂ emissions, and some empirical studies confirm this (see Menyah and Wolde-Rufael 2010; Lin and Moubarak 2014; Al-Mulali et al., 2015; Pata 2018a; Pata and Aydin 2020). In the face of rising global energy demand, energy-related CO₂ emissions increased by 1.7% in 2018, reaching an all-time high of 33.1 Gt CO₂, 70% higher than the average increase since 2010 (IEA 2019).

Figure 1 illustrates global energy–related CO₂ emissions by source from 1990 to 2018, revealing a continuous increase over this period. The increase in emissions is due to the ever-growing global economy, as well as increased
energy demand for heating and cooling systems in some parts of the world. However, despite global growth, the increase in emissions remained stable during the 2014–2016 period. This can be ascribed to increased energy efficiency and the use of low-emission energy sources. In 2018, CO₂ emissions increased again as energy efficiency did not meet higher economic growth targets. This shows that economic growth continues to take precedence over environmental protection policies. Rising CO₂ emissions have been discussed since the 1970s through numerous international conferences and conventions, and participating countries have reached consensus to curb the problem. One of the current agreements is the United Nations Framework Convention on Climate Change, and UN member states have committed to controlling greenhouse gas emissions in the Kyoto Protocol (Zerbo and Darné 2019).

The study aims to examine the stochastic characteristics of CO₂ emissions in the G7 countries (USA, UK, Japan, Canada, Germany, France, and Italy) from various perspectives. Although the G7 countries, which are among the most developed economies in the world, have strict environmental regulations, they experience significant environmental degradation (Nathaniel et al. 2021). While the G7 countries have made significant progress toward the Sustainable Development Goals, they have not fully addressed environmental problems such as inadequate waste treatment, biodiversity decline, and poor air quality (Nathaniel 2021). G7 countries are the largest emitters of CO₂ (Isik et al. 2020) and accounted for one-third of global CO₂ emissions in 2014 and 54% of total emissions since 1900 (Gil-Alana et al. 2017). In 2018, total CO₂ emissions from G7 countries account for approximately 26% of global emissions (BP 2019). Analyzing CO₂ emissions by country, the USA has the highest values with 5145.2 Mtoe, followed by Japan with 1148.4 Mtoe, Germany with 725.7 Mtoe, Canada with 550.3 Mtoe, the UK with 394.1 Mtoe, Italy with 336.3 Mtoe, and France with 311.8 Mtoe. Most G7 countries are aiming for net-zero emissions targets in 2050 and are applying carbon-pricing policies to avoid massive CO₂ emissions (Dogan et al. 2022). At the 47th G7 Summit, it was emphasized that countries could lose 8.5% of their wealth if they do not avoid climate change (Xu et al. 2022). To avoid this loss of wealth and reduce emissions globally, it is important to study the stochastic characteristics of CO₂ emissions in G7 countries, and the results can help other developed countries in their fight against environmental degradation.
Figure 2 shows the evolution of total CO₂ emissions of the G7 countries in the period 1868–2014. The trend in CO₂ emissions is a continuous increase with structural breaks. The Great Depression and other economic crises, energy and oil shocks, and climate change initiatives can explain these changes in CO₂ emissions. Economic and political crises have significant negative impacts on countries’ economic growth performance. Considering that economic growth is possible through production and industrialization, less fossil fuel–based production means fewer CO₂ emissions. For example, the 2008 financial crisis for the USA (Pata 2021) and China (Pata and Caglar 2021) and the 2001-banking crisis for Turkey (Pata 2019) led to a decrease in environmental pollution due to a decrease in production.

It can also be seen in Fig. 2 that CO₂ emissions decrease in times of crisis for G7 countries. According to Aktar et al. (2021), COVID-19 has different effects on CO₂ emissions. The COVID-19 pandemic disrupted human mobility, transportation use, and industrial activity. Therefore, all countries experienced a period of economic recession. The decrease in energy demand during this period also led to a reduction in CO₂ emissions. However, with high stockpiles and lockdown withdrawal, the economy will recover and the demand for energy, and therefore CO₂ emissions will increase. Figure 3 (in the Appendix) demonstrates the individual per-capita CO₂ emissions and possible structural breaks of the G7 countries during the review period. It can be seen that CO₂ emissions from the G7 countries increased significantly after World War II. The reason for the increase in this period was militarization and economic growth efforts (Bildirici 2017a, b). Militarization affects CO₂ emissions because military weapons and technologies consume enormous amounts of energy, and military equipment and wartime transportation rely on fossil fuels (Ahmed et al. 2021). Nuclear weapon testing, armed conflict, and pollution from air, land, and sea operations are just some of the environmental effects of militarization (Lawrence et al. 2015). In addition, the radical changes in the structure of production due to militarization lead to an increase in energy consumption and thus CO₂ emissions (Bildirici 2017b).

As the French economist Francois Perroux noted, the globalization process that took hold in the 1960s (Perroux 1962) also may play an important role in the rise of CO₂ emissions. The rapid increase in production and consumption of countries due to globalization process and the carbon-intensive fossil fuels used in production lead to an increase in CO₂ emissions (Pata 2021). In addition, the increasing economic activities due to globalization are leading to the unconscious use of natural resources, resulting in environmental degradation (Pata and Caglar 2021). These factors illustrate the impact of globalization in increasing CO₂ emissions from 1960 to the 2008 economic crisis.

Determining the stochastic behavior of per capita CO₂ emissions in G7 countries, which make up more than a quarter of global CO₂ emissions, is the main motivation for this study. According to Chang and Lee (2008), understanding the behavior of CO₂ emissions is very useful for policy-makers and researchers when discussing environmental regulations, and this is often studied through unit root tests. In this regard, environmental policies can be made to depend on whether the CO₂ emissions are stationary or contain a unit root. Theoretically, stationarity demonstrates that CO₂ emissions will revert to their mean value in the long term. Therefore, it is better to monitor and control the mean value of the series rather than to try to achieve a temporary reduction in environmental pollution along with the time process (Lee et al. 2008). If the series is stationary, the long-term forecasting of CO₂ emissions can be used to evaluate both the potential effects of climate change and the costs of emission reduction (Aldy 2006). In contrast, if CO₂ emissions follow a unit root process, shocks in CO₂ emissions have permanent effects, and these series do not return to equilibrium value after being exposed to the shocks. In such a case, instead of predicting CO₂ emissions, long-term permanent solutions can be provided by emission reduction measures.

For these various reasons, it is important to study the stochastic properties of CO₂ emissions. In this study, we therefore investigate whether CO₂ emissions from G7 countries were stationary during the period 1868–2014. The length of the study period allows us to conduct a stationary analysis using frequency-domain methods. Differently from previous studies, we make three main contributions to the literature: (i) Following Aydin and Pata (2020), we propose a new wavelet unit root test that incorporates the frequency domain properties. Previous studies analyzing the stochastic properties of CO₂ emissions for the G7 countries only consider the time-domain properties of the series, which may lead to information loss. With the unit root test we have developed, we aim to draw a more accurate inference by using all the information on the stationarity of CO₂ emissions, taking into account both time-domain and frequency-domain properties. (ii) Different unit root tests can lead to mixed results in time series analysis. In this context, we consider each of the frequency domain, linearity, nonlinearity, and time domain features of the series by using eight different tests. (iii) In previous studies, structural changes are generally considered endogenous. We include smooth structural breaks and wavelets in the analysis by using a combination of Fourier and wavelet transforms. With these three aspects, the study provides new and robust insights for the current literature.
This introduction section explains the theoretical background and main motivations of the study. The other sections of the study are organized as follows: the “Literature review” section reviews the empirical literature, the “Econometric methodology” section introduces the econometric methods, the “Data and empirical results” section presents the data and results of this study, the “Discussion” section discusses these results, and the “Conclusion and policy recommendation” section summarizes the main implications and policy recommendations.

Literature review

Over the past two decades, several studies have investigated the environmental impact of CO₂ emissions. Some of these studies focus on the relationship between CO₂ emissions and macroeconomic variables (see; Pata 2018b; Gorus and Aydin 2019; Ehiigiamusoe et al. 2020; Iheonu et al. 2021; Nathaniel and Adeleye 2021; Jahanger et al. 2022). In addition, some have investigated the validity of important environmental hypotheses such as the environmental Kuznets curve (EKC) hypothesis and the pollution haven hypothesis (PHH). According to the cointegration methods used in testing these hypotheses, CO₂ emissions have a unit root constraint. In testing the PHH, Solarin et al. (2017), Terzi and Pata (2019), Nathaniel et al. (2020), Pata and Kumar (2021), and Balsalobre-Lorente et al. (2022) found that CO₂ emissions have a unit root. Similarly, testing the validity of the EKC hypothesis, Dong et al. (2018), Zhang et al. (2019), Isik et al. (2020), Leal and Marques (2020), Fallahi (2020), Balsalobre-Lorente et al. (2021), and Zeraibi et al. (2022) stated that CO₂ emissions are non-stationary at levels. However, these studies applied unit root tests to meet the requirements of certain econometric tests and did not mention whether the effects of shocks on CO₂ emissions are permanent or transitory. In this context, some other researchers have directly focused on the stochastic nature of CO₂ emissions by using unit root tests and discussing the effectiveness of CO₂ reduction policies.

The stochastic nature of CO₂ emissions reveals whether this variable follows a random process over time. In the literature, studies examining the stationarity of CO₂ emissions differ by country, time period, and methodology. We focus primarily on the differences in the methods used. Some previous studies have examined the stationarity of CO₂ emissions using traditional linear unit root tests without structural breaks (see, e.g., Aldy 2006). However, environmental indicators may have a nonlinear structure, and ignoring this may lead to incorrect determination of the series’ stochastic properties. In later periods, only a few researchers used nonlinear unit root tests to investigate stochastic properties of CO₂ emissions. For example, Christidou et al. (2013) applied three different nonlinear unit root tests to data ranging from 1870 to 2006, and found that CO₂ emissions were stationary for 33 out of 36 analyzed countries. The authors stated that when linear unit root tests were used, the unit root hypothesis was valid in 15 of the 36 countries, and therefore concluded that nonlinear tests are more effective in determining the stationary. Gil-Alana et al. (2015) used nonlinear fractional integration models for the period 1751 to 2012, and found that CO₂ emissions were stationary in the UK and the USA, whereas the emissions contained a unit root in China and India. Gil-Alana et al. (2017) performed the same method for the period 1751 to 2012 for BRICS and G7 countries, and found that CO₂ emissions had a unit root in these countries with the exception of Germany, the USA, and the UK.

In addition, some researchers have identified sharp structural breaks in various unit root tests with dummies. They have reached mixed results on the stationarity of CO₂ emissions. Lanne and Liski (2004), McKitrick and Strazicich (2005), Lee and Lee (2009), and Churchill et al. (2020) concluded that CO₂ emissions contain a unit root. In contrast, Heil and Selden (1999), Strazicich and List (2003), Chang and Lee (2008), Lee et al. (2008), Romero-Avila (2008), Westerlund and Basher (2008), and Lee and Chang (2009) concluded that CO₂ emissions are stationary.

Environmental events and degradation may occur in a slow process in which case smooth structural changes may have an impact on CO₂ emissions. Moreover, the number and form of structural breaks may not be clearly endogenously determined. To avoid these problems, some researchers have utilized unit root tests that account for structural changes with an unknown number, date, and form of breaks. Sun et al. (2016) used the Fourier-Lagrange multiplier unit root test to investigate the stationarity of CO₂ emissions for the ten largest economies over the period from 1971 to 2010. Their findings showed that emissions in these countries were nonlinearly stationary. Tiwari et al. (2016) investigated the stationarity of CO₂ emissions for 35 countries in sub-Saharan Africa using unit root tests with and without a Fourier function. According to the results of the test without a Fourier function, CO₂ emissions were stationary in 15 of these countries. However, when a Fourier function was included in the analysis, these emissions were stationary for all countries. Cai et al. (2018) examined the stationary properties of CO₂ emissions for 21 OECD countries from 1950 to 2014. Using a quantile unit root test with a Fourier function, they found that CO₂ emissions contained a unit root in 12 out of 21 countries.

More recently, Cai and Wu (2019) examined the stationarity of CO₂ emissions for 21 OECD countries and 19 emerging economies using data from 1960 to 2014. They concluded that CO₂ emissions were stationary for 11 OECD and 10 emerging market economies. Erdogan and Acaravi
(2019) investigated the stochastic properties of CO₂ emissions in OECD countries from 1960 to 2014 using a Fourier panel stationarity test, and found that CO₂ emissions were stationary at the country-specific level, while emissions in the whole panel had a unit root. Ye et al. (2020) tested the stationarity of CO₂ emissions for China and the G7 countries from 1950 to 2013. They used Fourier quantile unit root test results and found that CO₂ emissions contained a unit root in Canada, China, France, Japan, and the USA. The authors also noted that the results varied according to the quantiles. Romero-Ávila and Omay (2022) performed hybrid Fourier-based time-dependent non-linear unit root tests for 35 countries from 1751 to 2014 and concluded that CO₂ emissions are stationary.

The outcomes of previous studies have shown that different empirical strategies provide different findings for stationarity properties of CO₂ emissions. As can be seen from this literature review, most of the studies were conducted using a time-dimensional analysis, and a limited number of the studies concerned G7 countries. Moreover, to the best of the authors’ knowledge, only Ahmed et al. (2017) and Erdogan et al. (2022) have performed their studies using a wavelet-based unit root test to investigate the stationarity of CO₂ emissions across the globe for the periods 1960 to 2010, and 0 to 2014, respectively. On the one hand, Ahmed et al. (2017) used Fan and Gencay’s (2010) wavelet-based variance ratio test of Fan and Gencay (2010). However, this test did not consider structural breaks. Erdogan et al. (2022), on the other hand, examines CO₂ emissions on a global scale and does not include country-specific findings. In this regard, our study fills the gap in the literature by using wavelet-based linear and nonlinear unit root tests that allow for smooth structural breaks.

Econometric methodology

Unit root tests, which form the basis of the econometric methodology, are used for many different purposes. The main reasons for using these tests in econometric analysis are as follows: (i) Some econometric tests are performed using stationary series, and some are performed using non-stationary series. Unit root tests are used to determine the degree of integration of the series, and therefore serve as a preliminary test to determine the appropriate analysis method. (ii) Unit root tests are also used to forecast the future behavior of the series, which can be done by determining the stochastic structure of the series. (iii) Unit root tests make it possible to test several economic and financial hypotheses—for example, purchasing power parity, unemployment hysteresis, and effective market hypotheses.

Since the development of the Dickey-Fuller test, which can be considered the first of the unit root tests, there has been a significant improvement in the literature. The first unit root tests were not designed to account for the structural breaks in the series, but this problem was later overcome and the structural breaks were exogenously included in the unit root model. Preliminary knowledge of the date of structural breaks was considered a deficiency, and therefore endogenous structural break unit root tests were introduced to allow endogenous inclusion of breaks in the model. Another topic of discussion in the literature is the structure of the breaks. All structural break unit root tests used in the early period allowed breaks to occur suddenly. However, recent developments in econometric techniques allow us to perform unit root tests considering a smooth form.

The current debate in the literature is on the behavior of unit root tests of different dimensions. Accordingly, time series analysis may be conducted in two different dimensions—time and frequency. All developments in the literature until the 2000s were based on the time dimension. Unlike time domain unit root tests, frequency domain tests use not only the time information of the series, but also the frequency information. In this way, they allow a more accurate analysis of the stochastic structure of the series. Considering the importance of the stochastic structure for policy recommendations, it is a correct approach to use frequency domain tests in analyses with enough observations. Gencay et al. (2001) were the first to consider unit root tests as applicable in the frequency dimension, and Fan and Gencay (2010) proposed the variance ratio unit root test, which is the first unit root test in the literature to consider frequency domain properties. The wavelet-based ADF unit root test is another test in the frequency domain, proposed by Eroglu and Soybilgen (2018). The last unit root tests in the frequency domain were proposed by Aydin (2019) and Aydin and Pata (2020).

Linear and nonlinear unit root tests in the time domain

This study used Kapetanios, Shin and Shell (KSS) and Fourier KSS (FKSS) unit root tests, which are based on a nonlinear model, and the Fourier ADF (FADF) unit root test, which is based on a linear model. Kapetanios et al. (2003) proposed the following exponential smooth transition autoregressive (ESTAR) model for the nonlinear unit root test:

\[ \Delta y_t = \gamma y_{t-1} \left[ 1 - e^{(-\beta y_{t-1}^2)} \right] + \epsilon_t \quad (1) \]
Table 1 Descriptive statistics of the CO₂ emissions

| Countries | Mean | Maximum | Minimum | Std. dev | CV |
|-----------|------|---------|---------|----------|----|
| Canada    | 2.691162 | 4.989570 | 0.049682 | 1.543782 | 57.364885 |
| France    | 1.315082 | 2.710235 | 0.358530 | 0.605144 | 46.015685 |
| Germany   | 1.915626 | 3.190374 | 0.453525 | 0.707290 | 36.922134 |
| Italy     | 0.754578 | 2.230500 | 0.016837 | 0.806138 | 106.83295 |
| Japan     | 0.950216 | 2.692927 | 0.000087 | 0.988500 | 104.02897 |
| UK        | 2.705310 | 3.232686 | 1.483931 | 0.318838 | 11.785636 |
| USA       | 3.759861 | 6.045404 | 0.575925 | 1.540895 | 40.982765 |
| Average CO₂ emissions | 2.013119 | 6.045403 | 0.000087 | 1.439401 | 71.501050 |

CV coefficient of variation

It is not possible to test the null hypothesis here, due to the uncertainty of the $\gamma$ parameter.¹ To overcome this problem, Kapetanios et al. (2003) applied first-order Taylor expansion to the model and obtained the following equation:

$$\Delta y_t = \delta y_{t-1} + u_t$$

(2)

This model is suitable for the application of t-type test statistics. The test statistic for the null unit root ($H_0: \delta = 0$) and alternative stationary ($H_0: \delta < 0$) hypotheses is as follows:

$$t_{NL} = \hat{\delta} / \text{s.h.}(\hat{\delta})$$

(3)

Christopoulos and León-Ledesma (2010) proposed three different unit root tests. One of these unit root tests is based on the KSS method, including the Fourier approximation. The model used for the FKSS unit root test is as follows:

$$y_t = \delta_0 + \delta_1 \sin \left( \frac{2\pi kt}{T} \right) + \delta_2 \cos \left( \frac{2\pi kt}{T} \right) + v_t$$

(4)

Christopoulos and León-Ledesma (2010) applied a three-step method for FKSS and FADF unit root tests. In the first step, the Eq. (4) is estimated in the range $1 \leq k \leq 5$, and the model with the lowest the sum of squared residuals (SSR) is selected as the appropriate model. In the second step, the SSR is obtained from the appropriate model, and unit root test is performed with the following models:

$$\Delta v_t = \lambda_1 v_{t-1} + \sum_{j=1}^{p} \beta_j \Delta v_{t-j} + u_t$$

(5)

$$\Delta v_t = \lambda_1 v_{t-1}^3 + \sum_{j=1}^{p} \beta_j \Delta v_{t-j} + u_t$$

(6)

Equations (5) and (6) represent FADF and FKSS unit root tests, respectively. In the last step, if the null of a unit root hypothesis is rejected, the significance of the Fourier term is tested using an $F$-test. The critical values of $F$-statistics are taken from Tables 1, 2, 3, 4, and 5 of Becker et al. (2006).

Linear and nonlinear unit root tests in the frequency domain

This study used wavelet ADF (WADF) and Fourier WADF (FWADF) unit root tests, which have a linear data generation process in the frequency domain. Eroglu and Soybilgen (2018) proposed the WADF unit root test, which is applied by performing the ADF test on the converted series from the time dimension to the frequency dimension with a generalized least square method. The authors used the discrete wavelet transform (DWT) for this process. They rely on the DWT to extract the most persistent component of time series called the scaling (approximation) coefficients. In DWT, wavelet and scaling coefficients are calculated as follows:

$$w_{l,j} = \sum_{k=0}^{L} h_l y_{k+1} - y_{k-1} \quad v_{l,j} = \sum_{k=0}^{L} 0.5 y_{k+1} - y_{k-1} \quad t = 0, \ldots, N/2 - 1$$

(7)

where $w_{l,j}$ and $v_{l,j}$ indicate wavelet and scaling coefficients, respectively. Eroglu and Soybilgen (2018) developed an ADF test procedure using the scaling coefficients as follows:

$$\Delta \hat{v}_{l,j} = \hat{\delta} \hat{v}_{l,j-1} + \sum_{k=1}^{n} \hat{\alpha}_k \Delta \hat{v}_{l,j-k} + \epsilon_{l,j}$$

(8)

The WADF unit root testing procedure is the same as the conventional ADF test. Accordingly, the null hypothesis indicates that the series contains unit root, while the alternative hypothesis states that the series is stationary. The test statistic is the same as that of the ADF test and is calculated as follows:

1 See Davies (1987) and Luukkonen et al. (1988) for more information.
Aydin and Pata (2020) proposed a new WADF unit root test with smooth structural breaks considering Fourier term. They followed Enders and Lee’s (2012) Fourier approximation. However, our study proposed the FWADF unit root test with smooth structural breaks based on the model of Christopoulos and León-Ledesma (2010) For this purpose, we followed Yazgan and Ozkan (2015) and Aydin (2019), and used the following deterministic term:

\[
A D F_i^{\ast} = \frac{\hat{\delta}}{\text{Std}(\hat{\delta})}
\]

Table 3 Linear unit root tests results

Panel a: Wavelet-based unit root tests results

| Countries | Test statistics | t(k*)-statistics | k | p | Test statistics | p |
|-----------|----------------|------------------|---|---|----------------|---|
| France    | −2.763         | −11.600*         | 1 | 0 | −1.560         | 0 |
| Germany   | −2.853         | −5.990*          | 1 | 1 | −1.990         | 0 |

Panel b: Fourier unit root tests results

| Countries | Test statistics | F-statistics | k | p | Test statistics | p |
|-----------|----------------|--------------|---|---|----------------|---|
| France    | −2.614         | 165.198*     | 1 | 0 | −1.608         | 1 |
| Germany   | −2.570         | 37.984*      | 2 | 0 | −2.173         | 6 |

* and ** denote the significant levels at 1% and 5%, respectively. Optimal lag lengths (p) are selected automatically using the SIC. The critical values of F-statistics are 4.133 (10%), 4.929 (5%), and 6.730 (1%) taken from Table 1 of Becker et al. (2006)

Table 4 Nonlinear unit root tests results

Panel a: Wavelet-based unit root tests results

| Countries | Test statistics | t-statistics | k | p | Test statistics | p |
|-----------|----------------|--------------|---|---|----------------|---|
| Canada    | −1.101         | 1.090        | 2 | 0 | −1.450         | 0 |
| Italy     | −2.500         | −2.270**     | 1 | 1 | −2.360         | 1 |
| Japan     | 0.074          | 1.612        | 5 | 1 | −2.280         | 1 |
| UK        | 0.180          | 3.499*       | 2 | 0 | −1.910         | 1 |
| USA       | −1.207         | 0.913        | 2 | 0 | −1.720         | 0 |

Panel b: Fourier unit root tests results

| Countries | Test statistics | F-statistics | k | p | Test statistics | p |
|-----------|----------------|--------------|---|---|----------------|---|
| Canada    | −2.263         | 113.884*     | 1 | 7 | −1.720         | 0 |
| Italy     | −2.322         | 178.483*     | 1 | 5 | −1.401         | 2 |
| Japan     | −1.342         | 140.679*     | 1 | 3 | −0.390         | 1 |
| UK        | −4.990*        | 80.146*      | 2 | 9 | −7.253*        | 0 |
| USA       | −1.210         | 93.786*      | 2 | 11| −2.731         | 0 |

*, **, and *** denote the significant levels at 1%, 5%, and 10%, respectively. Optimal lag lengths (p) are selected automatically using the SIC. The critical values of t-statistics are taken from Table 6 of Aydin (2019). For the KSS, WKSS, and FWKSS tests, de-meaned or the de-trended data are used according to the structural properties of the series.

Table 5 Summary of the results

| Countries | Linear tests | Nonlinear tests |
|-----------|--------------|-----------------|
|           | Frequency | Time | Frequency | Time |
|           | FWADF | FADF | FWKSS | FKSS |
| Canada    | Unit root | Unit root  | Unit root | Unit root |
| France    | Unit root | Unit root  | Unit root | Unit root |
| Germany   | Unit root | Unit root  | Unit root | Unit root |
| Italy     | Unit root | Unit root  | Unit root | Unit root |
| Japan     | Unit root | Unit root  | Unit root | Unit root |
| UK        | Unit root | Stationary  | Unit root | Unit root |
| USA       | Unit root | Unit root  | Unit root | Unit root |

Aydin and Pata (2020) proposed a new WADF unit root test with smooth structural breaks considering Fourier term. They followed Enders and Lee’s (2012) Fourier approximation. However, our study proposed the FWADF unit root test with smooth structural breaks based on the model of Christopoulos and León-Ledesma (2010) For this purpose, we followed Yazgan and Ozkan (2015) and Aydin (2019), and used the following deterministic term:
$\mu(t) \cong \alpha \sum_{i=1}^{n} \left\{ (2i-1)^{-1} \sin \left( \frac{2\pi(2i-1)kt}{T} \right) \right\} \tag{10}$

where \( n \) indicates the frequency of the deterministic component, and \( k \) indicates the frequency of the Fourier term. In the case of \( n = 1 \), smooth breaks occur in the series, whereas the form of breaks becomes more abrupt and sharp at values greater than 1. The model used for the FWADF unit root test is as follows:

\[ V_{1,t} = \delta_0 + \delta_1 \sin \left( \frac{2\pi kt}{T} \right) + \upsilon_t \tag{11} \]

where \( V_{1,t} \) shows the scaling (low frequency) coefficients obtained by using the Haar wavelet filtering method. We proposed a three-step method for FWADF unit root test. In the first step, Eq. (11) is estimated in the range of \( 1 \leq k \leq 5 \), and the lowest SSR is selected for the appropriate model. In the second step, the ordinary least squares residuals are obtained from the appropriate model, and a unit root test is performed using these residuals with the following Eq. (12):

\[ \Delta \upsilon_t = \lambda_1 \upsilon_{t-1} + \sum_{j=1}^{p} \beta_j \Delta \upsilon_{t-j} + u_t \tag{12} \]

In the last step, if the null hypothesis of the unit root is rejected, the significance of the Fourier term is tested using \( t(k^*) \) test. We calculated the critical values of the FWADF and \( t(k^*) \) tests, and they are presented in Table 6 (see the Appendix).

We also used wavelet KSS (WKSS) and Fourier WKSS (FWKSS) unit root tests, which have a nonlinear data generation process in the frequency domain. Aydin (2019) proposed a new nonlinear wavelet-based unit root test using the Haar wavelet filtering method. He followed the Kapetanios et al. (2003) method and used the following model for the unit root test:

\[ \Delta V_{1,t} = \sum_{j=1}^{p} \rho_j \Delta V_{1,t-j} + \delta V_{1,t-1}^2 + \epsilon_t \tag{13} \]

where \( V_{1,t} \) shows the scaling (low frequency) coefficients obtained by using the Haar wavelet filtering method. While the null hypothesis \( \delta = 0 \) states that the examined series includes a unit root, the alternative hypothesis \( \delta < 0 \) states that the series is stationary. The test statistics for the null and alternative hypotheses are as follows:

\[ \text{WKSS} = \hat{\delta} / \text{s.h.} \left( \hat{\delta} \right) \tag{14} \]

Aydin (2019) also proposed an FWKSS test that takes into account smooth structural breaks by adding a Fourier component to the WKSS test. He used the Eq. (10) as a deterministic term for the case of \( n = 1 \). In this way, the WKSS test becomes a form that takes into account smooth structural breaks.

\[ \Delta V_{1,t} = \sum_{j=1}^{p} \rho_j \Delta V_{1,t-j} + \delta V_{1,t-1}^2 + \beta \sin(2\pi kt/T) + \epsilon_t \tag{15} \]

The steps of the FWKSS test are similar to the methodology of Enders and Lee (2012). The only difference is that in the FWKSS test, \( t \)-statistics are used instead of an \( F \)-test for the significance of the Fourier term.2

### Data and empirical results

This study examined the stationarity of CO$_2$ emissions for G7 countries using data from the period 1868–2014. CO$_2$ emissions were defined as total CO$_2$ emissions from fossil fuels and cement production and measured in metric tons. The data used in the study were obtained from Boden et al. (2017). Table 1 shows the descriptive statistics for these countries. Accordingly, the USA had the highest mean per-capita CO$_2$ emissions (3.759861), followed by the UK (2.705310), Canada (2.691162), Germany (1.915626), France (1.315082), Japan (0.950216), and Italy (0.754578). Italy was the highest volatility country (106.83295), and the lowest was the UK (11.785636). Across all the countries included in the study, the mean per-capita CO$_2$ emission was 2.013119, and the variation was 71.50105.

The logic behind introducing nonlinear unit root tests is that classical ADF-type tests have weak predictive power for stationary in nonlinear data. This problem is eliminated by using a unit root test that includes nonlinear data generation processes. If the linearity is not considered in the series, the results may be biased. For this reason, we first examine the linearity of the series, and report the results in Table 3.

The null hypothesis of the \( W \) test of Harvey et al. (2008) states that the series is linear, while the alternative hypothesis implies nonlinearity. According to the results of the linearity test, CO$_2$ emissions are linear for France and Germany, but emissions have a nonlinear form for Canada, Italy, Japan, the UK, and the USA.

In addition to linearity, time and frequency domain properties are also considered in this study when testing for unit roots. Time domain approaches only include time periods of the series, while frequency domain approaches consider frequency periods. The wavelet theorem, one of the approaches in the frequency domain, considers both the time and frequency information of the series. In this case, all the information related to the series is used so that

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2 For more information, please see Aydin (2019).
robust results can be obtained. Therefore, we use both time domain (FADF and ADF), and frequency domain (FWADF and WADF) unit root tests. The results of the linear time and frequency domain linear unit root tests are reported in Table 4.

The results can be summarized as follows: (i) The Fourier term is significant for both countries in the frequency domain unit root tests (panel a). The FWADF unit root test illustrate that CO₂ emissions have a unit root for France and Germany. According to the FWADF and WADF unit root tests results, CO₂ emissions have a unit root for both countries. (ii) Considering the time domain unit root tests (in panel b), Fourier terms are significant for the FADF test in both countries, and the results show that CO₂ emissions have a unit root in France and Germany. The results obtained with the ADF unit root test are similar to those of the FADF.

Following Kim et al. (2010) and Li et al. (2014), we use nonlinear unit root tests (Fourier KSS and Fourier WKSS) of the ESTAR type, which can give effective results for both large and small values of the transition variable (Dijk et al., 2002). Table 5 shows the time and frequency domain nonlinear unit root test results.

In accordance with Table 5, (i) the frequency domain nonlinear unit root tests indicate that the Fourier term is not significant for all countries except Italy (in panel a). Therefore, the WKSS unit root test results are valid in these countries, and the results show that per-capita CO₂ emissions have a unit root. (ii) Fourier terms are significant for all countries in time domain nonlinear unit root test, and the FKSS test results show that per-capita CO₂ emissions are stationary in the UK, while they have a unit root in Canada, Italy, Japan, and the USA (in panel b). Meanwhile, KSS unit root test results show that while per-capita CO₂ emissions are stationary in the UK, they have a unit root in Canada, Italy, Japan, and the USA. Figures 4 and 5 (in the Appendix) show the graphs of CO₂ emissions and Fourier terms for different tests in the G7 countries. A look at the figures shows that Fourier terms are successful in identifying structural breaks.

Finally, the overall results are summarized in Table 6. The nonlinear time domain unit root test shows that CO₂ emissions are stationary in the UK, but as Aydin and Pata (2020) point out, neglecting the frequency domain in the analysis of environmental variables can lead to information loss and false inferences. In our study, this is the case for the UK. According to the results of the FWKSS test, CO₂ emissions in the UK also contain a unit root, and shocks can have permanent effects on this series. Taking into account the frequency domain and nonlinearity properties, the study highlights that CO₂ emissions for all G7 countries contain a unit root and that emission reduction measures can have long-lasting, permanent, and successful effects.

**Discussion**

Time series analysis has two different structures depending on the data creation process. Linear tests are used for series with a linear data generation process. Some of these tests are based on the traditional ADF method. On the other hand, nonlinear tests are applied to series with a nonlinear data generation process. Besides this basic assumption, the unit root tests for time series are divided into two different groups according to whether they consider structural breaks or not. Similarly, the unit root tests for structural breaks are divided into two different groups depending on whether the breaks are included endogenously or exogenously. In time series analysis, breaks were initially considered exogenously. However, the development of techniques has made it possible to determine structural changes endogenously. Depending on the form of the endogenously defined structural breaks, two different situations have eventually emerged. The first describes the dummy variable-based structural breaks in a sharp form, while the second—a Fourier approximation-based approach—describes them in a smooth form. In addition to the above discussions, the time series are divided into two groups according to the time and frequency approaches. In this study, we used different unit root tests together to compare the results and considered three different ones: linearity, dimensionality differences, and the structure of the breaks. To obtain robust results, we used eight different unit root tests: Fourier ADF, Fourier WADF, Fourier KSS, Fourier WKSS, ADF, WADF, KSS, and WKSS. The results of the Fourier tests are different. According to the time domain test results, per-capita CO₂ emissions are stationary in the UK, while according to the results of the frequency-domain test, all CO₂ series have a unit root. The findings of the unit root test in the frequency domain are more reliable because it uses all the information related to the series with a large number of observations. Therefore, frequency domain unit root test results were considered for this study. Accordingly, CO₂ emissions for the G7 countries have a unit root, implying that the effects of shocks on CO₂ emissions are permanent for these countries.

Our results are consistent with Lee and Lee (2009) for G7 countries except France; with Churchill et al. (2020) for all G7 countries; with Erdogan and Solarin (2021) for Japan, Gil-Alana et al. (2017) for Canada, Italy, France, and Japan; and with Zerbo and Darné (2019) for Canada, France, Japan, the UK, and the USA. As we mentioned in econometric methodology section, ignoring the different characteristics of the time series causes biased results. None of the studies conducted for the G7 countries so far have considered linearity, dimensional difference, and structure of the breaks simultaneously in unit root tests and the information about series may therefore be
incomplete. Our study takes into account these three principal features of the time series, and thus fills a gap in the literature.

**Conclusion and policy recommendation**

Determining the structure of CO₂ emissions is important for policy-makers. The effectiveness and appropriateness of pollution reduction policies can be decided by employing unit root tests to investigate the stochastic behavior of CO₂ emissions. It is crucial to use an appropriate unit root test in order to formulate suitable environmental conservation policies. For this reason, we investigated the stationarity properties of per-capita CO₂ emissions using eight different unit root tests, and were unable to reject the null hypothesis of unit root for six G7 countries.

The results suggest that stabilization policies are effective for almost all G7 countries. The means and variances of per-capita CO₂ emissions can change over time due to structural changes and shocks. In this regard, deviations from the trend path of CO₂ emissions require government interventions. According to the Canadian government, one of the five key themes of the 2018 G7 Summit was “working together on climate change, oceans and clean energy.” Moreover, G7 countries confirmed that they would explore new ways of working together for safer, sustainable, and low-carbon future. In order to determine appropriate environmental policies in the fight against global warming, it is important to examine whether the CO₂ emissions of the G7 countries contain a unit root. This is because depending on the presence of the unit root, a decision can be made on the persistence of shocks and the effectiveness of government action.

In terms of climate change, G7 countries have different characteristics in terms of energy consumption, GDP, and environmental policies. The 2018 Climate Transparency Report summarizes recent developments in G7 countries as follows: (i) The UK is the only G7 country that has supported the rise in fossil fuel use in recent years and increased subsidies for oil and gas production. (ii) Japan provides the highest amount of international climate finance relative as a share of GDP among the G7 countries. (iii) Italy has the second highest share of renewables (15%) in energy supply among the G7 countries. (iv) Although hydropower still predominates in Canada, the country has one of the highest rates of new wind power installations. (v) France is aiming for a zero-carbon electricity sector by 2050. (vi) Germany has a long-term strategy for low-emission development and a national strategy for near-zero energy buildings. These characteristics of the G7 countries and the findings of the study offer some policy recommendations.

The G7 countries should turn to renewable and alternative energy sources and support the introduction of low-emission technologies. In addition to increasing investment in renewable energy sources, fossil fuels can be replaced with such resources to reduce CO₂ emissions. Therefore, the UK should reduce incentives for fossil fuel consumption and increase the focus on renewable technologies. Further, G7 governments can assist consumers make informed choices about their energy consumption by adjusting taxes and creating environmental awareness programs. This type of renewable energy application will reduce CO₂ emissions and promote sustainable development. For G7 countries, permanent carbon taxes are another way to reduce carbon emissions. Last but not least, developing and incorporating energy efficiency technologies into production processes will have a long-lasting impact on reducing CO₂ emissions.

Overall, our empirical findings suggest that the effects of shocks on per-capita CO₂ emissions are permanent, and that policy-makers can alter the long-term growth path of emissions. G7 countries can therefore reduce air pollution in the long term by deploying cleaner technologies and enforcing environmental policies.

Finally, the study offers a number of research opportunities. Future studies can analyze the stationarity of CO₂ emissions for developing countries and groups of countries, taking into account time and frequency dimensions. A stochastic analysis of carbon intensity for G7 countries can also be used to discuss the economic dimension of pollution, as well as the persistence of policy measures to reduce carbon intensity.

**Appendix**

|  | 1% | 5% | 10% |
|---|---|---|---|
| k | 1% | 5% | 10% |
| 1 | −3.90 | −3.30 | −2.87 |
| 2 | −3.52 | −2.90 | −2.58 |
| 3 | −3.37 | −2.77 | −2.50 |
| 4 | −3.39 | −2.73 | −2.44 |
| 5 | −3.12 | −2.69 | −2.41 |
| t(k⁺) | −5.63 | −3.81 | −2.93 |

All critical values are calculated with 500 observations and 10,000 replications.
**Fig. 3** CO₂ emissions for G7 countries in metric tons, 1868–2014
Fig. 4  Linear CO$_2$ emissions and Fourier terms for Canada, France, Italy, and Japan. Note: The left and right sides of the figure show the time and frequency domain results, respectively.
Fig. 5  Non-linear CO₂ emissions and Fourier terms for Germany, the UK, and the USA. Note: The left and right sides of the figure show the time and frequency domain results, respectively.

Author contribution  Ugur Korkut Pata: data curation, conceptualism, investigation, resources, writing original draft, review, and editing; Mucahit Aydin: methodology, formal analysis writing original draft, investigation.

Data availability  Data are available from the authors upon reasonable request.

Declarations

Ethical approval  This article does not contain any studies with human participants performed by any of the authors.

Consent for publication  Our study does not contain individual person’s data.

Consent to participate  No human or animal subjects were used in our study, and no questionnaire was conducted.

Competing interests  The authors declare no competing interests.

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