Revisiting the EKC hypothesis in an emerging market: an application of ARDL-based bounds and wavelet coherence approaches

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Abstract

This study aims to reexamine long-run and causal effects of trade openness, energy usage, gross capital formation, and real growth on CO₂ emissions in Mexico utilizing recent econometric techniques. The study utilizes yearly data spanning between 1971 and 2016. No prior study has used the wavelet coherence approach to collect information on the correlation and/or causal relation between these economic variables at different frequencies and time frames. Thus, this study proposes to fill the gap in the literature. The motives of the study are to address the questions: (a) Is the EKC hypothesis valid for Mexico? (b) Is there a long-run and causal relationship between CO₂ emissions and its determinants? (c) How are the indicators related at different frequencies and various periods? To capture long-run effects, the study utilized ARDL, FMOLS, and DOLS estimators, while wavelet coherence technique is utilized to explore causal effects among the variables. The empirical findings confirm that (a) EKC hypothesis is valid for Mexico; and (b) gross capital formation, energy usage, and economic growth impact CO₂ emissions positively. The wavelet coherence technique revealed (a) bidirectional causality between economic growth and CO₂ emissions; (b) unidirectional causality from CO₂ emissions to energy usage; and (c) one-way causality running from CO₂ emissions to gross capital formation. Based on these findings, recommendations were suggested.

Keywords CO₂ emissions · Energy consumption · Economic growth · ARDL · Wavelet coherence technique · Mexico

1 Introduction

The growth in the global economy has improved people's living conditions in several different respects, including technical advancement, increased lifespan, higher wages, and improved educational prospects. Nevertheless, rising economic growth has also created certain negative results, including deprivation in certain countries, wealth inequalities, and environmental damage in addition to emissions and global warming. The increase in the production and consumption rates as well as the attempts of nations to attain rapid economic expansion has contributed to a dramatic rise in global CO₂ emissions. During this phase, governments have neglected the adverse environmental

effects in order to promote growth in the country's development, leading to a rise in CO₂ emissions over the years. According to research published by the Intergovernmental Panel on Climate Change (IPCC) research, global warming caused by human activities has caused average temperatures to increase by approximately 1 °C compared to previous industrial times. The effects of the recent global warming of 1 °C have also been witnessed as severe weather events, increasing water rates, the loss of Arctic sea ice, and other detrimental changes. If the rise in pollution persists in its current form, temperature increases caused by climate change will reach the 1.5 °C mark between 2030 and 2052. Global warming over 1.5 °C is expected to contribute to long-term and permanent shifts, including the loss of

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certain habitats [1]. Greenhouse gas (GHG) pollution, particularly CO₂ emissions, is believed to be the primary factor causing climate change and global warming. Since the adverse impacts of environmental degradation have begun to be experienced on a global level, including climate change and global warming over time, this problem has motivated governments to pursue a collective remedy. A range of forums on sustainable economic growth have been conducted on both domestic and foreign levels. The global community, particularly those residing in developing nations, has started to pay attention to these environmental problems, which has led to enhanced environmental consciousness and several international conventions, including the Kyoto Protocol, which was followed by the Paris Agreement. Such initiatives aimed at achieving environmental sustainability and enhancing environmental consciousness have pushed nations, particularly developing economies, to adopt environmental standards and procedures to preserve the climate. With the rise in globalization, weak environmental legislation, particularly in emerging economies, offers an enticing competitive advantage for foreign corporations, notably pollution-intensive firms [2]. Not only relaxed environmental standards, but also lower labor costs and natural resources for the manufacturing cycle have drawn international direct investments to emerging nations. On the other hand, foreign direct investment (FDI) has other benefits for developed nations, such as that it is a tool for funding high-cost infrastructure programs, providing strategic exposure to technologies, and managing know-how [3]. Based on debates on the flexibility of environmental standards (stringent or lenient), there are significant questions about the viability of growth plans given the rise in environmental pollution, particularly in emerging economies. Recent studies have indicated that changes in the climate are occurring much sooner than anticipated. The adverse effects will not only impact industrialized or emerging economies, but the whole world will be affected [4]. Thus, nations have also begun to create action strategies, not just for social and economic development, but also to mitigate climate change. For this reason, a 15-year plan of action, called the 2030 Agenda for Sustainable Growth, composed of 17 Sustainable Development Goals (SDGs) and agreed by all United Nations (UN) member states, was developed at the 2015 UN General Assembly. As stated in a report on the SDG in 2019, global warming is the most important area for intervention (SDG13). In particular, emerging nations that concentrate on the growth of their economies (SDG8) to enhance social welfare and eliminate poverty (SDG1) may neglect the environmental harm caused by this initiative. The naivety regarding environmental degradation has severe and permanent consequences, including adverse weather conditions, rising

water acidity, habitat destruction, and decreased biodiversity, in addition to social and economic implications that significantly impact human existence. Approximately 1.3 billion people lost their lives between 1998–2017 due to climate change and geophysical events, resulting in a total economic loss of \$US3 trillion [4]. Hence, it is important to understand all aspects of sustainable development. Mexico is categorized as an emerging nation with the GDP and GDP per Capita amounting to \$1.221 trillion and \$9,673.44, respectively, in 2018 [5]. According to the EIA [6], in 2017, Mexico was ranked 17th globally in per capita emissions. In 2013, the total GHG emissions in Mexico amounted to 665.3 million metric tons of CO₂ equivalent (MtCO₂e), accounting for 1.38% of global GHG emissions. In 2013, the transport and electricity generation sectors were the highest generating industries, accounting for 26.2% and 19% of total GHG emissions, respectively. Mexico generated 495.8 million tons of CO₂ emissions in 2018. Mexico's CO₂ emissions expanded from 372 m tons in 1999 to 495.8 m tons in 2018, which represents an annual increase of 1.54%. Recently, some studies have focused on the relationship among energy consumption, CO₂ emissions, and economic growth. However, these studies have generally produced mixed results (i.e. their findings vary depending on the country, the period, and the study method used), which indicates the need for further research to clarify this relationship [7–14]. In this regard, this study provides an empirical analysis of this relationship by considering the case of Mexico. Mexico is the second-largest economy in Latin America and has the third highest gross domestic product (GDP) per capita in the region. Mexico has the highest per capita power consumption in Latin America and 1 of the dirtiest energy matrices because its economic growth has led to a sharp rise in electricity demand, which has largely been met through fossil fuels. This economic growth is fueled by energy consumption. Mexico has become the 15th most energy-consuming country in the world. According to the World Bank [5], the amount of energy consumption in Mexico in 2008 was 180.6 million tons of oil equivalents, which represents about 2.4% of the total energy consumed around the world. Recently, Mexico has set ambitious targets for a reduction in domestic emissions, aiming to reduce carbon emissions by 50% by 2050 and obtain 50% of all electricity from renewable energy sources by 2050. Based on this, the paper intends to examine the linkage between CO₂ emissions and trade openness, real growth, gross capital formation, and energy usage by asking fundamental questions such as: What is the impact of trade openness on CO₂ emissions? Does real growth impact CO₂ emissions? What effects do energy usage and gross capital formation have on CO₂ emissions? Furthermore, the wavelet coherence method was used to simultaneously investigate the correlation and causality

between CO₂ emissions and the selected variables. The major innovation of this paper is to explore the interaction among CO₂ emissions, gross capital formation, trade openness, energy consumption, and economic growth in 1 model for the case of Mexico which has not been examined by applying the most recently developed econometric techniques. To the best of the author knowledge, no study has also previously utilized wavelet coherence technique to obtain information on dynamic correlation and/or causality among CO₂ emissions, gross capital formation, trade openness, energy consumption, and economic growth in Mexico at different frequencies and different time periods. Additionally, the investigator utilized also ARDL, FMOLS, and DOLS estimators to capture long-run effects of the gross capital formation, trade openness, energy consumption, and economic growth on CO₂ emissions in Mexico. The next segment entails synopsis of related studies. The third segment discusses the data and methods utilized. The fourth segment entails findings based on methods adopted. The fifth segment discusses the conclusion and policy direction.

2 Literature review

The fundamental relation between economic growth and environmental deterioration has been widely explored in recent studies. One of the theoretical roots of the dynamics of this interaction is the work of Kuznets [15]. As per this theory, economic growth generally measured by per capita income is related to a rise in environmental deterioration, which is usually calculated by the level of a certain form of pollution (emissions) up to a certain point, beyond which the relation has a detrimental effect [16]. The particular threshold is defined as the extent of such economic impact or stability. After that, economies have the potential to reduce the emissions they produce. Within this theoretical paradigm, sustainable development can be encouraged by energy-intensive industrial sectors and practices that are also emission-producing and harmful to the environment. Over the years, researchers have demonstrated curiosity and confidence in the Environmental Kuznets Curve (EKC) hypothesis. Grossman and Krueger [17] became the founders of EKC hypothesis at the beginning of the 1990s (see [14, 18]). The theory was tested for multiple air pollutants and other measures of environmental deterioration or sustainability, and specific research focused on various nations over different periods. In recent years, this theory's relevance has been illustrated in the literature due to the adverse effects of climate change at the world stage. The studies of Zambrano-Monserrate et al. [19], Ozatac et al. [20], Pata [18], and Bekun et al. [21] complied with the EKC hypothesis based on their findings. Using Pakistan and India as a case study, Tariq et al. [22] examined the

linkages between gross capital formation, CO₂ emissions and growth utilizing the OLS regression. Their findings revealed that energy usage, real growth, and gross capital formation impact CO₂ emissions positively. Also, Li et al.'s [23] study corroborated the findings of Tariq et al. [22] for the case of China. Using the Belt and Road Initiative as a case study, Rauf et al. [24] investigated the linkages between energy usage, CO₂ emissions and growth using the panel ARDL approach. The results obtained refuted the EKC hypothesis in these countries. However, it was found that energy usage and real growth impact CO₂ emissions positively. Similar to the study of Rauf et al. [24], the findings from the study of Sarkodie [25] on the interconnections amongst energy usage, birth rate, food prices, real growth, and CO₂ emissions refuted the EKC hypothesis. However, they concluded that energy use, birth rate, and GDP growth impact CO₂ emissions positively. In Turkey, Pata [18] revisited the EKC hypothesis using yearly data for the period between 1974 and 2014. The author found evidence supporting the EKC hypothesis, suggesting that financial development, urbanization, and electric consumption positively impact CO₂ emissions, while renewable energy and CO₂ emission have an insignificant linkage. The studies of Rana and Sharma [26], Cosmas et al. [27], and Bekun et al. [21] also found support for the EKC hypothesis. To examine the EKC hypothesis in European countries, Dogan and Inglesi-Lotz [28] used time-series data from 1980 to 2014. The results obtained disagree with the EKC hypothesis in these European countries. Pata and Aydin [29] explored the EKC hypothesis in Brazil, China, Canada, India, Norway, and the USA by employing yearly data between 1965 and 2016. The outcome showed that the EKC hypothesis is not valid. Additionally, in Brazil, it was determined that energy causes real growth, while a bidirectional causality was found between energy usage and GDP growth in China. Leal and Marques [30] explored the interaction between CO₂ emissions and real growth and energy usage in CO₂ emitting countries in the OECD between 1990 and 2016. The results showed that the EKC hypothesis is valid. In South Korea, Koc and Bulus [31] used yearly data for the period between 1971 and 2017 to examine the influence of trade openness, energy usage, renewable energy, and real growth on CO₂ emissions. The findings revealed an N-shaped relationship. Furthermore, energy usage, trade openness and renewable energy were found to impact CO₂ emissions positively. For Mexico, the USA, and Canada, Arango Miranda [32] examined the connection between CO₂ emissions, energy use, and growth using the OLS and VECM causality between 1990 and 2016. The outcome showed that the EKC hypothesis is valid for the USA and Mexico but not for Canada. Recently, several studies have explored the interconnection among CO₂ emissions, economic growth, energy consumption and trade openness using the wavelet tools. For instance, Adebayo and Akinsola [33] explored the link between CO₂ emissions,

energy consumption and economic growth in Thailand using wavelet coherence and continuous wavelet techniques. The empirical findings revealed positive comovement between energy consumption and CO₂ emissions and unidirectional causality running from CO₂ emissions to economic growth. In the study conducted by Arain et al. [34] on the causal linkage between economic growth and trade openness using monthly data between 1996 and 2015. The authors found unidirectional causality running from economic growth to trade openness. In China, the study of Raza et al. [35] found one-way causality from trade openness to CO₂ emissions. The study of Arain et al. [34] in China also found negative comovement between foreign direct investment and CO₂ emissions, while there is negative comovement between renewable energy and economic growth. In Turkey, Kalmaz and Kirikkaleli [14] examined the determinants of CO₂ emissions using wavelet coherence technique. The investigators found bidirectional causality between CO₂ emissions and economic growth. Furthermore, there is positive comovement between CO₂ emissions and trade openness. Table 1 presents a synopsis of previous studies.

It is clear from the reviewed studies that the relationship between economic growth, gross capital formation, trade openness, CO₂ emissions, and energy consumption has been thoroughly explored. However, the use of wavelet coherence technique to investigate the long-run and causal effects of trade openness, energy usage, gross capital formation, and real growth on CO₂ emissions has never been investigated in Mexico. The defined gaps in literature could thus be resolved to contribute to the current research on Mexico.

3 Data and methodology

3.1 Data

The investigator utilizes yearly time-series variables covering between 1971 and 2016. The dependent variable is carbon emission (CO₂), and the independent variables are gross capital formation (GCF), energy consumption (ENE), trade openness (TO) GDP squared (GDP²), and economic growth (GDP). The variables are sourced from the database of World Bank [5] and UNCTAD [41] correspondingly. Table 2 illustrates the short description of the times-series variables. Trade openness is less volatile compared to the other variables, while economic growth has the highest volatility. Furthermore, the Jarque–Bera reveal that CO₂ emissions, energy consumption, and gross capital formation are not normally distributed, while economic growth, economic growth square, and trade openness are normally distributed.

3.2 Methodology

The study aims to explore the linkage between CO₂ emissions and gross capital formation (GCF), energy consumption (ENE), trade openness (TO) GDP squared (GDP²), and economic growth (GDP). Furthermore, the study investigates the EKC hypothesis for the case of Mexico. This relationship will be examined by utilizing the ARDL techniques. Also, to explore the correlation and the causality amongst the variables, the study employs the wavelet coherence technique to fill this gap in the literature. It is vital to examine the stationarity property of series before examining any interconnections amongst the time series. The study uses the ADF, PP, and the Zivot–Andrew unit-root test to examine the stationarity property of these variables. As a further phase in this analysis, the long-run cointegration between CO₂ and GCF, TO, GDP², GDP, and ENE is examined by employing the ARDL bounds test. The advantage of the ARDL approach is that it provides the opportunity to analyze short- and long-term interconnections together when the series is either I(0) or I(1) or both I(0) and I(1), but it does not work with I(2) variables. Equations 1 and 2 depict the economic function and econometric model, respectively.

$$CO_2 = f(GDP, GDP^2, ENE, GCF, TO) \quad (1)$$

$$CO_2 = \vartheta_0 + \vartheta_1 GDP + \vartheta_2 GDP^2 + \vartheta_3 ENE + \vartheta_4 GCF + \vartheta_5 TO + \varepsilon_t \quad (2)$$

The ARDL framework for the model is depicted in Eq. 3 as follows:

$$\begin{aligned} \Delta CO_{2t} = & \vartheta_0 + \sum_{i=1}^t \vartheta_1 \Delta CO_{2t-i} + \sum_{i=1}^t \vartheta_2 \Delta GDP_{t-i} + \sum_{i=1}^t \vartheta_3 \Delta GDP_{t-i}^2 \\ & + \sum_{i=1}^t \vartheta_4 \Delta ENE_{t-i} + \sum_{i=1}^t \vartheta_5 \Delta GCF_{t-i} + \sum_{i=1}^t \vartheta_6 \Delta TO_{t-i} \\ & + \beta_1 CO_{2t-1} + \beta_2 GDP_{t-1} + \beta_3 GDP_{t-1}^2 + \beta_4 ENE_{t-1} \\ & + \beta_5 GCF_{t-1} + \beta_6 TO_{t-1} + \varepsilon_t \end{aligned} \quad (3)$$

wherein the first difference is depicted by Δ . The variables coefficients in the long-run are illustrated by $\vartheta_1, \dots, \vartheta_6$. After long-run linkages have been ascertained, short-run interrelationships are examined by utilizing the error correction model (ECM) created by Engle and Granger [42] for the analysis of the short-run coefficients and the error correction term (ECT). This is accomplished by incorporating the ECM to the ARDL framework for Model 5 as follows:

Table 1 Studies synopsis

Investigator(s)	Period	Nation(s)	Variable(s)	Technique(s)	Finding(s)
Lee and Yoo [36]	1971–2007	Mexico	GDP, ENE, CO ₂	Granger causality based on the error correction model (ECM)	GDP → CO ₂ GDP → ENE ENE → CO ₂
Bukhari et al. [37]	1974–2010	Pakistan	GDP, ENE, GCF, FDI, CO ₂	ARDL, VECM	FDI → CO ₂ (+) GCF → CO ₂ (–) GDP → CO ₂ (+) ENE → CO ₂ (+) GCF → CO ₂ (+)
Tariq et al. [22]	1971–2011	Pakistan and India	GDP, ENE, POP, GCF, CO ₂	OLS	EKC hypothesis is valid GDP → CO ₂ (+) EC → CO ₂ (–) ENE → CO ₂ (+)
Zambrano-Monserrate et al. [19]	1971–2011	Brazil	GDP, GDP ² ENE, HENE, CO ₂	VECM, Causality	GDP → CO ₂ (+) EC → CO ₂ (–) ENE → CO ₂ (+)
Liu (2016)		China	GDP, ENE, EC, GCF, MAN, CO ₂	Input-output technique	GDP → CO ₂ (+) EC → CO ₂ (+) GCF → CO ₂ (+)
Ozatac et al. [20]	1960–2013	Turkey	ENE, TR, URB, FD, CO ₂	ARDL, causality	EKC hypothesis is valid GDP → CO ₂ GDP → CO ₂ URB → CO ₂
Sharif et al. (2017)	1996M1–2015M8	USA	GDP, TO	Continuous wavelet transform, wavelet coherence, wavelet-based Granger causality	In the short run, GDP → TR In the long run, TO → GDP
Arshian et al. (2017)	1983Q1–2016Q1	Singapore	ELEC, GDP	ARDL, wavelet coherence	ELEC → GDP In the long run ELEC ↔ GDP In the medium run
Raza et al. [35]	1996Q1–2015Q3	USA	TD, CO ₂	Wavelet covariance, wavelet coherence spectrum, wavelet-based Granger causality analysis	In short, medium and long runs TD → CO ₂
Li et al. [38]	1993–2013	USA and China	HS, GCF, CO ₂	Input-output analysis	HS → CO ₂ (+) GCF → CO ₂ (+)
Rauf et al. [24]	1981–2016	Belt & Road Initiative (BRI) economies	ENE, GDP, GDP ² , CO ₂	CSD, PMG	EKC hypothesis is valid for developed nations ENE → CO ₂ (+) GDP → CO ₂ (+)
Sarkodie [25]	1971–2013	17 African Nations	ENE, GDP, FPRO, BR GDP ² , CO ₂	Westerlund error correction, Panel Cointegr	EKC hypothesis is not valid ENE → CO ₂ (+) GDP → CO ₂ (+) BR → CO ₂ (+) FPRO → CO ₂ (+)

Table 1 (continued)

Investigator(s)	Period	Nation(s)	Variable(s)	Technique(s)	Finding(s)
Pata [18]	1974–2014	Turkey	REN, GDP, GDP ² , CO ₂ , HCON, FD, URB, CO ₂	Gregory-Hansen, Hatemi-J cointegration tests, CCR, FMOLS	EKC hypothesis is valid FD → CO ₂ (+) GDP → CO ₂ (+) URB → CO ₂ (+) REN → CO ₂ (+) HCON ≠ CO ₂ HCON ≠ CO ₂
Rana and Sharma [26]	1982–2013	India	GDP, CO ₂ , FDI, IMP, EXP, CO ₂	TYGC	EKC hypothesis is valid FDI → CO ₂ IMP → CO ₂ (+) EXP → CO ₂ (+)
Cosmas et al. [27]	1981–2016	Nigeria	GDP, GDP ² , FD, POP, REN, TO, MAN, CO ₂	ARDL and NARDL	EKC hypothesis is valid GDP → CO ₂ (+) TO ≠ CO ₂ MAN → CO ₂ (−) REN → CO ₂ (−)
Shekhar et al. (2019)	2001M1–2017M2	USA	TR, TRANS, GDP, CO ₂	Partial and multiple wavelet coherence techniques	Comovements of the variables are observed to be unequal across the periods CO ₂ ↔ TR CO ₂ ↔ TRANS ICT → CO ₂ (−)
Batool et al. [39]	1973–2016	South Korea	ICT, ENE, CO ₂	Wavelet power spectrum, wavelet coherence, partial and multiple wavelet coherence	
Bekun et al. [21]	1971–2015	Nigeria	GDP, FDI, EC, CO ₂	ARDL	EKC hypothesis is valid GDP → CO ₂ (+) ENE → CO ₂ (+) FDI → CO ₂ (−)
Dogan and Inglesi-Lotz [28]	1980–2014	European countries	ENE, GDP, GDP ²	Panel OLS, FMOLS, FE	EKC hypothesis is not valid GDP → CO ₂ (−)
Pata and Aydin [29]	1965–2016	Brazil, China, Canada, India, Norway, and the USA	ENE, HENE, GDP, GDP ² , CO ₂	Fourier bootstrap ARDL, Fourier TYGC	EKC hypothesis is not valid HENE → GDP in Brazil HENE ↔ GDP in China
Leal and Marques [30]	1990–2016	CO ₂ emitting countries in the OECD	GDP, GDP ² , PGLO CO ₂	Driscoll–Kraay estimator	EKC hypothesis is valid for globalized countries EKC hypothesis is not valid for low-globalized nations PGLO → CO ₂ (+)
Mehmood and Tariq [40]	1971–2013	South Asian countries	GDP, GDP ² , CO ₂	VECM, impulse response	Differing results GDP → DEQ (+)

Table 1 (continued)

Investigator(s)	Period	Nation(s)	Variable(s)	Technique(s)	Finding(s)
Koc and Bulus [31]	1971–2017	South Korea	GDP, GDP ² , ENE, CO ₂	ARDL	N-shaped relationship GDP → CO ₂ (+) ENE → CO ₂ (+) TO → CO ₂ (–) REN → CO ₂ (–)
Odugbesan and Rjoub (2020)	1993–2017	Mexico, Indonesia, Nigeria, and Turkey	GDP, GDP ² , ENE, CO ₂ , TO	ARDL Bounds test approach	In Mexico and Turkey ENE ↔ GDP In Nigeria and Indonesia GDP → DEQ (+)
Leal and Marques [30]	1990–2014	OECD countries	GDP, GDP ² , TO, CO ₂	FMOLS, DOLS, AMG, CDS	EKC hypothesis is not valid OP → CO ₂ (+) REN → CO ₂ (+)
Arango Miranda (2020)	1990–2016	Mexico, USA, Canada	GDP, GDP ² , TO, HDI, CO ₂	OLS, VECM, Causality	EKC hypothesis is valid for USA and Mexico but not for Canada
Adebayo et al. [13]	1980–2018	Mint Nations	GDP, TO, URB, ENE, CO ₂	Westerlund Coint., PMG, CDS, Panel Causality	EKC hypothesis is refuted GDP ≠ CO ₂ TO → CO ₂ (–) TO → ENE (+) URB → CO ₂ (+)
Arain et al. [34]	1979–2017	China	REN, FDI, GDP	Wavelet correlation, continuous wavelet transform, partial and multiple wavelet coherence analyses	In the medium and long term FDI → CO ₂ (–) REN → GDP (+)

Table 2 Descriptive Statistics. Source: Author's Collation

Source	World Bank database	UNCTAD	World Bank database	World Bank database	UNCTAD	World Bank database
Time frame	1971–2016	1971–2016	1971–2016	1971–2016	1971–2016	1971–2016
Code	CO ₂	GDP	GDP ²	ENE	GCF	TO
Mean	3.811170	8245.918	69,375,966	1420.401	1.18E+11	40.86708
Median	3.928403	8185.268	67,003,261	1500.109	8.67E+10	38.65502
Maximum	4.455658	10,205.80	1.04E+08	1698.585	2.88E+11	76.10028
Minimum	2.380328	5561.182	30,926,744	809.6385	7.93E+09	16.35969
Std. Dev	0.537416	1188.063	19,076,588	225.0268	9.44E+10	17.53203
Skewness	−1.360470	−0.414007	−0.156649	−1.329089	0.543678	0.158748
Kurtosis	4.068952	2.368076	2.133493	3.793665	1.879798	1.724866
Jarque–Bera	16.38016	2.079460	1.627234	14.75032	4.671295	3.309642
Probability	0.000277	0.353550	0.443252	0.000627	0.096748	0.191126
Observations	46	46	46	46	46	46

$$\begin{aligned} \Delta \text{CO}_{2t} = & \vartheta_0 + \sum_{i=1}^t \vartheta_1 \Delta \text{CO}_{2t-i} + \sum_{i=1}^t \vartheta_2 \Delta \text{GDP}_{t-i} + \sum_{i=1}^t \vartheta_3 \text{GDP}_{t-i}^2 \\ & + \sum_{i=1}^t \vartheta_4 \Delta \text{ENE}_{t-i} + \sum_{i=1}^t \vartheta_5 \Delta \text{GCF}_{t-i} + \sum_{i=1}^t \vartheta_6 \Delta \text{TO}_{t-i} \\ & + \rho \text{ECT}_{t-1} + \varepsilon_{t-1} \end{aligned} \quad (4)$$

where the speed of adjustment is depicted by ρ and error correction term depicted by ECT_{t-1} .

The theme of this research is to utilize the time–frequency dependence to explore the correlation and causal linkage between CO₂ emissions, economic growth, gross capital formation, trade openness, and energy consumption in Mexico. As a conceptual study, the authors examined the integration order of energy consumption, real growth, and CO₂ emissions using Dickey & Fuller [43] and Perron & Ng [44] unit-root tests. Additionally, the Zivot & Andrews [45] and the Lee & Strazicich [46] unit-root tests are utilized to examine the presence of structural break(s) in the time-series. Concerning the main aim of this study, the investigators explored the time–frequency dependence between CO₂ emission and real growth and energy consumption in Thailand by employing the wavelet coherence approach. The main novelty of wavelet coherence is that the approach combines time-domain causality and frequency-domain causality. Therefore, this allows the present study to capture the long- and short-run causal links between CO₂ emissions, energy consumption, gross capital formation, trade openness, and economic growth in Mexico. It is well known that if there is structural break(s) in the time series, inaccurate findings are usually generated by using traditional causality tests. Therefore, this study utilized the wavelet coherence approach to avoid these issues. The main advantage of

wavelet coherence appears where the decomposition of one-dimensional time data into the bi-dimensional time–frequency sphere is allowed. Thus, we capture the long-run and short-run causal interactions between CO₂ emissions, trade openness, gross capital formation, economic growth, and energy consumption in Mexico at the same time. A multi-scale decomposition technique brings out a natural framework to show frequency-dependent behavior for examining the interconnection between CO₂ emissions, economic growth, and energy consumption [47]. This research offers an opportunity to reveal the long-term, medium-term, and short-term causal association between CO₂ emissions, trade openness, gross capital formation, economic growth, and energy consumption. Goupillaud et al. [48] first presented the methods. The present study utilizes the ϖ wavelet method, which is part of the Morlet wavelet family. The ϖ is represented by Eq. 5 underneath:

$$\varpi(t) = \pi^{-\frac{1}{4}} e^{-i\varpi t} e^{-\frac{1}{2}t^2} \quad (5)$$

where portrays the frequency used on the restricted time-series; i illustrate $p(t) = 0, 1, 2, 3 \dots N-1$; and $\sqrt{-1}$. As stated by Adebayo and Kalmaz [49] and Kirikkaleli [50], there is indeed a time transition to the time–frequency domain that corresponds to the wavelet change. ϖ is transformed; thus, it progressed into $\varpi_{k,f}$. Equation 6 illustrates this explanation;

$$\varpi_{k,f}(t) = \frac{1}{\sqrt{h}} \varpi\left(\frac{t-k}{f}\right), k, f \in \mathbb{R}, f \neq 0 \quad (6)$$

The $p(t)$ which is the time-series data is incorporated. Therefore, Eq. 7 illustrates the continuous wavelet function:

$$\varpi_p(k, f) = \int_{-\infty}^{\infty} p(t) \frac{1}{\sqrt{f}} \varpi\left(\frac{t-k}{f}\right) dt, \quad (7)$$

As Kirikkaleli [50] and Adebayo [51] stated, when ψ which is the coefficient is incorporated into the equation, Eqs. 8 and 9 are restored.

$$p(t) = \frac{1}{C_{\varpi}} \int_0^{\infty} \left[\int_{-\infty}^{\infty} |\varpi_p(a, b)|^2 da \right] \frac{db}{b^2} \quad (8)$$

The wavelet power spectrum (WPS) captures the vulnerability of CO₂ emission, trade openness, energy usage, gross capital formation, and GDP growth, which is illustrated in Eq. 9.

$$WPS_p(k, f) |W_p(k, f)|^2 \quad (9)$$

The cross-wavelet transformation (CWT) method converted the time-series variable in Eq. 9 into Eq. 10.

$$W_{pq}(k, f) = W_p(k, f) \overline{W_q(k, f)} \quad (10)$$

where: $W_p(k, f)$ and $W_q(k, f)$ portray the two variables. The squared wavelet coherence is depicted in Eq. 11 as follows:

$$R^2(k, f) = \frac{|S(f^{-1} W_{pq}(k, f))|^2}{S(f^{-1} |W_p(k, f)|^2) S(f^{-1} |W_q(k, f)|^2)} \quad (11)$$

If the $R^2(k, f)$ nears 1, indicates either the time-series indicators are correlated or that there is a causal interaction between the time-series indicators at a particular level, enclosed by a black line. Additionally, whenever $R^2(k, f)$ nears 0, it indicates that there is no proof of association or causality between the two variables. Despite the fact, $R^2(k, f)$ cannot provide any detailed information on the correlation symbol. Hence, Torrence & Compo [52] have developed a method for identifying distinctions in wavelet coherence through the use of deferral signs in the wavering of two-time

sequences. The equation for the wavelet coherence difference process developed is illustrated by Eq. 12 as follows:

$$\phi_{pq}(k, f) = \tan^{-1} \left(\frac{L\{S(f^{-1} W_{pj}(k, f))\}}{O\{S(f^{-1} W_{pj}(k, f))\}} \right) \quad (12)$$

An imaginary operator and a real part operator are symbolized by L and O separately.

4 Empirical results

As stated earlier, the study tends to explore the long-run and causal effects of trade openness, economic growth, energy consumption, and gross capital formation on CO₂ emissions. Furthermore, the study also tests the validity of EKC hypothesis in Mexico. The study's uniqueness stems from the fact that no prior studies in regards to Mexico have explored these linkages using the wavelet coherence technique. The outcome of the ADF, PP, KPSS, ZA, and LM unit-root tests denotes that all the indicators utilized in this investigation are stationary at mixed order i.e. $I(0)$ and $I(1)$. Therefore, the next thing is to verify the cointegration among the indicators in the long run in Tables 3, 4.

4.1 Cointegration result

Since the time-series variables are stationary at a mixed level, the ARDL bounds testing proposed by Pesaran et al. [53] was utilized to examine the cointegration between CO₂ emissions and the regressors. Table 5 illustrates the cointegration outcome. Findings reveal cointegration since the F -statistic (4.98) is higher than the lower-bound and upper-bound critical value. The null hypothesis is rejected on the grounds of this result. The outcome of this discovery lays the groundwork for the estimation of long- and short-term ARDL estimations in Fig. 1.

Table 3 Unit-root tests (Level). Source: Author's Own Compilation

		CO ₂	GDP	GDP ²	ENE	GCF	TO
ADF	K & T	-2.312	-2.985	-3.471 M	-2.830	-3.716 I	-4.014L
PP	K & T	-2.268	-3.034 M	-2.408	-2.771	-2.698	-2.910
KPSS	K & T	0.176L	0.157 ^L	0.136 M	0.177L	0.142L	0.162
ZA	K & T	-5.712 K [1983]	-4.223 [1983]	-3.074 [1992]	-3.604 [1981]	-4.373 [1982]	-5.347L [1995]
Lee Strazicich	K & T	-5.965 K [1988]	-5.389 [1984]	-6.067 M [1984] {1989}	-5.226 [1981]	-6.247 M [1984]	-6.422L [1990]
LM		{2004}	{1999}		{2003}	{1989}	{1996}

K & L, M signify 0.01, 0.05, and 0.10 level of significance, respectively. K and K & T indicate constants and constant and trend. [] represents the year of a structural break. {} illustrates the second year break

Table 4 Unit-root tests (first difference). *Source:* Author's Compilation

		CO ₂	GDP	GDP ²	ENE	GCF	TO
ADF	K & T	−8.023 M	−5.381 K	−6.185 K	−5.310 K	−6.018 K	−5.889 K
PP	K & T	−7.997 M	−5.338 K	−5.652 K	−5.310 k	−6.204 K	−12.016 K
KPSS	K & T	0.067	0.084	0.108	0.115	0.105	0.104
ZA	K & T	−9.733 M [1983]	−6.814 M [1982]	−7.157 K [1987]	−6.866 K [1982]	−7.431 K [1987]	−4.955 M [2001]
Lee Stra- zicich LM	K & T	−10.171 k [1981] {1985}	−6.702L [1984] {1999}	−6.708 k [1993] {2005}	−5.783L [1981] {1985}	−6.628L [1985] {2000}	−6.850 K [1991] {1998}

K & L, M stand for 0.01, 0.05, and 0.10 level of significance, respectively. K and K & T indicate constants and constant and trend. [] represents the year of a structural break. {} illustrates the second year break

Table 5 ARDL bounds test outcomes for estimated models. *Source:* Author's Compilation with EVIEWS 11

Model estimated	Optimal lag length	F-Statistics	Cointegration
Model 1 CO ₂ = f(GDP, GDP ² , ENE, GCF, TO)	(1, 2, 2, 1, 1, 0)	4.98 ^K	Yes
Significant level	L-B I(0)	U-B I(1)	
1%	3.41	4.68	
2.5%	2.96	4.18	
5%	2.62	3.79	
10%	2.26	3.35	

5% significance level is represented by K. L-B & U-B stands for lower and upper bound separately

4.2 Long-run and short-run estimations findings

After establishing cointegration between CO₂ and the regressors, the study investigates the short and long-run connection between CO₂ emissions and economic growth square, trade openness, gross capital formation, and energy usage. The result of the long-run linkage between CO₂ emissions and its determining factors is represented in Table 5. The estimate of ARDL long-run established the classical EKC hypothesis validity in the long run since the GDP² has a detrimental influence on CO₂ emissions. Thus, the EKC hypothesis hold for Mexico. The outcome complies with the findings of Zambrano-Monserrate et al. [19], Ozatac et al. [20], Pata [18], and Bekun et al. [21]. However, the EKC hypothesis was refuted in the studies of Dogan and Inglesi-Lotz [28], Pata and Aydin [29], Koc and Bulus [31], and Dogan and Inglesi-Lotz [28]. Furthermore,

Fig. 1 a CUSUM, b CUSUMSsq

findings revealed a positive and significant linkage between economic growth and CO₂ emissions in Mexico. This shows that a 1.01% increase in CO₂ emissions is due to a 1% increase in real growth when other factors are held constant. The outcome corroborates with the findings of Ozatac et al. [20], Bekun et al. [21], and Rana and Sharma [26]. Also, the interconnection between CO₂ emissions and energy usage is positive and statistically significant. It implies that a 1% increase in Mexico's energy usage will lead to a 1.29% increase in CO₂ emissions when other factors are held constant. The result aligns with prior studies [13, 21, 25, 31]. The linkage between gross capital formation and CO₂ emissions is positive and statically significant. The finding implies that when other factors are held constant, a 0.279% increase in CO₂ emissions is due to a 1% increase in gross capital formation. The result concurs with findings of Tariq et al. [22], Spetan [54] and Li et al. [38]. Finally, no significant link exists between trade openness and CO₂ emissions in Mexico. The outcome corroborates with the previous studies [14, 27]. However, it does not comply with prior studies [31], Adebayo et al. [13]. As anticipated, the ECM's coefficient is -0.91, which is negative and statistically significant at a 1% level of significance. The finding illustrates that prior periods correction can be corrected by the subsequent periods. This result corroborates with past studies [22, 26, 31, 54]. Furthermore, only energy usage significantly impact CO₂ emissions in the short run. This finding corroborates with the prior studies [13, 25, 31]. The study also conducts various diagnostic tests, which is revealed in Table 6. The diagnostic tests show that the model is good and meaningful conclusion can be drawn from it.

4.3 Robustness check

In order to verify the credibility of the ARDL long-run result, the FMOLS and DOLS long-run estimates were used as a robustness check. Table 7 illustrates result of FMOLS and DOLS, which complies with the ARDL long-run estimate.

4.4 Wavelet coherence result

In Figs. 2, 3, 4 and 5, the white cone is the cone of influence (COI) used for interpretation when analyzing wavelet coherence (WTC). The significance degree is shown by a thick black line calculated based on the Monte Carlo simulations. The thick black contour encloses regions where the wavelet coherence is significant at the 5% level against the red noise estimated from the Monte Carlo simulations using phase randomized surrogate series. The arrows indicate the phase difference between the two time series. The direction of the arrows captures the

Table 6 ARDL Estimations. *Source:* Author Compilation with EViews 11

Long-run result				
CO ₂ = f(GDP, GDP ² , ENE, GCF, TO)				
Dependent variable	Regressors	Coefficient	SE	T-prob
CO ₂	GDP	1.0112	0.3420	2.9567 K
	GDP ²	-0.0912	0.0325	-2.8031 K
	ENE	1.2932	0.2350	5.5020 K
	GCF	0.2793	0.1122	2.4867 L
	TO	0.0484	0.0347	1.3914
Short-run result				
Dependent variable	Regressors	Coefficient	SE	T-prob
CO ₂	ECM(-)	-0.9189	0.1558	-5.8949 K
	Δ GDP	0.4199	0.3069	1.3679
	Δ GDP ²	-0.0287	0.0228	-1.2522
	Δ ENE	1.2930	0.1835	7.0433 K
	Δ GCF	-0.1268	0.0844	-1.5016
Diagnostic tests				
R ²		0.95		
Adj R ²		0.94		
χ ² Heteroscedasticity		1.16(0.34)		
χ ² Ramsey		0.14(0.88)		
χ ² Normality		1.78(0.40)		
χ ² LM		0.83(0.44)		

K & L denotes 1% and 5% level of significance respectively

Table 7 Robustness check. *Source:* Author Compilation with EViews 11

Regressors	FMOLS		DOLS	
	Coefficient	T-prob	Coefficient	T-prob
GDP	0.9119	3.1509 K	1.0112	0.0130 L
GDP ²	-0.0813	-2.9954 K	-0.0912	-2.4983 L
ENE	1.2587	6.4314 K	1.2930	4.9038 M
GCF	0.2392	2.5356 L	0.2793	2.2164 L
TO	0.0288	0.9975	0.0484	1.2401
R ²	0.94	0.95		
Adj R ²	0.93	0.94		

K, L, and M represents 1%, 5% and 0% level of significance

phase difference between the two time series. Time and frequency (year) are represented on the horizontal and vertical axes, respectively. Table 8 depicts the interpretation of the wavelet coherence as explained by Aloui et al. [55], Mutascu [56], Adebayo [57], Kirikkaleli, [50] and Adebayo and Kalmaz [49].

Fig. 2 WTC between CO₂ and GDP

Fig. 4 WTC between CO₂ and GCF

Fig. 3 WTC between CO₂ and ENE

Fig. 5 WTC between CO₂ and TO

Figures 2, 3, 4 and 5 exemplify the wavelet coherence between CO₂ and its determinants in Mexico from 1971 to 2016. This approach captures the correlation and causality between CO₂ and the indicators at the same time. This approach is crafted from econophysics and incorporates information on the time and frequency domains. According to Kirikkaleli [50], the technique is adopted from mathematics by combining time- and frequency-domain information techniques to retrieve completely undiscovered information. The present study thus allows short-term, medium-term, and long-term correlation and

causality between CO₂ emissions and explanatory variables (gross capital formation, real growth, trade openness, and energy use). In Figs. 2, 3, 4 and 5, no correlation between the two time series is described by cold (blue) color, whereas proof of correlation is characterized by warmer (red) color. In Fig. 2, between 1976 and 1993, rightward-down and rightward-up arrows show that economic growth and CO₂ emissions are in phase at different scales (different frequencies), indicating that there is positive and significant correlation between economic

Table 8 Interpretation of wavelet coherence. Source: Investigator Collation

Arrows path	Meaning
Right arrows	A positive correlation (in-phase)
Left arrows	A negative correlation (anti-phase)
Right and up arrows	The second variable leads to (causes) the second variable
Right and down arrows	The first variable leads to (causes) the first variable
Left and up arrows	The second variable leads to (causes) the second variable
Left and down arrows	The first variable leads to (causes) the first variable

growth and CO₂ emissions. Furthermore, there is bidirectional causal relationship between CO₂ emissions and economic growth. This finding is similar with the outcome of Rafindadi and Ozturk [58], Mirza and Kanwal [59], Akadiri and Akadiri [60] and Nasreen et al. [61]. In Fig. 3, at different scales, from 1975 to 1995 and between 1998 and 2012, rightward-down arrows show that energy consumption and CO₂ emissions are in phase at different scales (different frequencies), indicating that there is positive and significant correlation between energy consumption and CO₂ emissions. Furthermore, there is unidirectional causality running from energy consumption to CO₂ emissions. This finding underlines how energy consumption is important predictor of CO₂ emissions. The result corroborates the findings of Dabachi et al. [62], Uddin et al. [63], Kalmaz, and Kirikkaleli [14]. In Fig. 4, at different scales, between 1978 and 1990, rightward-down arrows show that gross capital formation and CO₂ emissions are in phase at different scales (different frequencies), indicating that there is positive and significant correlation between gross capital formation and CO₂ emissions. In addition, there is unidirectional causality running from CO₂ emissions to gross capital formation, which indicate that CO₂ emissions can predict gross capital formation. This result complies with past studies (Soytas et al. [64] and Etokakpan et al. [65]). Lastly, in Fig. 5, there is no significant correlation between trade openness and CO₂ emissions.

5 Conclusion and policy direction

In the current era of globalization, global warming is seen as a significant challenge to humanity. From this perspective, even as nations are focused on achieving economic growth, this raises the question: what are the environmental implications of globalization? Based on this, the study aimed to explore the interconnection between CO₂ emissions, trade openness, energy usage, real growth, and the square of real output and gross capital formation in Mexico for the period between 1971 and 2016. The ARDL bounds testing technique was employed to investigate the potential cointegration of the variables, while the short-term and long-term estimation was examined using

the wavelet coherence technique. The FMOLS and DOLS were used as a robustness test for the ARDL technique. Furthermore, the study used the wavelet-based Granger technique to explore the causality between CO₂ emissions and its determining indicators. The novelty of the wavelet coherence technique is its ability to ascertain correlation and causality between the variables simultaneously. The ARDL bounds testing indicates that the examined variables are cointegrated at the 1% significance level. The findings from the ARDL, FMOLS and DOLS models revealed: (i) the validity of the EKC hypothesis; (ii) a positive and significant linkage between real growth and CO₂ emissions in Mexico; (iii) the interconnection between CO₂ emissions and energy usage is positive and statistically significant; (iv) the linkage between gross capital formation and CO₂ emissions is positive and statistically significant; and (v) surprisingly, the study did not find any significant of trade openness on CO₂ emissions in Mexico in the long-run. The wavelet coherence result confirms the results of the ARDL, FMOLS, and DOLS. Furthermore, the wavelet coherence reveals a bidirectional causality between economic growth and CO₂ emissions and a one-way causality from CO₂ emissions to energy consumption. Furthermore, CO₂ emissions cause gross capital formation, while no evidence of causality was found to suggest a relationship between CO₂ emissions and trade openness. Mexico's energy policy plays a critical role, both in terms of decreasing the environmental issues caused by CO₂ emissions and with regard to economic conditions, since energy production is heavily dependent on energy sources and production costs in Mexico. Therefore, to decrease the cost of production, policies encouraging the use of renewable energy sources should be assigned more importance. Mexico can increase the share of renewable energy production in total energy generation with appropriate energy policies, since it is a favorable country for renewable energy sources such as solar, wind, geothermal, biomass, and hydro-energy, as it is surrounded by sea on three sides and has many dams and lakes. There are two key reasons for the high rates of CO₂ pollution in Mexico. First, owing to the inefficiency of energy consumption in Mexico, energy intensity is high, and second, total energy output relies on non-renewable sources instead of renewable energy sources. Mexico is

below the global average in terms of energy efficiency, while energy intensity is higher compared to several nations. Hence, energy consumption should be decreased, followed by an increase in the share of renewable energy sources for the production of energy, in order to reduce CO₂ emissions via effective energy policies, including enhanced carbon taxes for the manufacturing industry, since such taxes may resultantly give financial support for research and innovation in the manufacturing sector to produce technological innovations to reduce energy consumption and/or for the construction of renewable energy plants. Although the current research examines substantial empirical results for the case of Mexico, one of the critical drawbacks of this analysis is the accessibility of data, which limits the power of the econometric techniques used because the variables accessible only encompass the period between 1971 and 2016. Also, CO₂ emissions is regarded as a proxy for environmental pollution, which is not the only cause of the reduction in the quality of the environment. Additional research for the case of Mexico should investigate this interconnection by including more environmental pollution indicators.

Compliance with ethical standards

Conflict of interests The author declares that there are no conflicts of interests regarding the publication of this paper.

Ethical approval This study follows all ethical practices during writing.

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