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Article

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Global determinants of methane emissions in OECD countries: A dynamic panel approach

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ABSTRACT

Methane (CH4), an often-overlooked greenhouse gas (GHG), has a significant impact on the environment. Although it receives less attention than carbon dioxide (CO2), it is the second most important GHG in terms of its ability to trap heat in the atmosphere. Few studies have analyzed the determinants of CH4 emissions, especially those from the energy sector. Therefore, this study provides relevant information on the impact of GDP, primary and renewable energy consumption, human development index and trade openness on methane emissions in OECD countries. Using advanced cointegration approaches, we find that GDP and primary energy consumption increase CH4 emissions, while renewable energy consumption and human development mitigate their growth. However, the impact of these variables varied over time. No significant effect of trade openness on methane emissions was found. We recommend specific policies for OECD countries to reduce methane emissions, especially for the most polluting countries. Governments should promote renewable energy sources (solar, wind, hydro) to reduce reliance on fossil fuels, thereby minimizing methane leakage during extraction and transport. In addition, investing in human development can promote sustainable behaviors and further reduce emissions, addressing both environmental and social concerns.

Introduction

After carbon dioxide, methane (CH4) is the second most important greenhouse gas (GHG) (Fernández-Amador et al., 2022). Approximately one-third of global warming is caused by this gas (European Union, 2021). Although its residence time in the atmosphere is shorter than that of CO2, its impact on climate change is 80 times more significant over a given period (UN, 2015).

In the last decade, there has been a remarkable increase in atmospheric methane emissions (EPA, 2022). In this context, the Sixth Assessment Report of the IPCC mentions that it is crucial to significantly reduce anthropogenic methane emissions by 2030 in order to keep the global temperature increase below 1.5 °C (European Parliament, 2023).

Human activities are responsible for 50–65 % of total global CH4 emissions, with energy-related activities being one of the main sources (IPCC, 2013). In this context, fossil fuels are one of the main sources of methane emissions in the energy sector (EPA, 2022). In addition, the exploration and production of oil and natural gas, as well as the transportation and distribution of these fuels, generate methane emissions into the atmosphere (UN, 2015).

Previous studies have examined the determinants of methane emissions in different countries. The literature has identified economic growth, energy consumption, urbanization, trade, agricultural production, and education, among others, as the primary variables. Several studies support the Environmental Kuznets Curve (EKC) theory, highlighting a U-shaped relationship between gross domestic product (GDP) per capita and methane emissions, suggesting an initial positive effect followed by a decline (Benavides et al., 2017; Adeel-Farooq et al., 2020; Djoukouo, 2021; Ericsson, 2022; Acevedo-Ramos et al., 2023; Magazzino et al., 2024). Furthermore, the literature has reached a consensus that primary energy consumption is positively related to methane

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Nomenclature

AMG	Augmented Mean Group
ARDL	Autoregressive Distributed Lag
ASEAN	Association of Southeast Asian Nations
CADF	Cross-Sectionally Augmented Dickey-Fuller
CDT	Cross-dependency test
CEMAC	Central African Economic and Monetary Union
CH_4	Methane
CIPS	Cross-Sectionally Augmented IPS
CO_2	Carbon Dioxide
CS-ARDL	Cross-Sectionally Augmented Autoregressive Distributed Lag
DOLS	Dynamic Ordinary Least Squares
EKC	Environmental Kuznets Curve
EPA	Environmental Protection Agency
FMOLS	Fully Modified Ordinary Least Squares
GDP	Gross Domestic Product
GDPC	Gross Domestic Product per Capita
GGDC	Groningen Growth and Development Centre
GHG	Greenhouse Gas
HCI	Human Capital Index
HDI	Human Development Index
IPCC	Intergovernmental Panel on Climate Change
N2O	Nitrous Oxide
NO_2	Nitrogen Dioxide
NRE	Non-Renewable Energy
OECD	Organisation for Economic Co-operation and Development
OPEC	Organization of the Petroleum Exporting Countries
RE	Renewable Energy
SHT	Slope non-heterogeneous test
UN	United Nations

emissions, highlighting the need for policies that promote energy efficiency and the transition to cleaner energy sources (Adeel-Farooq et al., 2020; Yusuf et al., 2020). In contrast, previous studies have found that renewable energy consumption reduces CH4 emissions (Benavides et al., 2017; Magazzino et al., 2024). Urbanization and deforestation yield mixed results, with urbanization showing positive effects on NO2 emissions and negative effects on CH4 emissions, while deforestation is mainly associated with increased methane emissions (Shittu et al., 2018). In addition, studies such as Adeel-Farooq et al. (2020) found no significant evidence of trade on methane emissions. Regarding agriculture and livestock production, their significant role in methane emissions has been highlighted, especially in the case of livestock activities (Tarazkar et al., 2021). On the other hand, education emerges as a mitigating factor that counteracts the negative impact of poverty on emissions (Subramaniam & Masron, 2019). Additionally, the importance of climate financing and environmental policies in reducing methane emissions, as well as the difference between production-based and consumption-based emissions, suggests that policies targeting the latter may be more effective and equitable (Doku et al., 2021; Fernández-Amador et al., 2022).

However, previous studies have focused on analyzing total methane emissions or those from the agricultural sector, overlooking emissions from the energy sector. As mentioned above, the energy sector is one of the major sources of air pollution, releasing large amounts of CH4 (IPCC, 2013). In this respect, the study by Shittu et al. (2018) stands out.

Another aspect to highlight is that the literature has not addressed aspects related to human capital and its impact on methane emissions. As mentioned above, only Subramaniam and Masron (2019) discussed the buffering role of education on methane emissions. We postulate that well-trained and committed human capital can play a crucial role in reducing methane emissions in the energy sector through the application of knowledge, technologies, and practices that minimize the release of this greenhouse gas into the atmosphere. In addition, we believe that the mitigating effect of human capital on methane emissions could be more pronounced in the long term due to the accumulation of knowledge and skills, cultural change toward sustainability, continued regulatory compliance, and the development of new technological solutions.

Hence, the objective of this paper is to analyze the factors influencing methane emissions in the energy sectors of 35 OECD countries over the period from 1990 to 2019. We consider five explanatory variables: GDP, renewable energy consumption, primary energy consumption, human capital index, and trade openness. For the causality analysis, we use the CS-ARDL cointegration approach of Chudik and Pesaran (2015) and the method of Dumitrescu and Hurlin (2012). The CS-ARDL approach has an advantage over other panel methods because of its ability to address issues such as endogeneity, cross-sectional dependence, heterogeneous slopes, and different orders of integration of variables. Previous studies, such as Acevedo-Ramos et al. (2023), used this approach for their analysis.

The main results indicate that economic growth and primary energy consumption contribute to an increase in methane emissions. On the other hand, renewable energy consumption and the human capital index have a mitigating effect on CH4 emissions. However, trade has no significant impact on pollution. Through Granger causality analysis, we identify specific policy recommendations. For example, promoting renewable energy sources such as solar, wind, and hydropower can reduce methane emissions by minimizing potential leakage during extraction and transportation. Increasing human capital can also reduce CH4 emissions by promoting sustainable behavior. Investing in human development effectively addresses both environmental and social concerns. Finally, governments can be confident that policies to reduce methane emissions will not affect economic growth.

The remainder of the paper is organized as follows. Section 2 presents the main previous studies on the topic. Section 3 describes the implementation of the proposed methodology. Section 4 presents the results of the study. Section 5 provides concluding remarks.

Literature review

The following are the most recent studies that have analyzed the determinants of global methane emissions. We start with the study by Benavides et al. (2017), who examined the relationship between methane emissions, gross domestic product, renewable energy production, and trade openness in Austria to determine the existence of an EKC. Using the autoregressive distributed lag (ARDL) method, they found a long-run inverted U-shaped relationship between the analyzed variables. In addition, Granger causality analysis revealed unidirectional causality between methane emissions and the studied variables. These results suggest the importance of considering economic and environmental factors when planning climate change mitigation strategies in Austria and other regions.

Shittu et al. (2018) used an ARDL regression approach to examine the relationship between environmental degradation, urbanization, and deforestation in Malaysia. They found mixed results regarding the influence of urbanization on NO2 and CH4 emissions, with an increase in NO2 emissions and a decrease in CH4 emissions in response to an increase in urbanization. In addition, deforestation had a positive effect on CH4 and NO2 emissions. Despite the lack of a significant effect on CH4 estimates, a positive moderating effect of the interaction between urbanization and deforestation on NO2 emissions was identified. These results highlight the complex interactions between urbanization, deforestation and environmental degradation in Malaysia, and suggest the need for integrated policies to improve the country's environmental quality.

Subramaniam and Masron (2019) examined the impact of education on the relationship between poverty and methane emissions in 22 developing countries from 1990 to 2016. Using an empirical approach based on the ARDL model, they find evidence to support the validity of the hypothesis that the negative impact of poverty on the environment can be mitigated by educating the poor. The results show that as education levels increase, the negative impact of poverty on pollution is counteracted, suggesting that education may be a key factor in mitigating the negative impact of poverty on the environment. These findings have important implications for policymakers and researchers interested in environmental economics and policy, and highlight the importance of promoting education as a means of improving environmental quality and reducing poverty.

Adeel-Farooq et al. (2020) studied the influence of economic growth, energy consumption, and trade openness on methane (CH4) emissions in six ASEAN countries over the period 1985–2012. Using ARDL estimation techniques, they found that economic growth followed the EKC hypothesis, with methane emissions decreasing as economic growth reached a certain level. They also found that energy consumption had a positive relationship with CH4 emissions, while trade openness had no significant relationship with methane emissions in these countries. These findings underscore the importance of implementing effective policies to reduce methane emissions and address environmental challenges in the ASEAN region.

Tarazkar et al. (2021) examined the factors affecting methane emissions in OPEC member countries, focusing on agricultural production using the EKC framework. Using panel data from 11 OPEC member countries during 1995–2012, they found an N-shaped relationship between gross domestic product and methane emissions. In addition, they found a significant positive relationship between energy consumption and methane emissions, as well as a significant positive impact of crop and livestock production on methane emissions. These results suggest that livestock activities are more likely to cause methane pollution than crop production in agricultural countries. They recommend that OPEC member countries focus on crop production rather than livestock production to diversify income and reduce methane emissions.

Yusuf et al. (2020) explored the relationship between greenhouse gas emissions, energy consumption, and economic growth in African OPEC member countries. Using a distributed autoregressive panel model, they analyzed carbon dioxide, methane, and nitrous oxide emissions in relation to economic growth and energy consumption. They found that economic growth had a significant positive effect on long-run carbon dioxide and methane emissions, while its effect on nitrous oxide emissions was statistically insignificant. Energy consumption also had a positive but insignificant long-term effect on emissions of the three greenhouse gases. In the short run, economic growth had a positive and significant effect on methane emissions, but not on carbon dioxide and nitrous oxide emissions. These results highlight the importance of considering the relationship between economic growth, energy consumption and greenhouse gas emissions when developing environmental policies for African OPEC member countries.

Djoukouo (2021) studied the relationship between methane emissions and gross domestic product per capita (GDPC) in the CEMAC monetary union over the period 1980–2018. Using Driscoll and Kraay standard error techniques, they find an inverted U-shaped curve between the variables, supporting the EKC hypothesis. Moreover, the Granger causality test suggests a bidirectional causality between CH4 and GDPC in the CEMAC countries. These results have important policy implications, highlighting the need for policies that reduce the harmful effects of economic growth, such as investments in renewable energy sources and the adoption of environmental protection policies. This finding underscores the importance of strengthening sustainable strategies for economic growth and environmental conservation in the CEMAC region.

Doku et al. (2021) examined the role of climate finance on the environmental Kuznets curve for sub-Saharan Africa. Using panel data from 19 countries between 2006 and 2017, they found that climate finance had a significant impact on the reduction of pollutant emissions (CO2, CH4, N2O) in these countries. Inflection points were identified for per capita income and climate finance, suggesting a non-linear relationship between economic development, climate finance and pollutant emissions. These results highlight the importance of considering climate finance in mitigation and adaptation strategies in sub-Saharan Africa.

Ericsson (2022) explored the relationship between methane emissions and economic growth in the G20 countries using the theoretical framework of the EKC. A U-shaped relationship was found between methane emissions and GDP, suggesting that economic growth initially increases methane emissions, but then decreases after reaching a tipping point. These results suggest that the tipping point has not yet been reached in the countries studied. This study highlights the importance of considering the complex dynamics between economic growth and greenhouse gas emissions when designing effective environmental policies.

Fernández-Amador et al. (2022) analyzed the convergence dynamics of global methane emissions, considering both production and consumption emissions. Using global panel data for 66 countries and 12 composite regions from 1997 to 2014, they found that per capita methane emissions from production do not converge internationally in methane-intensive sectors such as livestock, energy, transportation, and public administration. However, per capita consumption-based emissions did converge across countries, suggesting that policies targeting consumption-based emissions may be more effective and equitable. These results highlight the importance of considering different production and consumption perspectives when designing climate policies to address global methane emissions.

Ramos et al. (2023) investigated the relationships between GDP per capita growth, CO2 emissions, methane emissions, and ecological footprint in the context of Colombia. Using an ARDL model for each indicator of environmental degradation, they found that economic growth has different effects on each indicator. While they did not find evidence of an inverted U-shaped relationship between CO2 emissions and GDP per capita, they did find that industrialization could contribute to a long-term reduction in CO2 emissions, provided that it does not lead to an increase in the use of energy from non-renewable sources. They also found statistical evidence supporting the EKC hypothesis for methane emissions and the ecological footprint in Colombia. These findings imply that economic growth can potentially improve environmental quality in terms of methane emissions and ecological footprint, underscoring the importance of promoting cleaner technologies and sustainable agricultural practices to achieve environmental sustainability in the country.

Magazzino et al. (2024) examined the determinants of global methane emissions using a panel data approach and machine learning techniques. A total of 192 countries were included in the analysis, covering an extensive period from 1960 to 2022. The results showed that variables such as central government debt, aggregate income, and unemployment rate had a positive impact on methane emissions, while domestic credit to the private sector, exports, unemployment rate, renewable energy consumption, urbanization, and voice and accountability were associated with a decrease in methane emissions. In addition, the Gini index was found to have no statistically significant relationship with environmental degradation. These findings highlight the importance of considering a wide range of factors when designing effective environmental policy strategies to address global climate change.

Methodology

Definition of variables and data

The variables considered were methane emissions from the energy sector, GDP per capita, renewable energy consumption, primary energy consumption, human development index, and trade openness. Table 1 and Fig. 1 summarize these variables.

Data were obtained from the World Bank[1] and the Groningen Growth and Development Centre (GGDC).[2] Data were collected for 35 OECD countries[3] (Australia, Belgium, Japan, Canada, Colombia, Denmark, Mexico, Estonia, Sweden, Finland, Austria, France, Slovenia, Greece, Germany, Hungary, Chile, Iceland, Israel, Switzerland, Ireland, South Korea, Luxembourg, Norway, the Netherlands, Italy, New Zealand, Portugal, Poland, the Slovak Republic, Spain, Turkey, the United Kingdom, and the United States) over the period 1990–2019. The database is organized in panels. It is a balanced panel because information is available for all cross-sectional units in all time periods. In addition, our panel is short because there are more data for cross-sectional units (countries) than for time (years).

Econometric strategy

Taking the basic structure of a panel model as a reference, and following Hsiao (2022), the econometric model must be estimated as follows:

$$\text{lnMethanepc}_{it} = \xi_0 + \beta_1\text{lnGDPper}_{it} + \beta_2\text{RE}_{it} + \beta_3\text{lnNRE}_{it} + \beta_4\text{HCI}_{it} + \beta_5\text{Trade}_{it} + u_{it} \quad (1)$$

where ξ_0 represents the constant term of the equation and the $\beta's$ represents the parameters of exogenous factors. Each cross-sectional unit (nation) and time period are denoted by subscripts i and t, respectively. The stochastic disturbance term is u_{it}.

In order to examine the relationship between the variables, we use the cointegration method of augmented panel ARDL. Specifically, we use the cross-sectional augmented ARDL (CS-ARDL) approach formulated by Chudik and Pesaran (2015). In addition, we use the methodology of Dumitrescu and Hurlin (2012) to identify causal relationships in the Granger sense. Our empirical strategy includes several steps.

Cross-dependency test (CDT)

The first step in any analysis using panel data is to determine whether there are interdependencies between the cross-sectional units. For this purpose, we use Pesaran's (2004) cross-dependence test (CDT). This test can be expressed mathematically as:

$$CDT = \sqrt{\frac{2T}{N(N-1)}}\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\widehat{\Theta}_{ij} \quad (2)$$

$CDT = 1, 2, 3, 4, 5 \cdots 35.$

$$M = \sqrt{\frac{2T}{N(N-1)}}\left(\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\widehat{\Theta}_{ij}\right)\frac{(T-k)\widehat{\Theta}_{ij}^2 - E(T-k)\widehat{\Theta}_{ij}^2}{Var(T-k)\widehat{\Theta}_{ij}^2} \quad (3)$$

The value $\widehat{\Theta}_{ij}^2$ denotes the residual association factor among sets of OLS residuals. H_0 should not be rejected if there is no cross-interdependence among the observations.

Slope non-heterogeneous test (SHT)

The assumption of slope homogeneity also needs to be checked in models using panel data. Normally, slopes are heterogeneous due to the intrinsic characteristics of countries. To verify this, we use the test of Pesaran and Yamagata (2008). This test is defined as follows:

$$\widetilde{\Delta}_{SHT} = (N)^{\frac{1}{2}}(2K)^{-\frac{1}{2}}\left(\frac{1}{N}\widetilde{E} - K\right) \quad (4)$$

$$\widetilde{\Delta}_{SHTadj} = (N)^{0.5}\left[\frac{2K(T-K-1)}{T+1}\right]^{-0.5}\left(\frac{1}{N}\widetilde{E} - K\right) \quad (5)$$

Where N and T denote the quantity of cross-sectional and temporal observations, respectively.

Random walk test

Once the above assumptions have been verified, the next step is to verify the order of integration of the variables. Classical tests such as the Dickey-Fuller or Phillips-Perron tests are used to do this. However, in the case of cross-interdependence and unequal slopes, these tests produce biased results. Therefore, we used the so-called "second generation tests". The best-known second-generation tests are the cross-sectionally augmented Dickey-Fuller (CADF) and the cross-sectionally augmented IPS (CIPS) tests introduced by Pesaran (2007). The latter has been shown to be more efficient than the CADF. The CIPS test can be represented as follows:

$$\Delta W_{i,t} = \varnothing_i + \varnothing_i Z_{i,t-1} + \varnothing_i \overline{Z}_{t-1} + \sum_{l=0}^{p}\varnothing_{il}\Delta\overline{W}_{t-1} + \sum_{l=0}^{p}\varnothing_{il}\Delta W_{i,t-1} + u_{it} \quad (6)$$

The mean value of the cross-sectional data is represented by the symbol $\overline{W}$, and is expressed as follows:

$$W^{i,t} = \phi^1\overline{\text{lnGDPper}}^{i,t} + \phi^2\overline{\text{RE}}^{i,t} + \phi^3\overline{\text{lnNRE}}^{i,t} + \phi^4\overline{\text{HCI}}^{i,t} + \phi^5\overline{\text{Trade}}^{i,t} \quad (7)$$

The CIPS test statistics are showcased in the following manner:

$$\widehat{CIPS} = N^{-1}\sum_{i=1}^{n}CADF_i \quad (8)$$

Where CADF stands for Cross-Sectionally Augmented Dickey-Fuller.

Cointegration test for panel data

Testing for cointegration is the next step after determining the order of integration of the variables. Several cointegration methods have been developed for panel data, such as Westerlund's (2007) approach, which is one of the most efficient in the presence of cross-interdependence and inhomogeneous slopes. Following Ahmad et al. (2020), the null hypothesis for the test is that there is no cointegration for at least one country for J_t and for all countries for P_t.

The mathematical representation of the cointegration test of Westerlund (2007) is as follows:

$$\varpi_i(A)\Delta y_{it} = \delta_{1i} + \delta_{2i}t + \varpi_i(y_{it-1} - \beta'_i x_{it-1} + \lambda_i(A)' v_{it} + e_{it}) \quad (9)$$

$$\delta_{1i} = \varpi_i(1)\varphi_{2i} - \varpi_i\varphi_{1i} + \varpi_i\varphi_{2i} and \delta_{2i} = -\varpi_i\varphi_{2i}$$

In the equation (9), ϖ_i denotes the vector of "long-term stable relationship" between the explained variable and the explanatory variables, while e_{it} is the non-determinist disturbance term. Statistical tests were performed as follows:

$$J_t = \frac{1}{N}\sum_{i=1}^{N}\frac{\varpi'_i}{SE(\varpi'_i)} \quad (9.1)$$

$$J_\varpi = \frac{1}{N}\sum_{i=1}^{N}\frac{T\varpi'_i}{\varpi'_i(1)} \quad (9.2)$$

$$P_t = \frac{\varpi'}{SE(\varpi')} \quad (9.3)$$

$$\varpi' = \frac{P_\varpi}{T} \quad (9.4)$$

[1] https://n9.cl/wzx5u.
[2] https://n9.cl/yvjti.
[3] The Czech Republic was omitted due to lack of information on methane emissions.

Table 1
Variables analyzed in the paper.

Variable	Abbreviation	Definition	Treatment	Source
Methane emissions	lnMethanepc	Methane emissions (thousands of tons CO2 equivalent per person) in the energy sector.	Natural logarithm	World Bank
GDP per capita	lnGDPper	GDP per capita (constant 2015 US$).	Natural logarithm	World Bank
Renewable energy consumption	RE	Consumption of renewable energy as a proportion of total energy consumption.	—	World Bank
Primary energy consumption	lnNRE	Primary energy consumption (kg oil equivalent per person).	Natural logarithm	World Bank
Human development index	HCI	A human capital index based on years of schooling and return to education.	—	Groningen Growth and Development Centre
Trade openness	Trade	Trade is the sum of imports and exports of products and offerings measured as a percent of gross home product.	—	World Bank

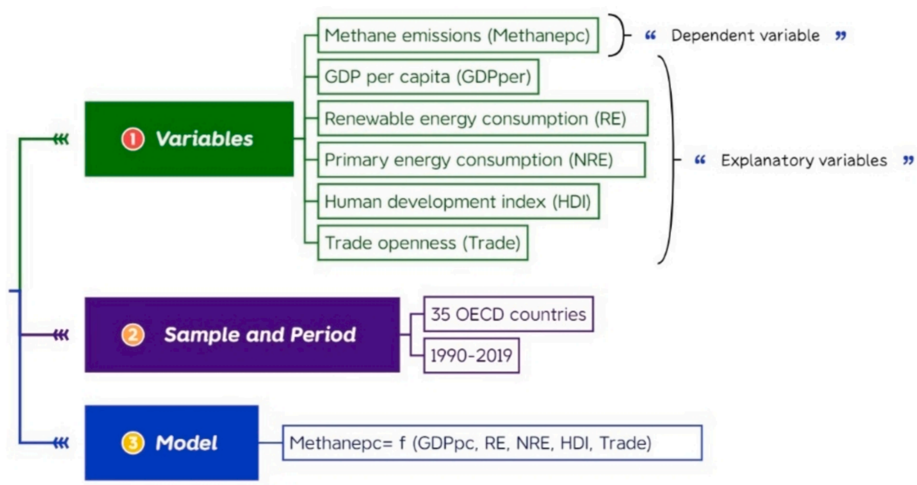

Fig. 1. Flow chart of variables and proposed model design.

Within the context above, J_t and J_ϖ denote group mean statistics, whereas P_t and P_ϖ stand for the panel statistics.

Estimation of coefficients for both short-term and long-term effects

We then examined the short- and long-term relationships between the variables studied. The literature emphasizes certain traditional methodological techniques such as FMOLS or DOLS. The disadvantage of these first-generation methods is that they do not take into account heterogeneous slopes or cross-dependencies between variables. Second-generation methods, such as the CS-ARDL process of Chudik and Pesaran (2015), have been developed to overcome these limitations. This approach also has the advantage of effectively addressing the endogeneity issues commonly present in this type of data, in addition to allowing the inclusion of variables integrated in different orders (Zambrano-Monserrate & Ormeño-Candelario, 2023; Zambrano-Monserrate, 2024; Chovancová et al., 2024; Yadav & Mahalik, 2024). We used this method in this investigation, which is described as follows:

$$\ln\text{Methanepc}_{it} = \alpha_0 + \sum_{j=1}^{p}\lambda_{it}\ln\text{Methanepc}_{i,t-j}PC + \sum_{j=1}^{p}\alpha'_{it}X_{t-j} + \sum_{j=0}^{3}\ddot{\upsilon}'_{it}\overline{Z}_{t-j} + \mu_{it} \quad (10)$$

Whereas $\overline{Z}_t = (\Delta\overline{\ln\text{Methanepc}_t},\overline{X}'_t) and X_{it} = (\ln\text{GDPper}_{it} + \text{RE}_{it} + \ln\text{NRE}_{it} + \text{HCI}_{it} + \text{Trade}_{it})'$ and X is a vector of explanatory variables.

Robustness test

Finally, this study employs the Augmented Mean Group (AMG) technique introduced by Eberhardt (2012) to examine the strength of the previously estimated equations. The main advantage of this method is that it is suitable for addressing the challenges of non-exogeneity, random walk, cross-sectional dependence, and heterogeneity that are often present in panel data analyses. As a result, the AMG method produces more accurate results than traditional methods. In addition, the AMG method takes into account cross-sectional correlation, which is a typical feature of panel data. Therefore, this technique offers significant improvements over the other methods. The equation for the AMG method is as follows:

$$\Delta\ln\text{Methanepc}_{it} = \phi_0 + \phi_1\Delta\ln\text{GDPper}_{it} + \phi_2\Delta\text{RE}_{it} + \phi_3\Delta\ln\text{NRE}_{it} + \phi_4\Delta\text{HCI}_{it} + \phi_5\Delta\text{Trade}_{it} + \sum_{t=2}^{T}p_t(AD_t) + \mu_{it} \quad (11)$$

The equation's first difference $T-1$ period dummy is denoted by the variable AD_t. Furthermore, the common dynamic process is represented by variable ω, which is substituted for p_t.

$$\Delta\ln\text{Methanepc}_{it} = \phi_0 + \phi_1\Delta\ln\text{GDPper}_{it} + \phi_2\Delta\text{RE}_{it} + \phi_3\Delta\text{NRE}_{it} + \phi_4\Delta\text{HCI}_{it} + \phi_5\Delta\text{Trade}_{it} + d_1(\lambda_t) + \mu_{it} \quad (12)$$

$$\Delta\ln\text{Methanepc}_{it} - \lambda_t = \phi_0 + \phi_1\Delta\ln\text{GDPper}_{it} + \phi_2\Delta\text{RE}_{it} + \phi_3\Delta\text{NRE}_{it} + \phi_4\Delta\text{HCI}_{it} + \phi_5\Delta\text{Trade}_{it} + \mu_{it} \quad (13)$$

In this study, ϕ_t was first included in the reconstruction of the regression model for group-specific variables. Then, the model means unique to each group are calculated. Fig. 2 summarizes the methodology used.

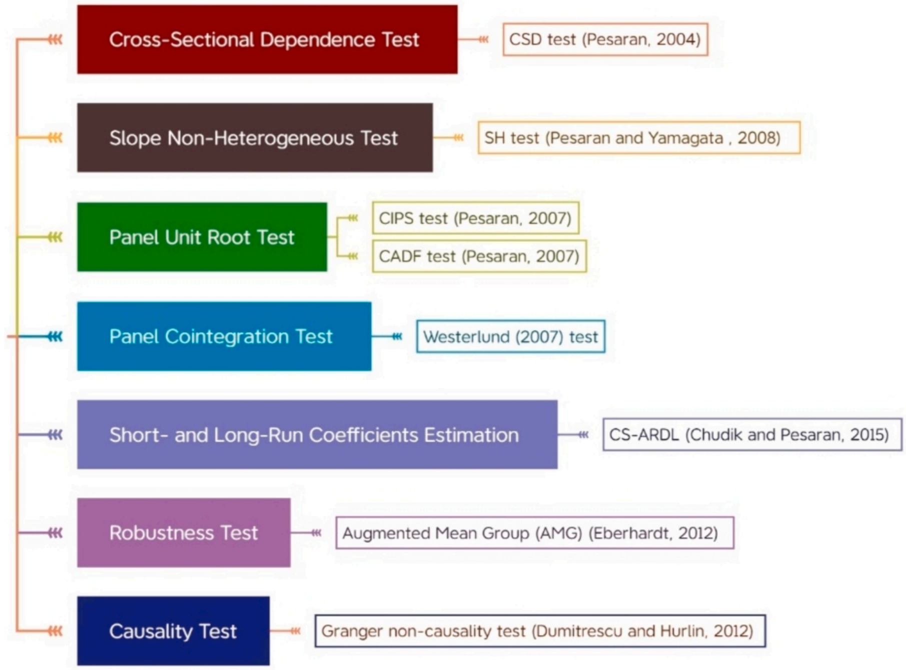

Fig. 2. Summary of the methodology used.

Results

Descriptive statistics

We begin our analysis of the results with the main descriptive statistics of the variables studied (Table 2). It was observed that methane emissions show a moderately high variation among countries, although the variations over time within the same country are relatively small. With respect to GDP per capita, there is also significant heterogeneity among countries, with an average of US$32900.13. In addition, the data show that some countries have a high use of renewable energy (62.37 %), while others have a minimal use (0.44 %). As for the Human Development Index, there is some variability among countries; however, over time, countries have shown constants trends in this indicator.

Fig. 3 shows the evolution of methane emissions in OECD countries. In most countries, CH4 emissions are stable. However, countries such as Australia and Israel have significantly increased their emissions in recent years. In contrast, some countries show a decreasing trend in CH4 emissions from the energy sector. These include Ireland and Hungary. It should also be noted that there are countries with methane emissions well above the average, such as Canada, Australia and the United States.

CDT and SHT results

The inferential analysis begins by analyzing the presence of cross-sectional dependence (CDT) in the data. For this purpose, we used Pesaran's (2004) test. The results are presented in Table 3.

The results show a high degree of correlation between the data. In fact, this correlation is significant at 1 %, suggesting that a shock occurring in one country with respect to one of the variables analyzed may affect other countries. There are several ways to interpret this finding. For example, the relationship between methane emissions and the environmental impact of other countries implies that the environmental policies of one country may affect other countries. The results also highlight the significant cross-sectional dependence between renewable energy consumption across countries, with a high and

Table 2
Main descriptive statistics.

Variable		Mean	Std. dev.	Min	Max
Methane emissions	overall	0.00024	0.00032	0.00002	0.00171
	between		0.00032	0.00005	0.00130
	within		0.00006	−0.00013	0.00066
GDP per capita	overall	32900.13	20936.38	4735.93	112417.90
	between		20337.44	7853.01	94325.19
	within		5633.98	4602.02	63557.61
Renewable energy consumption	overall	16.00	13.41	0.44	62.37
	between		12.87	1.35	58.87
	within		4.35	−0.52	35.96
Primary energy consumption	overall	4219.73	1927.43	939.52	9428.81
	between		1928.27	1235.35	8204.17
	within		374.13	2344.87	5590.87
Human development index	overall	3.10	0.40	1.80	3.73
	between		0.38	2.04	3.60
	within		0.14	2.64	3.49
Trade openness	overall	77.83	53.71	15.81	377.84
	between		51.72	25.12	270.63
	within		17.71	−11.40	185.04

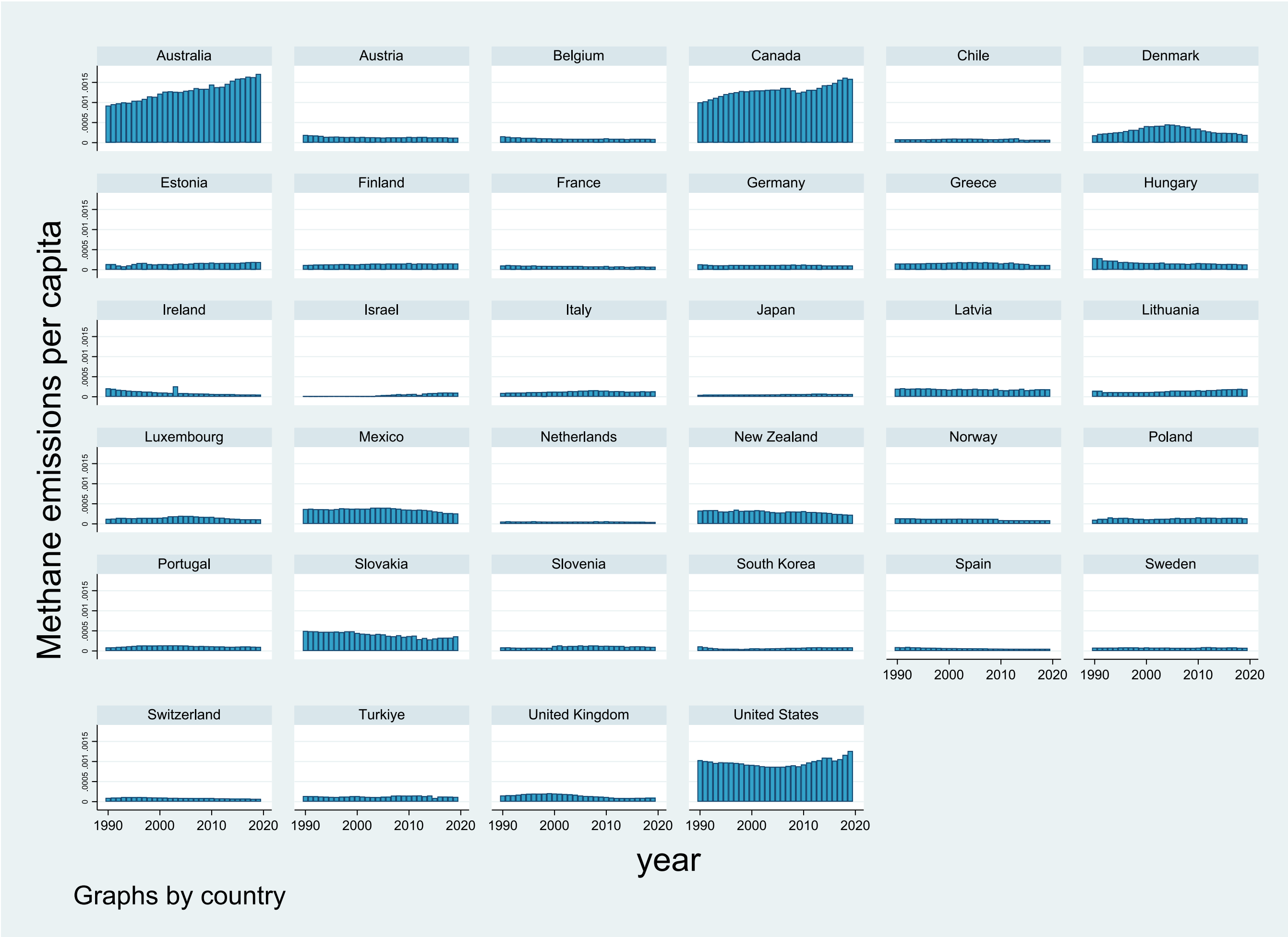

Fig. 3. Evolution of methane emissions.

Table 3
CDT results.

Variables	CDT	p-value	Association index
lnMethanepc	13.64	0.000*	0.481
lnGDPper	45.23	0.000*	0.634
RE	40.28	0.000*	0.586
lnNRE	51.36	0.000*	0.746
HCI	74.58	0.000*	0.456
Trade	42.55	0.000*	0.705

* Significant at 1 %.

statistically significant value of 0.586. In addition, the level of human development in a given country is influenced by the level of development of neighboring countries.

The results of the heterogeneous slope tests are presented in Table 4. H_0, which states that the slope coefficients are uniform at the 1 % level, is rejected, indicating that the regression slopes for each country are statistically unique.

Table 4
SHT results.

	Statistics	Associated p-value
$\tilde{\Delta}_{SHT}$	28.367	0.000*
$\tilde{\Delta}_{SHTadj}$	33.549	0.000*

Note: * Significant at 1%.

Random walk tests

As noted above, the random walk and cointegration tests that should be used in panel data analysis depend on the existence of cross-sectional dependence and slope heterogeneity. Thus, second-generation tests are suggested. Therefore, we use the CADF and CIPS unit root tests described in the previous section. The results of these tests are reported in Table 5.

Table 5
Random walk tests.

Variable type	Level	First-difference	Conclusion
CADF			
lnMethanepc	0.653	5.358*	All variables are integrated of order 1.
lnGDPper	0.034	6.354*	
RE	0.246	4.597*	
lnNRE	0.379	5.346*	
HCI	0.567	5.984*	
Trade	0.454	2.569**	
CIPS			
lnMethanepc	0.236	4.569*	All variables are integrated of order 1.
lnGDPper	0.018	5.374*	
RE	0.159	3.586*	
lnNRE	0.224	4.997*	
HCI	0.397	4.364*	
Trade	0.334	1.994***	

Note: *, **, and *** indicate significance at the 1%, 5%, and 10% levels, respectively.

The results of the random walk tests indicate that the variables are of first order integration, which means that they are stationary in first difference. These results allow the CS-ARDL approach to be applied without difficulty.

Westerlund's cointegration test

After defining the integration orders of the variables, the next step was to perform the cointegration test. Table 6 shows the results of Westerlund's (2007) test, which is based on the group mean (J_t, J_ϖ) and panel (P_t, P_ϖ) statistics. In each case, the H_0 of no cointegration was not accepted, which rules out possible spurious relationships between the variables.

Short- and long-run estimates and robustness test

Once possible, spurious relationships are ruled out, and estimation of the short-run and long-run coefficients is the next step. Table 6 shows the estimates. In general, the coefficients have the expected signs and most of the variables are significant.

The results in Table 7 show that GDP increases methane emissions in the short run. Thus, a 1 % increase in GDP translates into a 0.08 % increase in CH4 emissions. However, in the long term, the effect of GDP on methane production was not significant. A positive relationship between CH4 and economic growth has been demonstrated in previous studies such as Subramaniam and Masron (2019), Fernández-Amador et al. (2022), and Magazzino et al. (2024).

Conversely, the consumption of renewable energy reduces methane emissions. This effect is significant in both the short and long runs. Thus, a 1 % increase in clean energy consumption counteracts CH4 emissions by 0.89 % in the long term. Our results are consistent with those of Doku et al. (2021), but contradict the findings of Ericsson (2022).

In contrast, an increase in primary energy consumption increases CH4 emissions. The long-term elasticity coefficient is higher than the short-term elasticity coefficient. Other studies have reported similar results (Shittu et al., 2018; Adeel-Farooq et al., 2020; Tarazkar et al., 2021). However, our results contradict those of Yusuf et al. (2020) and Acevedo-Ramos et al. (2023).

We also found that human development had a positive impact on the environment. A significant effect was observed in both the short and long term. In fact, the effect is even larger in the long run. Previous research (Subramaniam & Masron, 2019) has also shown that human capital (education) has a positive impact on the environment.

In addition, trade liberalization increases methane emissions. However, the effect is not statistically significant. Our results are consistent with those of Adeel-Farooq et al. (2020) and Ericsson (2022). However, our results are inconsistent with those of Benavides et al. (2017).

The error correction terms for the short-run equations are listed in Table 7. The following interpretation of the figure −0.4867 is possible: each year the deviations from the short-run equilibrium are corrected by about 48 %.

Table 7 shows the results for the AMG estimator. Recall that this estimator serves as a robustness test for the CS-ARDL method estimates. The results effectively validate the previous short-run and long-run estimates. Finally, the White and Wooldridge tests show that there are no problems with heteroscedasticity or autocorrelation in the estimated model.

Table 6
Cointegration test.

Parameter	Value	Associated p-value
J_t	−2.947**	0.038
J_ϖ	−2.889**	0.044
P_t	−2.194***	0.068
P_ϖ	−2.108***	0.082

Note: *, **, and *** indicate significance at the 1%, 5%, and 10% levels, respectively.

Causality analysis

The results of the CS-ARDL approach do not indicate that one variable causes another variable. Therefore, we conducted a non-causality test (Table 8). The results of this test form the basis for policy recommendations.

The results are mixed. However, there was a tendency for bidirectional causality between the variables. For example, renewable energy consumption reduces CH4 emissions. However, reducing methane emissions also has a positive effect on renewable energy consumption. Consequently, policies against methane emissions have a significant impact on renewable energy consumption. Similarly, there is a double causality between CH4 and primary energy consumption. Therefore, a decrease in methane emissions would lead to a decrease in non-renewable energy consumption.

Similarly, human capital causes methane emissions with feedback effects. Methane is a potent greenhouse gas that has a major impact on temperature and climate events, leading to losses in productive sectors. In addition, the most vulnerable populations face enormous challenges in terms of health, access to basic services, and resilience to climate change. However, the finding that human capital also causes methane emissions implies that policymakers should promote investment in education. Future human capital should mitigate CH4 emissions by developing and implementing new technologies in the energy sector.

On the other hand, GDP causes methane emissions, but there is no reverse effect. Policymakers can support policies to reduce methane emissions without compromising their countries' economic growth. This result contradicts the findings of Djoukouo (2021). Finally, there is no evidence of causality between CH4 and trade. This somewhat corroborates the CS-ARDL model estimates that trade has a positive effect on methane emissions, although the effect is not significant. Fig. 4 summarizes these causal relationships.

Discussion and policy implications

Methane is the second most important greenhouse gas after carbon dioxide (CO2). It absorbs solar radiation more effectively than carbon dioxide but has a far shorter atmospheric persistence. However, CH4 has almost 25 times the environmental impact of CO2 over a 100-year period (EPA, 2022). Despite the relevance of this topic to the scientific community, few studies have analyzed the variables that enhance or decrease its production, specifically in the energy sector.

Hence, this paper aimed to provide fresh evidence of the variables affecting methane emissions in 35 OECD countries. To achieve this, we first identified the countries with the highest methane emissions, namely Australia, Canada, and the United States, while Israel and Japan had the lowest pollution levels. Our main findings show that economic growth has a significant and positive impact on CH4 emissions, but only in the short term. This suggests that countries may be approaching a tipping point towards sustainable development. Furthermore, we found no causal relationship between methane emissions and GDP. Consequently, reducing CH4 emissions should not hinder economic growth in OECD countries.

On the other hand, we found that increasing renewable energy reduces CH4 emissions. The evidence is strong, especially in the long run. Moreover, the existence of dual causality between these variables implies that methane reductions lead countries to transition to cleaner energy sources. In contrast, we find no significant effect of trade openness on methane emissions. Granger causality tests confirm these findings.

Our results also highlight the importance of human capital as a mitigating factor for CH4 emissions. Indeed, we show that an increase in the Human Development Index reduces methane pollution.

Table 7
CS-ARDL method and robustness test.

	CS-ARDL			Robustness test (AMG estimator)			
Variables	Betas	S.E.	z	Variables	Betas	S.E.	z
Short-term estimates							
lnGDPper	0.0823*	0.0234	3.52	lnGDPper	0.0542***	0.0299	1.81
RE	−0.7566**	0.2567	−2.95	RE	−0.8047**	0.2704	−2.98
lnNRE	0.3091***	0.1534	2.01	lnNRE	0.3946***	0.2185	1.81
HCI	−0.5239*	0.1288	−4.07	HCI	−0.6044*	0.1462	− 4.13
Trade	0.0054	0.1581	0.03	Trade	0.0012	0.1794	0.01
ECM (−1)	−0.4867*	0.0846	−5.75	Constant	−1.9623	1.5543	−1.26
Long-term estimates							
lnGDPper	0.0352	0.0255	1.38				
RE	−0.8944*	0.2654	−3.37				
lnNRE	0.4558***	0.2199	2.07				
HCI	−0.6853*	0.1359	−5.04				
Trade	0.0024	0.1654	0.01				
Diagnostic tests							
Heteroscedasticity							
White's test	56.32*						
Autocorrelation							
Wooldridge test	34.622*						

Note: *, **, and *** indicate significance at the 1%, 5%, and 10% levels, respectively.

Table 8
Granger non-causality test by D&H (2012).

Causality between variables	Z-bar	Associated p-value	Decision
lnGDPper ↛ lnMethanepc	7.33*	0.000	lnGDPper→lnMethanepc
lnMethanepc ↛ lnGDPper	0.82	0.567	
RE ↛ lnMethanepc	4.36*	0.000	RE ↔ lnMethanepc
lnMethanepc ↛ RE	8.36*	0.000	
lnNRE ↛ lnMethanepc	6.57*	0.000	lnNRE ↔ lnMethanepc
lnMethanepc ↛ lnNRE	5.77*	0.002	
HCI ↛ lnMethanepc	10.25*	0.000	HCI ↔ lnMethanepc
lnMethanepc ↛ HCI	4.55*	0.005	
Trade ↛ lnMethanepc	0.56	0.501	Non-causality in any sense.
lnMethanepc ↛ Trade	0.44	0.649	

Note: *, **, and *** indicate significance at the 1%, 5%, and 10% levels, respectively. → (unidirectional causality) ↔ (bidirectional causality).

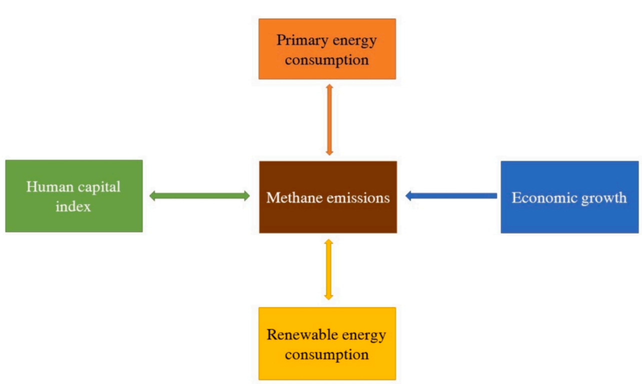

Fig. 4. Results of the Granger's non-causality test.

Furthermore, we show that if countries do not commit to reducing their CH4 emissions, their human capital could be at risk, especially in vulnerable areas.

Placing these findings in a global context, it is important to consider that methane not only contributes to climate change but also affects air quality and human health. Transitioning to renewable energy sources and enhancing human capital are not only environmental goals but also broader sustainable development goals in line with the UN Sustainable Development Goals (SDGs), in particular SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action).

The role of economic growth in methane emissions highlights the need for economic models that integrate environmental sustainability. In many countries, economic growth has traditionally been associated with increased fossil fuel use, leading to higher methane emissions (Fernández-Amador et al., 2022; Magazzino et al., 2024). However, our study suggests that economies may be moving towards a phase where growth is not necessarily associated with higher emissions, reflecting a possible decoupling between economic growth and greenhouse gas emissions.

Reducing methane emissions through the deployment of renewable energy has positive implications not only for global climate change, but also for energy security and economic independence (Djoukouo 2021). Investment in renewable technologies can create jobs, foster technological development and enhance energy security, which is particularly important in the current global context, where the climate crisis and the need for sustainable economic recovery are priorities.

Improving human capital by raising the Human Development Index not only helps reduce emissions, but also makes communities more resilient to the impacts of climate change (Subramaniam & Masron, 2019). In vulnerable regions, higher human development can facilitate the adoption of sustainable practices and clean technologies, and improve the ability of populations to adapt to adverse environmental changes.

Our findings allow us to recommend specific policy actions for OECD countries. Governments (especially in the most polluting countries) should seek mechanisms to reduce methane emissions in the energy sector. As mentioned above, one alternative identified in this study is the promotion of renewable energy. When renewable energy, such as solar, wind, or hydroelectric power, is used instead of fossil fuels, such as oil and natural gas, the need to extract, process, and burn these fuels is reduced. This means that there is less opportunity for methane to escape during the extraction and transportation of fossil fuels. Similarly, another way to reduce CH4 emissions is to increase human capital. Promoting human development can create the social, economic, and educational conditions necessary to encourage more sustainable behavior and reduce methane emissions in the long term. Therefore, investing in human development can be an effective strategy for addressing both environmental and social concerns.

This paper has some limitations that should be taken into consideration. First, our results are based on data from a specific set of countries;

therefore, caution should be exercised in generalizing our findings. In addition, we only assessed the impact of the independent variables on average CH4 emissions. However, it is important to note that the effects of these variables could differ across quantiles, an aspect that was not addressed in this study. Further research could address these limitations by expanding the analysis to different countries and using additional methodologies to examine how the variables studied affect different levels of CH4 emissions. In addition, it would be important to examine other factors, such as policies and technological advances, that may influence methane emissions from the energy sector.

CRediT authorship contribution statement

Jana Chovancová: Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Funding acquisition, Formal analysis. **Manuel A. Zambrano-Monserrate:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Formal analysis, Data curation, Conceptualization, Investigation, Project administration. **Brahim Bergougui:** Methodology, Investigation, Formal analysis, Conceptualization, Writing – review & editing. **Isaac Ahakwa:** Software, Writing – original draft, Writing – review & editing. **Mehmet Metin Dam:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization, Data curation, Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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