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Exploring the determinants of methane emissions from a worldwide perspective using panel data and machine learning analyses☆

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ABSTRACT

This article contributes to the scant literature exploring the determinants of methane emissions. A lot is explored considering CO_2 emissions, but fewer studies concentrate on the other most long-lived greenhouse gas (GHG), methane which contributes largely to climate change. For the empirical analysis, a large dataset is used considering 192 countries with data ranging from 1960 up to 2022 and considering a wide set of determinants (total central government debt, domestic credit to the private sector, exports of goods and services, GDP per capita, total unemployment, renewable energy consumption, urban population, Gini Index, and Voice and Accountability). Panel Quantile Regression (PQR) estimates show a non-negligible statistical effect of all the selected variables (except for the Gini Index) over the distribution's quantiles. Moreover, the Simple Regression Tree (SRT) model allows us to observe that the losing countries, located in the poorest world regions, abundant in natural resources, are those expected to curb methane emissions. For that, public interventions like digitalization, green education, green financing, ensuring the increase in Voice and Accountability, and green jobs, would lead losers to be positioned in the winner's rankings and would ensure an effective fight against climate change.

1. Introduction

Climate change is a real-world problem, faced by all countries at the same time, and with extreme weather events being felt each time stronger. Therefore, fighting climate change and achieving environmental quality imposes a worldwide compromise to reduce emissions. Like carbon dioxide (CO_2), methane (CH_4) is a greenhouse gas (GHG), whose amount in the atmosphere has increased lately due to human activity, enhancing the climate change problem. In the IPCC et al. (2013) report it may be read that methane is particularly problematic as its impact is 34 times greater than CO_2 over 100 years. More recently, in the IPCC AR6 (2021), the global warming potential for CH_4 is given as 81.2 and 27.9 for the 20-year and 100-year time horizon. Most of human-made methane emissions come from fossil fuel production like natural gas. Livestock digestive processes and landfills emit methane as waste decomposes, being two other top sources. UNEP (2022) further states that methane is responsible for more than 25 percent of global warming, being a potent greenhouse gas. Methane traps more heat in the atmosphere per molecule than carbon dioxide, and it is 80 times more harmful than CO_2 for 20 years after it is released (UNEP, 2022).

Abbreviations: ANN, Artificial Neural Networks; ARDL, AutoRegressive Distributed Lags; BRICS, Brazil, Russia, India, China, and South Africa; CH_4, methane; CO_2, carbon dioxide; CV, Cross-Validation; DCCE, Dynamic Common Correlated Effects; EKC, Environmental Kuznets Curve; ENR, Elastic Net Regularization; FGLS, Feasible Generalized Least Squares; FMOLS, Fully Modified Ordinary Least Squares; GBT, Gradient Boosted Tree; GDP, Gross Domestic Product; GHG, Greenhouse Gas; GMM, Generalized Method of Moments; LR, Linear Regression; MAE, Mean Absolute Error; MENA, Middle East and North Africa; MG, Mean Group; ML, Machine Learning; MSD, Mean Signed Difference; MSE, Mean Standard Error; OPEC, Organization of the Petroleum Exporting Countries; PCSE, Panel-Corrected Standard Errors; PMG, Pooled Mean Group; PNN, Probabilistic Neural Networks; PQR, Panel Quantile Regression; PR, Polynomial Regression; R&D, Research and Development; RFR, Random Forest Regression; RMSE, Root Mean Square Error; RR, Ridge Regression; SRT, Simple Regression Tree; TER, Tree Ensemble Regression; VECM, Vector Error Correction Model; WB, World Bank; WDI, World Development Indicators.

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Additionally, Djoukouo (2021) stated that CH_4 is a GHG with a warming potential 28 times higher than that of CO_2 while exploring the relationship between CH_4 emissions and economic growth in Africa.

Despite the highest CH_4 reported impact, much of the literature on convergence has focused on CO_2 emissions. Concentrating on other potent GHG emissions provides further insights into the factors that influence them allowing policymakers to formulate policies able to positively contribute to the fighting of climate change. Previous and current research emphasizes CO_2 emissions rather than other GHG, even if methane is as significant as CO_2 (e.g., Ratna et al., 2023). Indeed, methane emission is accelerated by both the industrial and agriculture sectors and economic growth has been used by several authors as a vital variable driving environmental pollution. For example, China's abandoned mine methane emissions are equivalent to one-third of China's CO_2 emissions in 2060, under a carbon-neutral scenario (Chen et al., 2022). In South Africa, cattle methane is one of the main sources of greenhouse gas emissions (Mphethe, et al., 2021).

Many have been the determinants identified and explored in the literature as exerting effects over emissions. Ivanovski and Churchill (2020) investigated the convergence process of carbon dioxide, nitrous oxide, and methane emissions at the regional level over the period 1990 to 2017. For Australian regions, it is found that state income per capita, urbanization, and international trade play a crucial role in the convergence path of GHG emissions. Increases in urbanization lead to higher energy consumption demands, and GHG emissions are higher in densely inhabited areas (Ivanovski and Churchill, 2020; Shahbaz and Sinha, 2019; Liu et al., 2019; Shahbaz et al., 2017). Ari and Şentürk (2020) argue that urbanization affects methane emissions from solid waste negatively in G7 countries, finding evidence of an inverted N-shaped curve between methane emissions and per capita Gross Domestic Product (GDP). Alhassan and Kwakwa (2023) studied the effect of natural resource extraction and government debt on CO_2 emissions using the Fully Modified Ordinary Least Squares (FMOLS) model with Ghana data while testing the Environmental Kuznets Curve (EKC) hypothesis. Climate-related damages (e.g., floods and wildfires) affect public debt considering financial recovery help that is provided to households, firms, and local governments (Alhassan and Kwakwa, 2023). Effective governance systems and sustainable urbanization strategies can enhance carbon neutrality (Kakar et al., 2023; Dash et al., 2020). The institutional framework was proven to directly affect CO_2 emissions (Granoff et al., 2016) and to moderate the financial development impact through funds channeling to energy-efficient projects (Hasni et al., 2023; Kumar et al., 2021; Omri et al., 2021).

Conclusions from many of the above-mentioned studies indicate the need to empirically include other variables not yet considered. In our study we use 192 countries, considering the largest possible and available data span (from 1960 until 2022) provided by the World Bank (WB). The paper's contribution to the literature is as follows. First, we contribute to the literature examining methane emission determinants, whereas most of the previous empirical applications available concentrate on CO_2 emissions. Second, while research indicates the need to reduce GHG emissions, empirical research concentrates on a reduced group of countries, or individual and specific countries. Being a worldwide problem the fight for carbon neutrality, demands a general analysis of methane emission determinants. We have used all countries in the world whose data were available covering all continents. The economic structure of these countries is different provided they have achieved different development stages. Third, by including a large set of determinants, like unemployment (Xin et al., 2023) which is less explored, and Voice and Accountability, not included in this type of study previously as far as we are aware. Chhabra et al. (2023) studied the impact of trade openness and institutional quality on CO_2 emissions in Brazil, Russia, India, China, and South Africa (BRICS) from 1991 to 2019, using the created indexes of institutional quality, political stability, and political efficiency to measure the overall institutional impact on emissions using a Dynamic Common Correlated Effects (DCCE) method. Higher-quality institutions promote renewable energy allowing to development and adoption of greener technologies, favoring knowledge spillovers, and encouraging and leading to environmental improvements (Haldar and Sethi, 2021; Khan and Rana, 2021; Ali et al., 2019) or not (Azam et al., 2021; Teng et al., 2021). Still, this mixed evidence cares only for CO_2 emissions. Fourth, we apply ML methodologies considering possible heterogeneity and endogeneity problems for using 192 countries at once in the analysis. Results indicate we should use and include all regressors (central government debt, domestic credit to the private sector, exports of goods and services, GDP per capita, unemployment, renewable energy consumption, urbanization, Gini Index, and Voice and Accountability). Finally, by applying the Simple Regression Tree (SRT) model we can identify losing (countries for which increased methane emissions are predicted) and winning (those for which reduced methane emissions are predicted) countries, providing important guidelines for policymakers while implementing environmental policies. This will allow them to effectively fight climate change by positioning losers in the winners' rankings.

The rest of the article develops as follows. Section 2 provided a literature review summary of the determinants of emissions, ending by exposing the known articles concentrating on methane emissions. Section 3 presents the data, and Section 4 presents the main results while discussing their implications. Finally, Section 5 concludes this work and provides useful policy recommendations.

2. Literature review

GHG emissions are the product of economic activities that are necessary for development and growth. However, if this growth cannot be done sustainably worldwide, fighting climate change efforts will be inadequate.

2.1. Methane emissions importance and impacts

Methane has greater warming potential than CO_2 being a significant GHG source. Even so, most of the literature exploring the determinants of emissions concentrates on CO_2. Thus, this paper aims to contribute to the literature on methane emission determinants considering total central government debt, domestic credit to the private sector, exports of goods and services, GDP per capita, total unemployment, renewable energy consumption, urban population, Gini Index, and Voice and Accountability variables.

Methane emissions result from a complex interplay of various natural and anthropogenic factors. Understanding these determinants is essential in mitigating their impact on climate change.

- Fossil fuel production: a significant contributor to methane emissions is the extraction, processing, and distribution of fossil fuels. Methane often escapes during drilling, transportation, and storage of natural gas and oil.
- Agriculture: agricultural practices, particularly livestock production and rice cultivation, release substantial methane. Microbes in the stomachs of ruminant animals produce methane during digestion, while flooded rice paddies create anaerobic conditions that foster methane-producing bacteria.
- Wetlands: natural wetlands are a natural source of methane due to anaerobic conditions in waterlogged soils. However, human activities like draining wetlands for agriculture or urban development can alter these emissions.
- Landfills: landfills are a notable source of anthropogenic methane emissions. The decomposition of organic waste in the absence of oxygen generates significant amounts of methane.
- Energy production: methane emissions occur in the production and distribution of energy, including coal mining and natural gas power plants. Poorly managed infrastructure can leak methane into the atmosphere.

- Deforestation: deforestation and land-use changes can indirectly affect methane emissions by altering ecosystems and water tables, influencing methane production and release from soils.
- Livestock management: livestock practices, such as manure management and enteric fermentation, can be mitigated through improved management and dietary changes.
- Waste management: proper waste management practices, like methane capture at landfills or wastewater treatment facilities, can significantly reduce methane emissions.
- Methane hydrates: methane hydrates in the oceans and polar regions represent a potentially massive, but currently untapped, source of methane emissions if disturbed due to climate change or resource extraction.
- Climate change feedback loops: rising temperatures can trigger positive feedback loops, releasing more methane. For example, thawing permafrost can release stored methane, exacerbating global warming.

Efforts to curb methane emissions range from improving energy infrastructure to sustainable agricultural practices and waste management, all aimed at mitigating the impact of this GHG on climate. Green technologies play a pivotal role in enhancing natural resource management efficiency and curbing methane emissions, contributing to a more sustainable and environmentally responsible future. These innovative technologies encompass a wide array of solutions that prioritize renewable energy sources, energy efficiency, and resource conservation. By harnessing clean energy sources like solar, wind, and hydroelectric power, a country can reduce its dependence on fossil fuels and mitigate the environmental impact of energy production. In parallel, advancements in energy-efficient technologies and practices enable us to optimize the use of resources while minimizing waste and emissions. In particular, green technologies hold great potential in mitigating methane emissions which often result from industrial processes, agriculture, and waste management. Implementing technologies such as anaerobic digesters, which capture methane from organic waste, and precision agriculture methods that reduce methane-producing practices in farming, offers promising solutions. When incorporated into broader resource management strategies, these green technologies not only lower emissions but also enhance resource utilization efficiency. Embracing such innovations is not just an environmental imperative but a prudent pathway to a more sustainable and resilient future. Ali et al. (2023) found that urbanization increases carbon emissions intensity in Saudi Arabia, while technological innovation decreases it. Mehmood et al. (2024) found that technological innovation drives greener industry and environmental regulation in Pakistan. These different viewpoints lead us to revisit the determinants of emissions, from a worldwide perspective, this turn considering CH_4 for its relevance despite being rarely considered in the previous literature.

Climate change implies the deterioration of human and social development potentials, hindering economic growth and development (Chen et al., 2022). Whereas carbon emissions account for almost half of global air pollution, methane is the main ground-level ozone source. Considering that most of the existent empirical literature studies concentrate on CO_2 emission determinants (as a GHG measure), this study extends the literature using methane as a GHG measure. Table 1 summarizes the literature found whose dependent variable used was methane.

2.2. The ground backs of (methane) emissions determinants

GDP growth and industrialization in developing economies increase CO_2 emissions (Sikder et al., 2022), with recent research evidencing that emerging markets and developing countries account for more than two-thirds of global CO_2 emissions (Gielen et al., 2019). The environmental pollution theory allows us to analyze the nexus between emissions and economic indicators like some of those used in this article:

Table 1
Summary of existing literature on methane emissions.

Author(s)	Region	Period	Variables	Methodology
Liu et al. (2019)	Shanghai (China)	April and May 2014	Land cover, population, road and traffic, planetary boundary layer height, land surface temperature	Lindemand-Merenda-Gold (LMG) metric
Nguyen et al. (2021)	89 countries	1995–2012	Income, economic integration, trade, FDI, energy consumption, agriculture value-added	Dynamic fixed effects ARDL
Ari and Şentürk (2020)	G7 countries	1960–2016	GDP, GDP^2, GDP^3, urbanization	Panel ARDL, MG, PMG
Akintande et al. (2020)	5 African countries	1996–2016	RE consumption, population growth, electricity power consumption, energy use, oil demand, GDP, CO2 emission growth, Government effectiveness, natural gas, external debt	BMA
Ivanovski and Churchill (2020)	Australian regions	1990–2017	Gross state product per capita (GSP), GSP^2, urbanization, trade, industry structure	β- and σ-convergence tests; log-t-test; Logit; AME
Zeraibi et al. (2023)	6 African OPEC countries	1970–2016	Energy consumption, GDP, GDP^2	Panel ARDL, MG, PMG
Beşe, et al. (2021)	India	1971–2012	Total external debt, economic development (GDP pc), GDP^2, energy consumption	ARDL
Djoukouo (2021)	6 Central African EMCC	1980–2018	GDP, GDP^2 (EKC hypothesis)	Panel regression with Driscoll-Kraay; DHC
Tarazkar et al. (2021)	110 OPEC countries	1995–2012	GDP, GDP^2, GDP^3, crop and livestock production, economic growth, energy consumption	DOLS, ECM
Ahmed et al. (2023)	China, India, the USA, Russia	1990/ 1992–2018; (/Russia)	Coal, petroleum liquids, natural gas, RE Consumption	Advanced Machine Learning methods ([a])
Ratna et al. (2023)	Bangladesh	1986–2018	Livestock index, GDP per capita	VECM

Notes: AME: Average Marginal Effects; ARDL: Auto-Regressive Distributed Lags; BMA: Bayesian Model Averaging; DHC: Dumitrescu-Hulin Causality; DOLS: Dynamic Ordinary Least Squares; EMCC: Economic and Monetary Community Countries; FDI: Foreign Direct Investments; FGLS: Feasible Generalized Least Squares; FMOLS: Fully Modified Ordinary Least Squares; GC: Granger Causality; GDP: Gross Domestic Product; MG: Mean Group; PCSE: Panel-Corrected Standard Errors; PMG: Pooled Mean Group; PQR: Panel Quantile Regression; RE: Renewable Energy; TYC: Toda-Yamamoto Causality; VECM: vector error correction model.

[a] These include Support Vector Machines, Artificial Neural Networks, and Long-Short Term Memory.

GDP per capita, unemployment, and urbanization. Following the EKC hypothesis, as the economic growth of a country increases, its ability to surpass the level of environmental degradation generated in the early stages of development increases (inverted U-shaped relationship). Income growth is linked to economic growth and as such factors like industrialization, population growth, and urbanization should be considered in the equation to avoid potential variable bias (Abbasi et al., 2021). Salari et al. (2021) argued that although increased energy use can lead to higher carbon emission levels if renewable sources are used these can be important in curbing rising carbon levels moving forward. Outcomes from empirical research vary because of different econometric techniques employed, regions, countries, institutions, variable proxies, and periods used (Uma et al., 2023). However, it is generally found that increased economic growth demands more fossil fuel energy consumption, increasing temperature, and deteriorating environmental quality. Thus, an increase in output is a severe threat to the environment (Uma et al., 2023; Alhassan and Kwakwa, 2023; Ali et al., 2020). Yusuf et al. (2020) explored the relationship between GHG (nitrous oxide, CO_2, and methane), energy consumption, and output growth using a sample of 6 African Organization of the Petroleum Exporting Countries (OPEC) countries. Empirical estimations using the panel AutoRegressive Distributed Lags (ARDL) model using Mean Group (MG) and Pooled Mean Group (PMG) estimators revealed an increase in CO_2 and methane emissions with increased economic growth. The literature also evidences that economic growth and methane emissions nexus improve as countries reach higher income levels, but the magnitude of the improvement remains low. This leads to very small methane-efficiency gains from economic development (Fernández-Amador et al., 2018).

Natural resources and debt effects have received increased attention recently (Auteri et al., 2024; Alhassan and Kwakwa, 2023). Government debt puts pressure on environmentally friendly investments, innovation, and technology adoption (Boly et al., 2022; Zhao and Liu, 2022) once it may reduce renewable energy development (Alhassan and Kwakwa, 2023; Zhao and Liu, 2022), and this depends on the development stage of the country (Sommer et al., 2020; Didia, 2001). However, the literature also finds that public debt may reduce CO_2 emissions (Zeraibi et al., 2023) when emerging countries are considered. To ensure the right policy formulation it is necessary to know the exact effect of government debt on environmental quality. Previously, considering heavily indebted poor countries, Akam et al. (2021) found that external debt increases carbon dioxide emissions, a similar result to that found for South Africa and Algerian economies (Akam et al., 2022). Zhao and Liu (2022) found contradictory results dependent on the development stage of the country. The authors clarified that debt increases carbon emissions in emerging countries, but that debt structure reduces carbon emissions when advanced economies are included in the equation. However, when ignoring the development of a country, the general conclusion is that debt leads to higher carbon emissions. Beşe et al. (2021) confirmed the positive and significant effect of external debt on CO_2 and CH_4 emissions in India. Finally, Han et al. (2024) found that government debt does not impact efforts to reduce emissions, deviating financial resources in China, India, Pakistan, and Kazakhstan.

For eighteen different Asia-Pacific economies, Hasni et al. (2023) explore the influence of renewable energy consumption, economic growth, financial development index, Z-score, and control of corruption on CO_2 emissions using the PMG-ARDL model and Granger causality tests. Both economic growth and renewable energy seem to increase carbon emissions, whereas financial development, *Z*-score, and carbon emissions seem to decrease them. It is common in the literature to use domestic credit to the private sector as a share of GDP as a proxy for the degree of financial development (Hasni et al., 2023; Magazzino, 2018). However, different results are being reported in the empirical literature, namely, positive effects on carbon emissions (Shahbaz et al., 2013), negative (Hasni et al., 2023; Shahbaz and Lean, 2012), or insignificant (Omri et al., 2015). Usually, the effect of financial development on environmental quality through emissions reduction is evaluated by considering economic growth. Thus, countries with developed financial systems drive higher economic growth, which will affect the quality of the environment. This is so considering that more funds for research into new green technologies in the energy sector would be available (D'Orazio and Dirks, 2022; Kumar and Firoz, 2018). For 88 developing countries, Khan and Ozturk (2021) added trade and foreign direct investment as determinants of carbon emissions as channels of financial development effects on emissions reduction.

Previous research on trade openness-emissions linkage argues that trade helps to sustain environmental pollution through resources efficient allocation, stimulating financial development, resource expedition, and technology transfers (Salman et al., 2019a). Ali et al. (2020) investigated the effect of international trade, environmentally friendly technological innovation, and renewable energy consumption on carbon emissions for the top 10 carbon emitter countries. They found that an increase in exports, renewable energy consumption, and eco-innovation decrease CO_2, whereas imports and GDP increases lead to rising CO_2 emissions. In principle, access to technologies due to trade enables countries to decrease emissions, enhancing environmental quality, and exports should decrease CO_2 emissions (Hassan et al., 2022; Nathaniel, 2020; Ali et al., 2020; Apergis et al., 2018). Other studies found that exports intensify the use of nonrenewable energy sources, thus damaging environmental quality (Salman et al., 2019a). The literature associates exports with improved environmental quality since production exports require efficient technologies and an energy system able to decrease CO_2 emissions (Ali et al., 2020). In opposition, imports are found to be positively related to CO_2 emissions considering that opening of trade by increasing imports to ensure growth would deteriorate environmental quality (Gozgor and Can, 2016).

Xin et al. (2023) examined the dynamic linkage between education, unemployment, and CO_2 emissions in China, through the ARDL model. Empirical findings point to increased emissions with increased unemployment. Despite the relative importance of unemployment for environmental quality, the literature seems to have ignored its effect. It has been proved that unemployment deteriorates people's health and their environmentally friendly behavior, mostly considering that financial problems to consumption behavioral patterns change (Duarte et al., 2016). Also, for China, considering 30 provinces, Cui et al. (2022) employed OLS, Generalized Method of Moments (GMM), Feasible Generalized Least Squares (FGLS), and Prais-Winsten estimator with Panel-Corrected Standard Errors (PCSE) methods to conclude that increasing the unemployment rate will increase carbon emissions significantly. They argue that green finance leads to lower emissions and lower unemployment rates. Wang and Li (2021) explored the effects of human factors (population aging, life expectancy, population density, unemployment rate, per capita GDP, urbanization) on CO_2 emissions. They performed linear panel data models and panel threshold regression considering data from 154 countries. Urbanization is found to increase CO_2, which is offset by the unemployment rate. Their results confirm the complexity and heterogeneity of the impact of human factors on carbon emissions. Indeed, high employment rates lead to high energy use, driving more CO_2 releases (Adesina and Mwamba, 2019). In the United States, there is evidence that the unemployment rate restrains CO_2 emissions (Granados and Spash, 2019). Still, there are relatively few studies on the impact of the unemployment rate on methane emissions, even if methane is a significant source of GHGs (Hanif et al., 2022; Tarazkar et al., 2021).

Agriculture production, economic growth, and renewable and nonrenewable energy are found to degrade environmental quality (Usman et al., 2021) in South Asia. However, renewable energy has the potential to improve the environment's quality (Hanif et al., 2022; Brady and Magazzino, 2018). This is confirmed by Anwar et al. (2022) findings for Asian countries which in accordance state that while urbanization and economic expansion raised carbon emissions, renewable energy reduced them. Tarazkar et al. (2021), considering 11 OPEC countries, try to infer the main factors that lead to methane emissions. The authors report that energy consumption and crop and livestock production increase methane emissions. Thus, it was suggested the switch from conventional sources to renewable energy sources to reduce methane emissions. Considering the Turkish economy, ensuring energy efficiency enhances energy production through renewable energy sources (lower emission emitters) and reducing fossil fuel use, is vital to help the country move towards green development (Aslan et al., 2021). Qayyum et al. (2021) explore the interaction between financial development, renewable energy consumption, technological innovations, and CO_2 emissions in India. Using ARDL and the Vector Error Correction Model (VECM), they found that financial development increases carbon emissions, whereas renewable energy consumption and technical innovations reduce them. Through FMOLS and VECM models with data from the 15 major renewable energy-consuming countries, Saidi and Omri (2020) show the efficiency of renewable energy in increasing economic growth and reducing carbon emissions. Soukiazis et al. (2019) provided robust evidence for 28 OECD countries that renewable energy consumption is determined by higher levels of human capital, research and development (R&D), and countries' development stage, curbing emissions. Kartal et al. (2023) found that hydropower generation does not reduce CO_2 emissions in the USA, China, France, and Russia.

Urbanization is one of the main used variables to infer its impact on environmental quality (Ali et al., 2023; Cheng and Hu, 2023; Anwar et al., 2022; Hashmi et al., 2021; Wang and Li, 2021; Ari and Şentürk, 2020; Ivanovsky and Churchill, 2020). Both urbanization and urban sprawl have increased CO_2 emissions in China (Cheng and Hu, 2023). Global energy consumption is led by the rapid growth of urbanization (Kuldasheva and Salahodjaev, 2023). Urbanization increases the usage of energy and, therefore, carbon emissions. However, it improves people's living conditions (Al-mulali et al., 2012) despite the negative impact on the environment. In the literature, we find positive and statistically significant results of urbanization over environmental quality (Chen et al., 2022; Hanif et al., 2022; Qayyum et al., 2021). Hanif et al. (2022) results point out that total methane emissions, natural resource depletion, and urbanization will likely increase carbon emissions in the next ten years in Asian countries. They even state that urbanization and excessive resource exploitation should be curtailed if we wish to achieve the necessary carbon neutrality. However, we also find in the literature a negative and statistically significant sign of urbanization in environmental quality (Hashmi et al., 2021; Wang et al., 2021; Huo et al., 2020; Abdallh and Abugamos, 2017; Didenko et al., 2017). Hashmi et al. (2021) examine the non-linear effects of urbanization paths on CO_2 emissions in Asian countries. Results point that urbanization and urban agglomerations contribute to environmental quality in the long run. Wang et al. (2021) also found that urbanization negatively impacts carbon emissions in developed countries. It is argued that OECD member countries have achieved the decoupling of urbanization and carbon emissions. Thus, urbanization will impact emissions through its impact on economic growth, energy efficiency, and energy consumption structure. So, the negative impact of urbanization on emissions may mean that the scale effect of urbanization reduces resource consumption intensity if it is accompanied by energy efficiency and technological advancements, reducing emissions. Other authors affirm that with the continuation of the urbanization process, carbon emissions decrease in developing countries such as those of the Middle East and North Africa (MENA) region (Abdallh and Abugamos, 2017), with energy use and economic growth being the main determinants of emissions for this type of country.

Social-institutional determinants of emissions are being used more recently. Results in the literature argue that good governance and life quality are relevant to decrease emissions. Recently, Han et al. (2024) pointed out that a stable government is crucial to lower CO_2 emissions. This is true for BRICS (Chhabra et al., 2023), 126 developing nations (Jalil and Mohamed, 2021), E−7 countries (Uzar, 2021), Indonesia, South Korea, and Thailand (Salman et al., 2019b), and Sub-Saharan African countries (Abid, 2016). Karim et al. (2022) and Sheraz et al. (2022) showed a bidirectional causality between institutional quality indexes and emissions. For 38 OECD countries, Kang's (2022) results suggest that resolving income inequality (measured through the Gini Index and the top income share) is crucial to solving environmental problems. Lower-income equality is one of the determinants of CO_2 emissions and global warming (Kang, 2022; Ravallion et al., 2000). Institutional quality, political stability, and political efficiency are used to measure the overall institutional impact on emissions in BRICS (Chhabra et al., 2023). If corruption is reduced, political stability is improved, bureaucratic accountability is reduced and law and order are improved, the authors argue it will be positive for the environment.

Voice and Accountability is one of the governance indicators which are composed of elements like political process, civil liberties, and political rights. These measure the extent to which citizens can be active members of government selection, and capture media independence in a country considering its important role in holding monitored those in authority, and responsible for their adopted decisions (Kaufmann et al., 1999). Thus, with a higher Voice and Accountability within a country, citizens demand more environmental policies discipline and responsibility. However, despite its importance, we are not aware of previous studies using this indicator as a determinant of emissions, namely, methane emissions.

Jalil and Mohamed (2021) used dynamic panel data models to investigate the impact of the Kyoto Protocol, political stability, property rights, corruption, and freedom of trade over CO_2 emissions in 126 developing nations. Their results confirm that institutional factors are relevant in the process of cutting CO_2 emissions. Indeed, with good governance indicators, there is room to impose cutting restrictions for environmental improvements, as also confirmed by Uzar (2021) and Salman et al. (2019b). While Uzar (2021) discovered that institutional quality reduces the ecological footprint, Salman et al. (2019b) concluded that impartial and effective domestic institutions are very important in reducing carbon emissions in the course of economic growth. For 30 Sub-Saharan African countries, Karim et al. (2022) evidenced that CO_2 emissions are substantially reduced by corruption control, regulatory quality, and the rule of law. Policymakers should efficiently implement strategies for pollution control, promote environmental regulations with public benefit increases, and substitute, the use of renewable energy sources decreasing the use of fossil fuels through technological green advancements and innovative strategies. This would increase the overall society's health conditions and ensure the appropriate levels of environmental quality.

As for income inequality impacts on emissions, Kang (2022) suggested that resolving income inequality is crucial. Income distribution or inequality impacts social demand for environmental quality (Kang, 2022). This influences environmental policy considering that inequality may reduce the ability to cooperative solutions that enhance environmental protection (Boyce, 1994). Wan et al. (2022) estimated the impact of income inequality on carbon emissions for a panel of 217 countries. They highlighted that rising income inequality would contribute to lower energy consumption and increased R&D expenditure, which would lead to lower CO_2 emissions. Nevertheless, this implies that higher poverty levels contribute to lower emissions with huge impacts in terms of development and socioeconomic living conditions. Demir et al. (2019) also found a negative association between CO_2 emissions and income inequality in Turkey. They justify the result considering that higher inequality decreases consumption and that considering the lower propensity to emit in the richer households, this would lead to environmental quality improvements. Therefore, for developing countries, up to a certain level of development, environmental degradation will rise while income inequality lowers.

3. Data

This study improves the empirical literature on the determinants of CH_4 emissions, considering a large set of determinants of the dependent variable as highlighted in the literature. The choice to include domestic credit in the private sector is related to the evidence that economic development is a complex process that causes a structural change (D'Orazio and Dirks, 2022; Al-mulali and Sab, 2012). The association between unemployment and the environment has drawn little attention in the existing literature. People with high incomes generally have more opportunities to fulfill their desires and maintain a good lifestyle that improves their environment (Xin et al., 2023). Shahbaz et al. (2012) argued that trade openness provides a possibility for a nation to access international markets, improving market share among countries. The result is competition between countries, with increased efficiency in the use of scarce resources and more imported cleaner technologies to reduce emissions (Helpman, 1998).

Thus, the following model is estimated to explore the impacts of the selected variables on CH_4 emissions all over the world.

$$CH4Em_{i,t} = \beta_0 + \beta_1\, CGD_{i,t} + \beta_2\, DCPS_{i,t} + \beta_3\, Export_{i,t} + \beta_4\, GDPPC_{i,t} + \beta_5\, Unemployment_{i,t} + \beta_6\, REC_{i,t} + \beta_7\, Urban_{i,t} + \beta_8\, GI_{i,t} + \beta_9\, VA_{i,t} + \varepsilon_{i,t} \quad [1]$$

The data cover the period 1960–2022, for a total of 192 countries. The period is chosen on data availability. The series considered are the following: methane emissions (*CH4Em*, kt of CO_2 equivalent), total central government debt, (*CGD*, as a % of GDP), domestic credit to private sector (*DCPS*, as a % of GDP), exports of goods and services (*Export*, as a % of GDP), GDP per capita (*GDPPC*, in Purchasing Power Parity at constant 2017 international $), total unemployment (*Unemployment*, as a % of total labor force, national estimate), renewable energy consumption (*REC*, as a % of total final energy consumption), urban population (*Urban*, as a % of total population), Gini Index (*GI*, scale: 0–100), Voice and Accountability (*VA*, Percentile Rank). All the series were obtained from the World Development Indicators (WDI) database by the World Bank (WB).[1] For methane emissions, government debt, domestic credit to the private sector, export, real per capita GDP, renewable energy consumption, and urban population the log form is calculated, to restrict the variance of the series. table Ain the Appendix provides the exploratory data analysis. Table 2 summarizes the main information on the dataset constructed.

4. Empirical results

In this section, both panel data regression results are presented as well as ML results obtained for prediction of future methane emissions. In the latter, we can identify the losers and winners' groups of countries.

4.1. Panel regression estimates and causalities: exploring methane emissions determinants

The results of panel bootstrapped Panel Quantile Regression (PQR) in Table 3 evidence that the effect of central government debt on methane emissions is positive and it becomes statistically significant in the higher quantiles (figure Bin the Appendix reports the Q-Q plot). This finding could imply that a higher-indebted country, having less room for maneuver from a public finance perspective, may face difficulties in financing the environmental transition process, being less effective with its environmental regulations. The finding is in line with the conclusions by Alhassan and Kwakwa (2023), Boly et al. (2022), Zhao and Liu (2022), Ike et al. (2020), Sommer et al. (2020), Bachner and Bednar-Friedl (2019), Jalles (2019), Fodha and Seegmuller (2014), and Didia (2001) but in contrast with evidence provided by Zeraibi et al. (2023). The effect of the credit to the private sector on emissions is negative, and its effect becomes larger at higher quantiles and more statistically significant, showing that an increase in private credit contributes to improving environmental quality. An analogous effect is shown by Hasni et al. (2023), D'Orazio and Dirks (2022), Pacca et al. (2020), Shoaib et al. (2020), and Kumar and Firoz (2018). The estimated coefficients of exports are negative and statistically significant (at least at a 5% significance level) everywhere, as found by Uma et al. (2023), Hassan et al. (2022), Ali et al. (2020), and Apergis et al. (2018), but contrarily to Salman et al. (2019a).

For aggregate income, the estimated beta is positive and statistically significant in all quantiles, showing a mild tendency to decrease. Among the vast literature that provided the same effect of GDP on methane emissions, see Djoukouo (2021), Yusuf et al. (2020), Fernández-Amador et al. (2018), Jorgenson and Birkholz (2010), Jorgenson (2006), Rosa et al. (2004), and Burns et al. (1997). The impact of unemployment on CH_4 emissions is found to be relatively small but statistically significant (at 1% in all quantiles), in line with previous results by Xin et al. (2023) and Cui et al. (2022), but not with those in Wang and Li (2021), and Granados and Spash (2019). Moreover, the results of the PQR method show the ability of renewable energy consumption to curb emissions, as highlighted by Hanif et al. (2022), Qayyum et al. (2021), Saidi and Omri (2020), Soukiazis et al. (2019). The impact of urbanization on emissions is controversial. According to our estimates, this variable positively contributes to the environmental quality; in fact, the estimated sign is negative and statistically highly significant, although it declines from −0.65 in the first quantile to −0.36 in the last one. Similar results are shown by Hashmi et al. (2021), Wang et al. (2021), Huo et al. (2020), Abdallh and Abugamos (2017), and Didenko et al. (2017), but contrast to those reported by Chen et al. (2022), Hanif et al. (2022), and Qayyum et al. (2021). Finally, regarding the socio-institutional variables the Gini Index does not affect emissions, whilst Voice and Accountability variable exhibits the predicted negative sign, confirming that the institutional factors are relevant in cutting the emissions, corroborating previous analyses (Chhabra et al., 2023; Jalil and Mohamed, 2021; Uzar, 2021; Salman et al., 2019b; Abid, 2016).

The causality analysis results (see Table 4) reveal some interesting results (considering a 5% significance level).

- a bidirectional causal flow (with a feedback mechanism) between central government debt and methane emissions, real per capita GDP and methane emissions, urbanization and methane emissions, and Voice and Accountability and methane emissions;
- a unidirectional causal flow, from domestic credit to methane emissions, from export to methane emissions, from renewable energy consumption to methane emissions;
- no causal flow between unemployment and methane emissions, as well as between the Gini Index and methane emissions.

Therefore, the link between inequality and emissions is confirmed to be questionable, in contrast with findings by Kang (2022) and Demir et al. (2019). Moreover, a bidirectional causality between debt and emissions is also found by Zeraibi et al. (2023) and Akram et al. (2021); a bidirectional causality between aggregate income and emissions is reported by Dissanayake et al. (2023), Yang et al. (2022), Magazzino (2016a, 2016b), Shahbaz et al. (2013), and Tiwari et al. (2013); a bidirectional causality between urbanization and emissions is established in Yazdi and Dariani (2019) and Al-mulali et al. (2013); a bidirectional causality between institutional quality indices and emissions is shown in Karim et al. (2022) and Sheraz et al. (2022).

As concerns the unidirectional causal flow detected, Kasman and Duman (2015) and Tiwari et al. (2013) found a similar effect of trade openness on emissions; while Olowu et al. (2018) and Shahbaz et al. (2013) provided evidence of a significant causal impact of financial development on emissions. Finally, the empirical analyses in Charfeddine and Kahia (2019), Jaforullah and King (2015), and Shafiei and

[1] https://databank.worldbank.org/source/world-development-indicators.

Table 2
Variables' description.

Variable	Abbreviations	Measurement units	Definition
1. Methane emissions	CH4Em	kt of CO_2 equivalent	Methane emissions are those stemming from human activities such as agriculture and industrial methane production.
2. Central government debt	CGD	Total, % of GDP	Debt is the entire stock of direct government fixed-term contractual obligations to others outstanding on a particular date.
3. Domestic credit to private sector	DCPS	% of GDP	Domestic credit to the private sector refers to financial resources provided to the private sector by financial corporations, such as through loans, purchases of nonequity securities, and trade credits and other accounts receivable, that establish a claim for repayment.
4. Exports of goods and services	Export	% of GDP	Exports of goods and services represent the value of all goods and other market services provided to the rest of the world.
5. GDP per capita	GDPPC	Purchasing Power Parity, constant 2017 international $	PPP GDP is Gross Domestic Product converted to international dollars using Purchasing Power Parity rates.
6. Unemployment	Unemployment	Total, % of the total labor force	Unemployment refers to the share of the labor force that is without work but available for and seeking employment.
7. Renewable energy consumption	REC	% of total final energy consumption	Renewable energy consumption is the share of renewable energy in total final energy consumption.
8. Urban population	Urban	% of the total population	Urban population refers to people living in urban areas as defined by national statistical offices.
9. Gini Index	GI	Scale: 0-100	Gini Index measures the extent to which the distribution of income (or, in some cases, consumption expenditure) among individuals or households within an economy deviates from a perfectly equal distribution.
10. Voice and Accountability	VA	Percentile Rank	Voice and Accountability captures perceptions of the extent to which a country's citizens are able to participate in selecting their government, as well as freedom of expression, freedom of association, and free media.

Sources: authors' elaborations.

Table 3
Results of bootstrapped PQR.

Variable	Panel Quantile Regressions			
	0.20	*0.40*	*0.60*	*0.80*
CGD	0.0173	0.0224	0.0277*	0.0334**
	(0.0206)	(0.0167)	(0.0144)	(0.0149)
DCPS	−0.0184	−0.0374*	−0.0572***	−0.0786***
	(0.0200)	(0.0192)	(0.0206)	(0.0241)
Export	−0.0546**	−0.0730***	−0.0923***	−0.1130***
	(0.02778)	(0.0257)	(0.0260)	(0.0293)
GDPPC	0.1965***	0.1946***	0.1926***	0.1905***
	(0.0442)	(0.0399)	(0.0398)	(0.0445)
Unemployment	0.0073***	0.0075***	0.0077***	0.0080***
	(0.0020)	(0.0016)	(0.0015)	(0.0016)
REC	−0.1957***	−0.2043***	−0.2134***	−0.2231***
	(0.0174)	(0.0173)	(0.0190)	(0.0225)
Urban	−0.6515***	−0.5609***	−0.4664***	−0.3643***
	(0.2146)	(0.1834)	(0.1657)	(0.1692)
GI	−0.0001	−0.0008	−0.0015	−0.0023
	(0.0020)	(0.0018)	(0.0018)	(0.0021)
VA	−0.0018*	−0.0027***	−0.0036***	−0.0047***
	(0.0010)	(0.0009)	(0.0010)	(0.0011)
Constant	11.3283***	11.2298***	11.1270***	11.0161***
	(0.8767)	(0.7620)	(0.6985)	(0.7111)

Notes: Number of bootstraps: 100. Standard Errors that are robust to heteroskedasticity (based on the White Huber estimator/sandwich estimator) in parentheses. Nonparametric density estimation technique: empirical quantile function using fitted values. Bandwidth method used by the density estimator: Hall-Sheather's bandwidth. Degrees of freedom adjustment applied. $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.10$.

Table 4
Granger's panel pairwise causality tests.

Null Hypothesis	*F* Statistics	P-Value
CH4Em ⇏ CGD	3.3584	0.0351**
CGD ⇏ CH4Em	4.6376	0.0098***
CH4Em ⇏ DCPS	1.7334	0.1768
DCPS ⇏ CH4Em	11.1628	0.0000***
CH4Em ⇏ Export	0.2636	0.7683
Export ⇏ CH4Em	9.7580	0.0000***
CH4Em ⇏ GDPPC	10.6861	0.0000***
GDPPC ⇏ CH4Em	18.9625	0.0000***
CH4Em ⇏ Unemployment	0.1590	0.8530
Unemployment ⇏ CH4Em	1.6470	0.1928
CH4Em ⇏ REC	2.4965	0.0825*
REC ⇏ CH4Em	3.4477	0.0319**
CH4Em ⇏ Urban	7.9141	0.0004***
Urban ⇏ CH4Em	19.0807	0.0000***
CH4Em ⇏ GI	2.3533	0.0956*
GI ⇏ CH4Em	1.1297	0.3235
CH4Em ⇏ VA	10.7098	0.0000***
VA ⇏ CH4Em	19.4483	0.0000***

Notes: $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.10$.

Table 5
Ridge Regression estimates.

	Minimum	(+1 SE)	(+2 SE)
Lambda	1.447	6.325	10.500
Variable		**Coefficients**	
CGD	0.0466	0.0510	0.0542
DCPS	−0.1289	−0.1117	−0.0983
Export	−1.5972	−1.5767	−1.5599
GDPPC	1.1828	1.1227	1.0760
Unemployment	0.0322	0.0325	0.0326
REC	−0.6717	−0.6710	−0.6699
Urban	−0.5617	−0.5069	−0.4638
GI	0.0774	0.0762	0.0753
VA	−0.0191	−0.0183	−0.0176
Constant	7.4099	7.6401	7.8134
L1 Norm	11.7275	11.8069	11.8612
R-squared	0.8284	0.8281	0.8277

Notes: Regressor transformation: Standardization by sample. Cross-Validation method: Rolling Window. Selection measure: Mean Absolute Error (MAE). Weights type: Inverse Standard Deviation.
Source: authors' elaborations in EViews.

Salim (2014) showed the existence of a causal flow from renewable consumption to emissions.

The results from PQR have been checked through the Elastic Net Regularization (ENR) method. Thus, for robustness purposes, an ML test through a Ridge Regression (RR) is performed. The results for the analytic solution are shown in Table 5.

Out of the list of lambda values used in the Cross-Validation (CV) procedure, the value of 1.447 is chosen as having the lowest Mean Absolute Error (MAE). As for previous PQR estimates, all the estimated coefficients of the regressors exhibit the same sign. It is worth noticing the high R-squared values for each estimate. For more diagnostic tools, see figure Ain the Appendix, which reports the actual versus fitted residual graph.

The evolution of the coefficients concerning the penalization lambda parameter reveals that when the value of the regularization penalty lambda increases, the absolute value of each of the coefficients decreases, as expected with a penalized regression. Thus, as lambda increases, the complexity of the model decreases (Fig. 1).

For an alternative inspection of the diagnostics, in Fig. 2 the coefficients against the L1 norm of the coefficients are reported. Here, the proportion of each coefficient in the norm varies as the norm of all the coefficients varies.

To better evaluate these results, after the selection of the Rolling Window method for CV, the Training/Test Error graph, containing the evolution of the errors produced by CV against the lambda values, is evaluated. The training error is smaller than the test error over the whole spectrum, as expected. The same conclusions can be derived by looking at the Training/Test Error sets.

4.2. Machine Learning algorithms for the prediction of the future value of methane emissions

In the following analysis, we compare eight different ML algorithms for predicting the future value of methane emissions. The algorithms were compared based on their ability to maximize the goodness of fit and minimize the statistical errors: R-squared, Mean Average Error (MAE), Mean Standard Error (MSE), Root Mean Square Error (RMSE), and Mean Signed Difference (MSD). Specifically, the following definitions have been used:

$$R^2 = 1 - \frac{SumSquaredRegression}{TotalSumOfSquares} = 1 - \frac{\sum (y_i - \hat{y}_i)^2}{\sum (y_i - \bar{y}_i)(y_i - \bar{y}_i)} \quad [2]$$

$$MAE = \frac{\sum_{i=1}^{n} |y_i - x_i|}{n} = \frac{\sum_{i=1}^{n} |e_i|}{n} \quad [3]$$

$$MSE = \frac{1}{n} \sum_{i=1}^{n} (Y_i - \hat{Y}_i)(Y_i - \hat{Y}_i) \quad [4]$$

$$RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (\hat{y}_i - y_i)(\hat{y}_i - y_i)} \quad [5]$$

$$MSD\left(\hat{\theta}\right) = \frac{1}{n} \sum_{i=1}^{n} \hat{\theta}_i - \theta_i \quad [6]$$

A ranking has been created for each of these statistical indicators. Subsequently, an aggregate ranking has been created, merging the rankings on each indicator. The algorithm that receives the lowest score is to be preferred as it has the highest placement in the individual indicator rankings. The sample was split into two components, with 70% of the data belonging to the training set, and the remaining 30% for testing.

The results from Table 6 clearly show how the overall ranking is almost identical to the single rankings produced by each criterion. The only difference is represented by the first two positions assigned to SRT and PNN models (see also figure Cin the Appendix).

Thus, the following ordering of the applied algorithms is obtained.

1. Simple Regression Tree (SRT), with a payoff equal to 6;
2. Probabilistic Neural Networks (PNN), with a payoff value of 9;
3. Artificial Neural Networks (ANN), with a payoff value of 15;
4. Gradient Boosted Tree (GBT), with a payoff value of 20;
5. Linear Regression (LR), with a payoff value equal to 25;
6. Tree Ensemble Regression (TER), with a payoff value of 30;
7. Random Forest Regression (RFR), with a payoff value of 35;
8. Polynomial Regression (PR), with a payoff value of 40.

Moreover, in Fig. 3 we present the scores obtained by each algorithm for the single statistical indicator.

Considering the workflow of the best predictor algorithm (STR), we can observe that it consists of three elements: a) data preparation; b) ML and predictions; and c) statistical errors and scores (see figure Din the Appendix for the complete description of ML procedures that we followed).

By applying the STR model, it is possible to identify both the so-called losing countries (or the countries for which a growth in the value of methane emissions is predicted) and the winning countries, (or the countries for which a reduction in the value of methane emissions is predicted). On average, however, the algorithm predicts a growth in methane emissions of around 10.61% for the whole panel.

Losing countries. Among the countries for which a significant growth in the value of methane emissions is predicted we found Libya (+166.69%), Venezuela (+131.87%), Belize (+94.51%), Japan

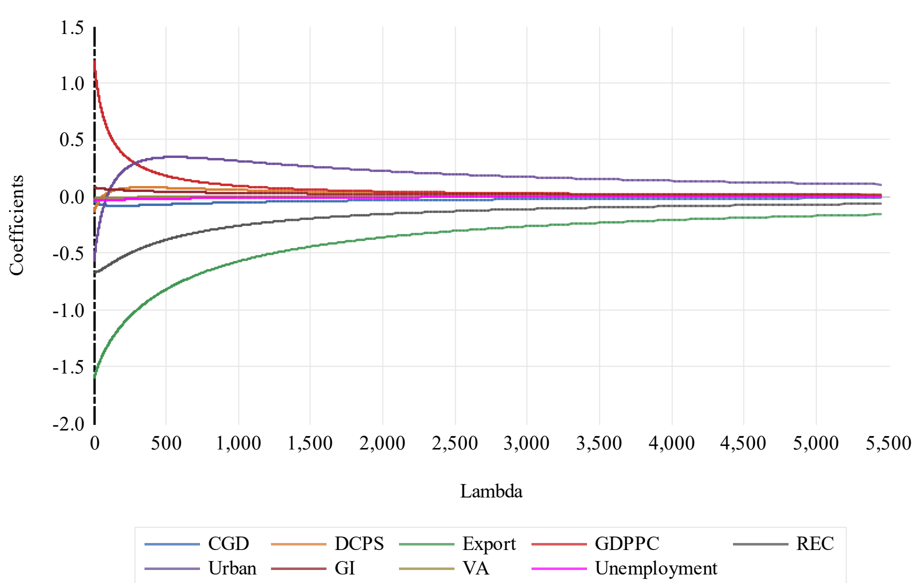

Fig. 1. Coefficients' evolution (by lambda).
Source: authors' elaborations in EViews.

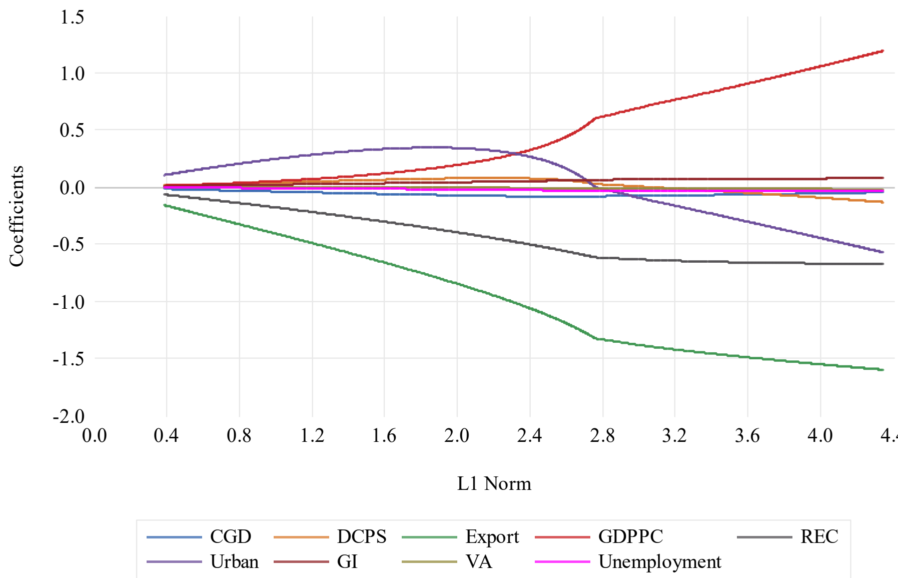

Fig. 2. Coefficients' evolution (by L1 norm of the coefficients).
Source: authors' elaborations in EViews.

Table 6
Statistical indicators for evaluating the predictive efficiency of ML algorithms.

Algorithm	R2	MAE	MSE	RMSE	MSD
ANN	0.9195	0.0208	0.0022	0.0469	0.0158
PNN	0.9260	0.0272	0.0020	0.0450	0.0010
SRT	0.9513	0.0155	0.0013	0.0365	0.0152
GBT	0.8542	0.0355	0.0040	0.0631	0.0353
RFR	0.0788	0.0397	0.0058	0.0760	0.0396
LR	0.7915	0.0387	0.0057	0.0755	0.0386
PR	0.6416	0.0837	0.0122	0.1103	0.0446
TER	0.7915	0.0387	0.0057	0.0755	0.0386

Notes: ANN: Artificial Neural Networks; PNN: Probabilistic Neural Networks; SRT: Simple Regression Tree; GBT: Gradient Boosted Tree; RFR: Random Forest Regression; LR: Linear Regression; PR: Polynomial Regression; TER: Tree Ensemble Regression.

(+66.76%), Cabo Verde (+33.69%), Australia (+25.16%), Saudi Arabia (+23.52%), and Argentina (+20.85%). However, only for the first four countries, an exceptional growth in emissions is predicted. From a geographical point of view, one can observe that the losing countries are mainly located in South America, Africa, and Oceania. On average, the value of methane emissions is predicted to grow by 14.82% for Western countries (see Fig. 4).

Winning countries. The countries for which a significant reduction in methane emissions is predicted are Slovak Republic (−6.77%), Palau (−7.53%), Moldova (−7.61%), Myanmar (−8.19%), Guinea (−12.39%), Grenada (−14.67%), and Maldives (−29.87%). Generally speaking, the winning countries belong to the Southeast Asian area. However, a significant reduction in emissions is also predicted in Canada as well as for several European countries (i.e., Slovakia, Moldova, Greece, Cyprus, and Estonia). Mali is the only African country for which a decrease in emissions is forecasted. From a strictly political-institutional point of view, we can note that among the Western countries, a reduction in the value of methane emissions is predicted only for Canada and some small European countries. That is, the large European countries, the USA, and Western Asian countries are not predicted to reduce their methane emissions (see Fig. 5).

5. Conclusions and policy implications

Fighting climate change demands all countries' commitment, irrespective of the level of development (Magazzino, 2023). Climate change harms economic growth by negatively affecting food production, generating extreme climatic conditions, aggravating poverty, and affecting social and economic lifestyles and status. Thus, lowering economic performance (Alhassan and Kwakwa, 2023; UNEP, 2022; Djoukouo, 2021). A lot has been written thus far considering the determinants of CO_2 emissions, but less is known about methane emission determinants despite their harmful impact on the environment. This article tries to fill this literature gap using ML algorithms able to define the group of losers and winners and thus unable to lower methane emissions up to this moment, performing a worldwide analysis using data from 192 countries for the period 1960–2022.

Results from bootstrapped PQR allowed us to see that central government debt, aggregate income, and unemployment positively affect methane emissions; while an increase in domestic credit to the private sector, export, unemployment rate, renewable energy consumption, urbanization degree, and Voice and Accountability is associated to a reduction in CH_4 emissions. Finally, the inequality degree of the country (measured by the Gini Index) is discovered to be statistically unrelated to environmental degradation.

The negative and significant impact found of urbanization on methane emissions can be a sign that urbanization (worldwide) entered a stage of stagnation. With that, environmental degradation would slow down (Abdallh and Abugamos, 2017). Thus, policymakers should adopt policies that reduce the urbanization process to ensure environmental improvements. A suggestion would be to facilitate rural-urban migration to maintain good environmental quality levels. For that, employment, education, health, and quality of life, despite facilities, need to be ensured, also leading to rural economic growth, and a balance should be made to ensure that higher rural development, industrialization, and consequent energy consumption would not increase emissions.

Tax incentives, the development of infrastructures able to promote environmentally friendly industrialization, low carbon technologies, sustainable forms of urbanization, urban planning, and becoming carbon neutral through renewable production capacity, are important policy initiatives to be pursued worldwide. To curb methane emissions, we need to improve energy infrastructure. These would ensure sustainable agricultural practices and waste management, being more urgent for the list of losers, as identified in this article. Moreover, effective governance systems can facilitate funds channeling to energy-efficient projects. Considering that the literature favors the easiness of quality

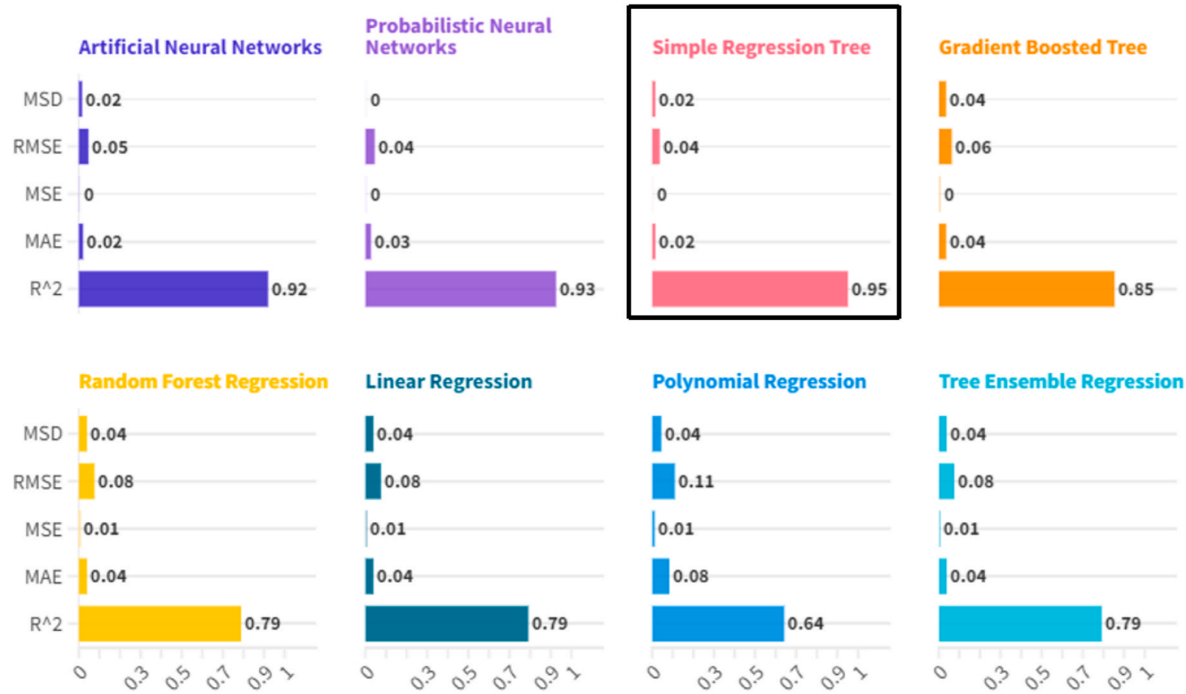

Fig. 3. Statistical performance of ML algorithms.
Source: authors' elaborations in KNIME and Fluorish.Studio.

institutions in favoring the adoption and spillover of greener technologies, political stability, and Voice and Accountability should be enhanced, but for that a correct fight against corruption is urgent.

No great reductions are expected in the short medium-run for large European, the USA, and Western Asian countries in accordance with the presented results. The highest expected values of future methane emissions (losing countries) are for the poorest world regions, which are abundant in natural resources. Liu et al. (2022) pointed to the need for government governance capacity to ensure efficiency in natural resources management. Additionally, Aysan et al. (2023) explored the nexus between natural resources and governance identifying governance challenges (capacity, connectivity, and knowledge), and domains of good governance (effectiveness, involvement, and efficiency). Thus, ensuring an appropriate level of government digitalization of services would contribute to more effective management of resources, decreasing emissions (Yang Z. et al., 2022), considering that the digital economy is able to reduce carbon emissions (Dong et al., 2022). However, there can exist many challenges regarding the coordination among the many stakeholders (Aysan et al., 2023) involved in governmental intervention to be effective in resource management and for countries to achieve sustainable development. Whereas digital economy and digital governance can enhance energy efficiency and sustainable development, it is also proved that digitalization can harm the environment and increase emissions (Zhang et al., 2022). Therefore, only efficient and effective policies regarding digitalization and technology adoption, can lead to energy efficiency, the full production of energy with renewable sources, technology adoption for the development of energy production based on natural resources, disregarding fossil fuel resources, and achieving the desired emissions neutrality (Hu, 2023; Zhang et al., 2022). Yan et al. (2023) further evidence that the digital economy in the urban agglomerations can indirectly reduce carbon emission intensity. This is achieved through the channels of green technology innovation and the Information and Communication Technology industry, turning government digitalization of services even more urgent.

Once the countries in our analysis have achieved different development stages, the general results obtained from the bootstrapped PQR evidence that policymakers should control central government debt, enhance growth, favor a sustainable development path, and create greener employment. To curb emissions, policymakers should facilitate credit to the private sector, favor renewable energy consumption and production, ensure sustainable urbanization, increase trade with a higher emphasis on exports, and offer conditions to increase Voice and Accountability country indexes. Even if the link between inequality and emissions is found to be weak through causality analysis, combined efforts to reduce unemployment, or redirect current employees to greener sectors betting in formation or specific educational levels, fossil fuels usage and dependence, and central government debt, would incentivize higher renewable energy consumption, private initiative and investment, privileging the private sector financial support and investment, able to reduce methane emissions. With these public interventions, losers would be positioned in the winner's rankings and would ensure an effective fight against climate change.

In the future, the economies studied jointly in this article might be divided by regions heavily, middle, and little dependent on agriculture, livestock, and fossil fuels, as these are the main sources of methane emissions, for the redirection of more specific policies in fighting environmental degradation. Looking at the individual country heterogeneity characteristics would further promote new policies to be pursued while ensuring the decreased dependence on fossil fuels like oil and gas, favoring the direct channeling of efforts to GHG emissions decrease, promoting environmental quality, awareness in the consumption society, and among stakeholders to ensure the correct fight against climate change. Individual efforts can be enhanced through regional efforts, and these would be translated into worldwide efforts in this which is an assumed general issue to be solved.

CRediT authorship contribution statement

Cosimo Magazzino: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Mara Madaleno:** Writing – review & editing, Investigation, Data curation, Conceptualization. **Muhammad Waqas:** Project administration, Writing – review & editing. **Angelo Leogrande:**

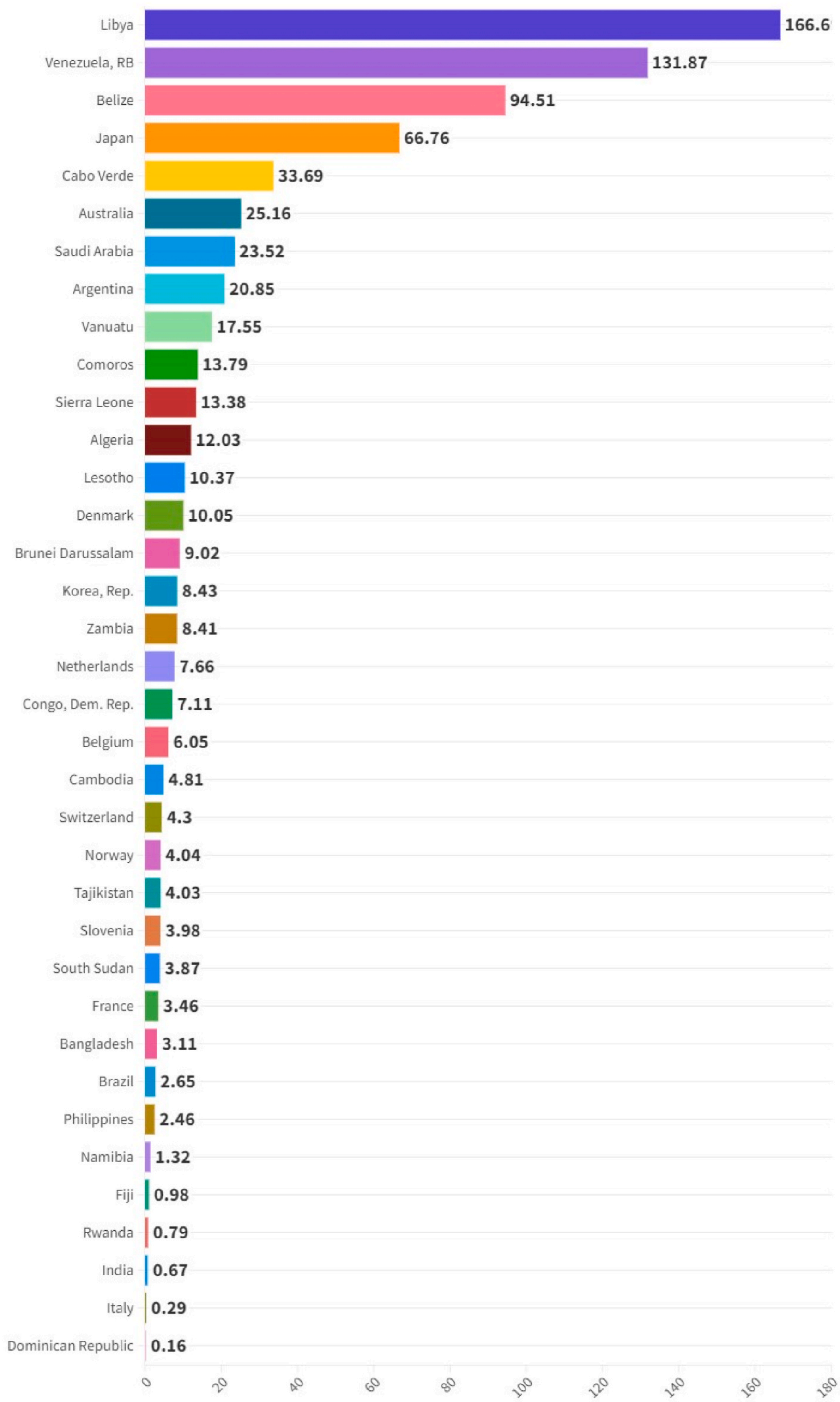

Fig. 4. Losing countries.
Notes: Countries for which the highest performance of the ML algorithm predicts an increase in the value of methane emissions. The graph shows the percentage increase in methane emissions compared to the last survey by country.
Source: authors' elaborations in KNIME and Fluorish.Studio.

Software, Methodology, Data curation, Conceptualization.

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.

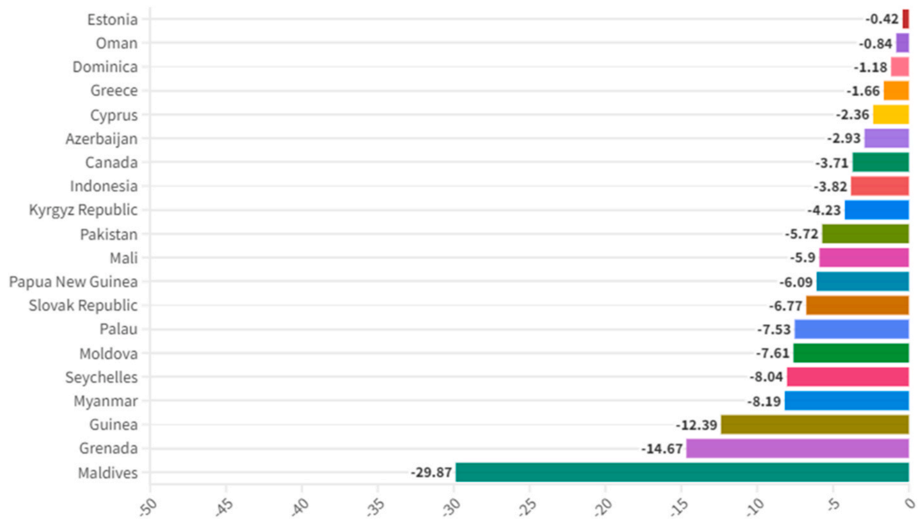

Fig. 5. Winning countries.
Notes: Countries for which the highest performance of the ML algorithm predicts a reduction in the value of methane emissions. The graph shows the decreasing percentage change in methane emissions compared to the last survey by country.
Source: authors' elaborations with KNIME and Fluorish.Studio.

Data availability

Data will be made available on request.

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Appendix

Table A
Descriptive statistics.

Variable	Mean	Median	Std. Dev.	Skewness	Kurtosis	Range	IQR	CV
CH4Em	8.6711	9.0484	2.3633	−0.8107	3.8134	13.3242	2.6265	0.2725
CGD	3.7850	3.8891	0.8958	−0.9183	6.1706	8.8837	0.9274	0.2367
DCPS	3.2029	3.2504	1.1294	−1.5622	12.8593	12.6939	1.3705	0.3526
Export	3.3999	3.3849	0.9406	2.2504	22.5304	16.0652	0.9551	0.2766
GDPPC	9.1344	9.2387	1.2841	−0.5117	3.6744	8.5242	2.0073	0.1406
Unemployment	9.7858	6.8000	12.1602	4.3145	24.9812	86.4480	7.1000	1.2426
REC	2.5449	3.0945	1.8870	−1.2966	4.5200	9.1936	2.4154	0.7415
Urban	3.7723	3.9249	0.6516	−1.1093	4.2483	3.8742	0.8587	0.1727
GI	37.7304	35.7000	9.2240	0.4582	3.4733	65.3080	11.9500	0.2445
VA	49.1420	48.3568	29.0081	0.0413	1.8051	100.0000	50.1101	0.5903

Notes: Std. Dev.: Standard Deviation; IQR: Inter-Quartile Range; CV: Coefficient of Variation.
Sources: authors' calculations.

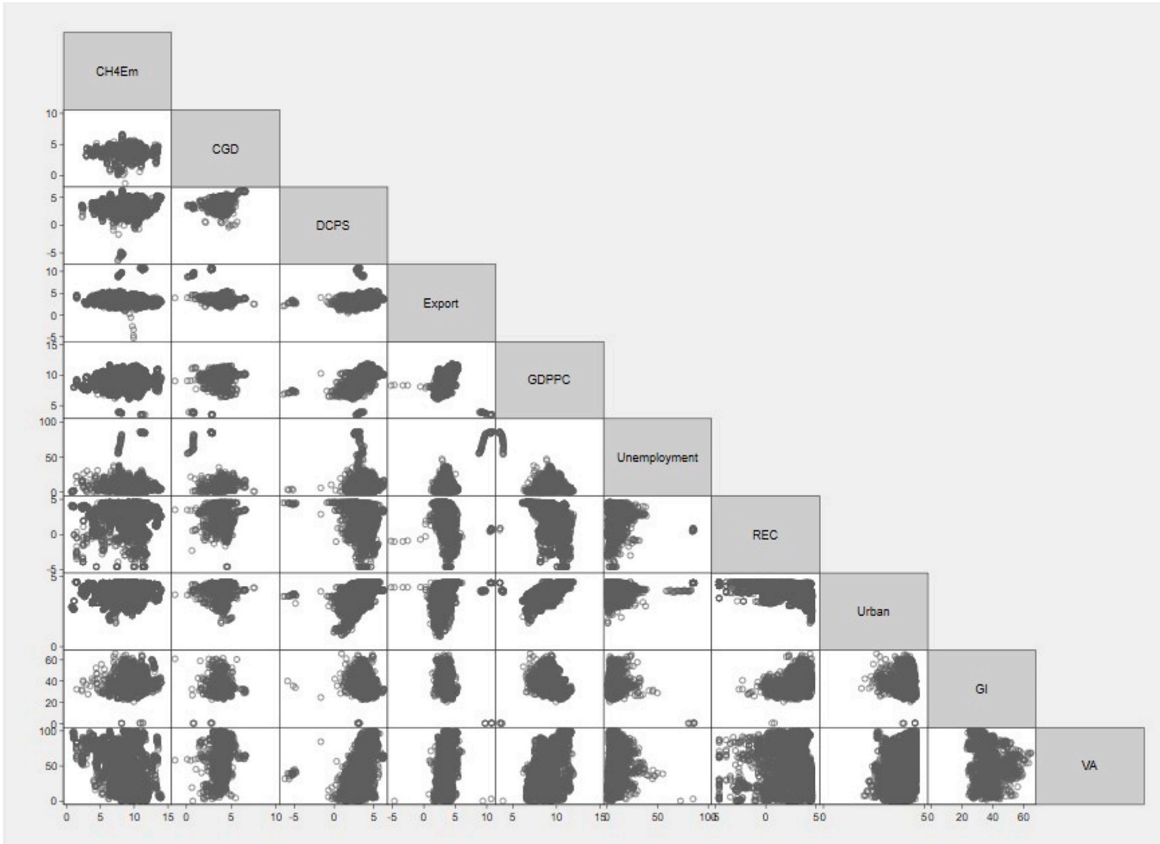


Fig. A. Scatterplot matrix.
Source: authors' elaborations in STATA.

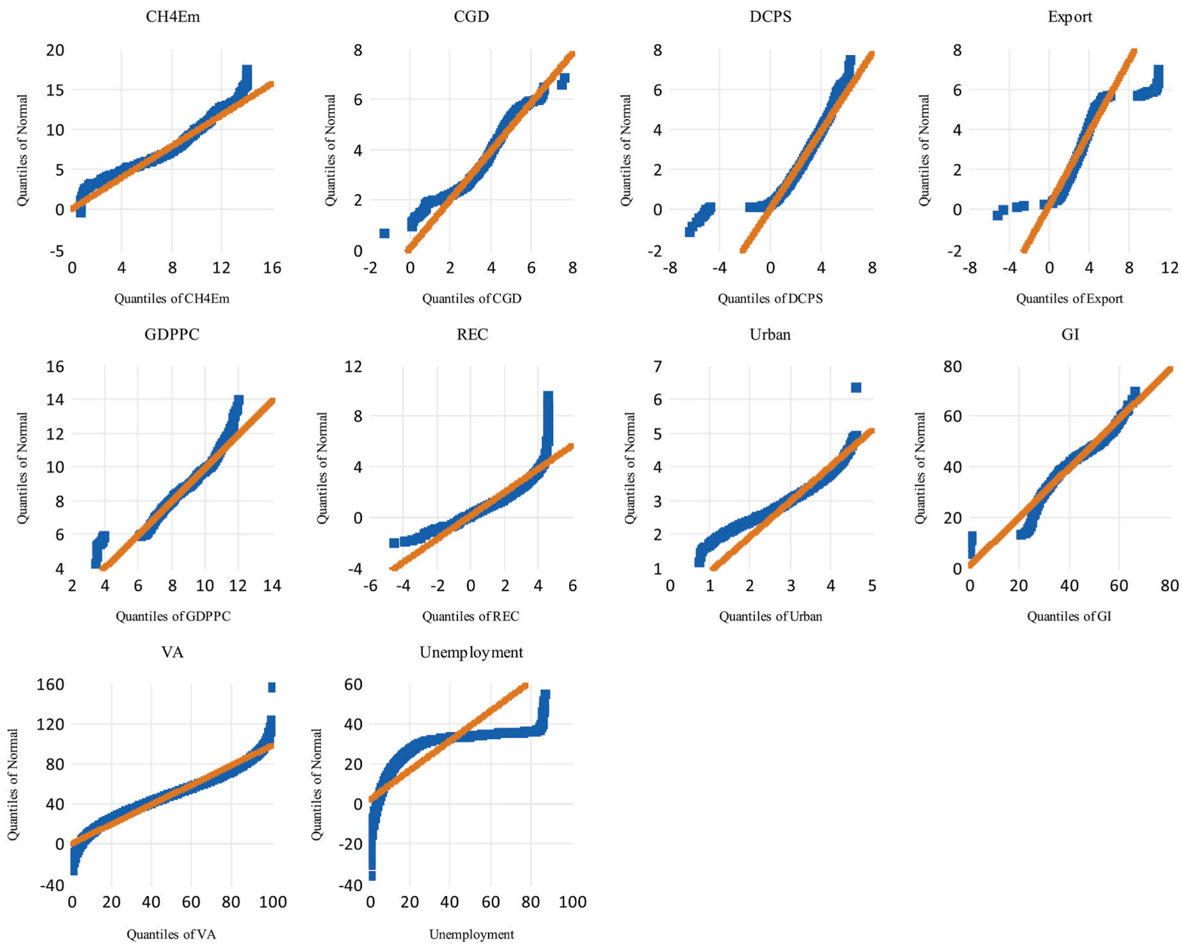
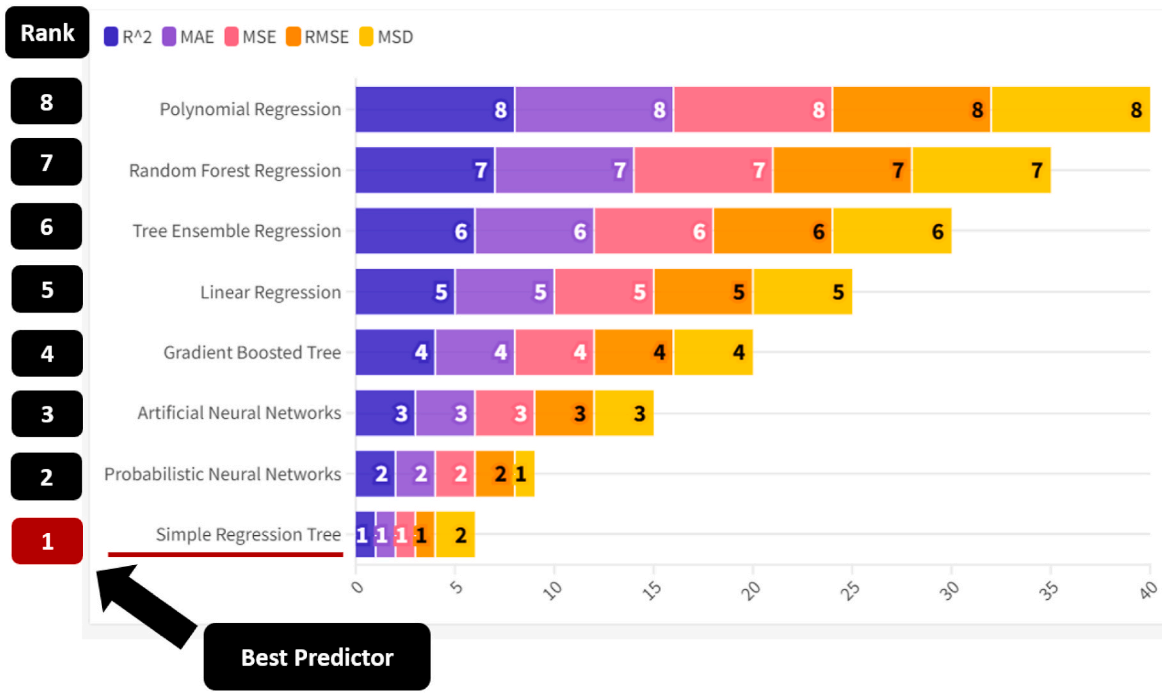


Fig. B. Quantile-Quantile (Q-Q) distribution plots.
Sources: authors' elaborations in EVIEWS.



Source: authors' elaborations in Knime and Fluorish.Studio.

Figure D. Workflow of ML analyses.

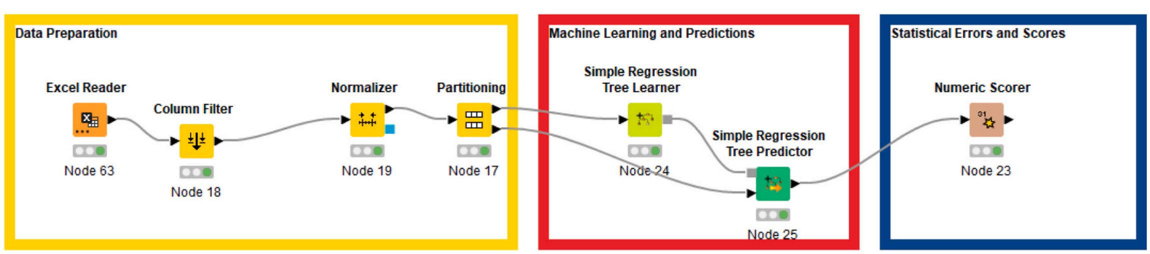


Fig. C. Ranking of alternative ML algorithms.
Source: authors' elaborations in Knime and Fluorish.Studio.

Fig. D. Workflow of ML analyses.
Source: authors' elaborations in Knime and Fluorish.

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