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Exploring the impact of entrepreneurial indicators on CO2 emissions within the environmental Kuznets curve framework: a cross-sectional study

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Abstract

Many countries emphasize entrepreneurship promotion as a policy focus. However, empirical research has often neglected the complex environmental consequences associated with such initiatives. In this study, we analyzed data using a panel model from 14 countries, covering the years 2002 to 2018. Our goal was to thoroughly assess the impact of eleven distinct entrepreneurship indicators on CO2 emissions. Our findings indicate that some control variables, like trade liberalization, are fundamental in reducing emissions. This contrasts with traditional views, which typically revolve around a consistent Kuznets curve that depicts the environmental effects of economic growth. Instead, our research uncovers a dynamic pattern transitioning from a concave upward trajectory to an inverted U-shaped curve, primarily due to increased levels of entrepreneurship. Remarkably, various entrepreneurial indicators, such as government support and policies, taxes and bureaucracy, governmental programs, and cultural and social norms, demonstrate direct positive impacts on CO2 emissions. Conversely, other indicators show a mix of positive and negative effects. Furthermore, examining the spill-over effects of entrepreneurship indicators, particularly in their role in energy use intensity and GDP per capita, reveals significant implications for improving energy consumption efficiency. However, it is important to acknowledge that despite the potential for enhanced efficiency, the negative effects resulting from an increased scale of output may not be completely counteracted.

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1 Introduction

The spotlight on climate change has progressively intensified across societal, industrial, and governmental spheres. The pressing need for a low-carbon, resource-efficient economy has fueled a surge in research efforts, aiming to illuminate pathways and remedies for the formidable global challenge.[1] Recent projections from a comprehensive study[2] indicate that by 2050, climate change could precipitate a staggering 4 percent annual economic decline on a global scale, equating to a staggering $202 million in daily economic losses across diverse sectors such as energy (Chilkoti et al., 2017), infrastructure (Forzieri et al., 2018), tourism, and transportation (Steiger et al., 2019). The growing recognition of the issue underscores the imperative for substantial transformations in energy production and consumption paradigms, as prerequisites for meaningful strides in combating environmental deterioration (Dhahri & Omri, 2018).

In this context, previous research has vividly delineated the pivotal role of entrepreneurship in tackling some of the most pressing economic and societal predicaments. The transformative potential of entrepreneurship dates back to as early as 1934 when Schumpeter laid the foundation for entrepreneurship theories, recognizing its impact on societal and economic evolution (Schumpeter, 1934). By infusing innovative business models and harnessing technological and financial innovations, entrepreneurship has emerged as a potent driver of change (Cojoinau et al., 2020; Malen & Marcus, 2017; York & Venkataraman, 2010). However, the existing literature about the environmental implications of entrepreneurship bifurcates into two distinct streams. The first stream embraces the notion of a positive nexus between entrepreneurship and economic development, grounded in economic observations and the logical assertion that the translation of innovative concepts into economic ventures drives growth and productivity (Pradhan et al., 2020; Galindo-Martin et al., 2021; Audretsch et al., 2015; Sanyang & Huang, 2010). Conversely, the second stream furnishes robust evidence of the adverse impact of modernization, industrialization, and subsequent economic growth on environmental degradation (Menegarki et al., 2021; Nasir et al., 2021; Givens & Jorgenson, 2011; Mrabet et al., 2017), underlining the confluence of environmental challenges with economic advancement (Nakamura & Managi, 2020).

More contemporary perspectives recognize entrepreneurship as a critical avenue for sustainable development, although findings have been polarized. On one hand, Dhahri et al. (2021) present compelling evidence highlighting the positive influence of opportunity entrepreneurship on all three dimensions of sustainable development. Their work underscores the enduring impact of early-stage entrepreneurship on both economic and environmental sustainability. Similarly, Gu et al. (2021) illustrate a close interconnection between entrepreneurship and the triple bottom line of sustainable development, shedding light on the moderating roles played by foreign direct investment, business environment indices, and environmental regulations. Likewise, York and Venkataraman (2010) propose

[1] Climate change is recognized as one of the biggest threats that modern humans have ever faced and has profound implications for health, peace and economic stability (Attenborough, 2021). Similarly, Rockstrom et al. (2009) indicate that of all the grand challenges facing humanity, none is more profound than climate change.

[2] https://www.weforum.org/agenda/2022/04/climate-change-global-gdp-risk/.

that, under certain conditions, entrepreneurship within a nation can outpace the efforts of governments, NGOs, and established enterprises in attaining environmental sustainability. Conversely, diverging viewpoints arise. Employing a refined environmental Kuznet curve model, Ben Youssef et al. (2018) reveal an adverse impact of entrepreneurship on environmental quality and sustainability, particularly within the informal sector of African countries. Furthermore, Dhahri and Omri (2018) probe the ramifications of entrepreneurial activities on economic advancement, environmental factors, and social conditions in developing nations. Their findings affirm the favorable contribution of entrepreneurship to economic progress and societal conditions, while concurrently identifying a negative correlation between entrepreneurship and environmental dimensions.

The primary gaps identified in the literature include, first the inconsistency in findings on economic development and CO2 emissions. We identified a significant discrepancy in findings regarding the relationship between economic growth and CO2 emissions. While some studies find a positive association, suggesting that economic expansion leads to increased emissions, others report a negative or negligible impact. This inconsistency points to a gap in understanding the nuanced interactions between economic activities and environmental outcomes. Second lack of consensus on the Environmental Kuznets Curve (EKC) hypothesis. Although some studies support the EKC hypothesis, which posits an inverted U-shaped relationship between income levels and environmental degradation, others challenge this view or propose alternative patterns (e.g., L-shaped, M-shaped). The divergent findings on the EKC hypothesis indicate a need for further investigation into the conditions under which economic growth aligns with environmental sustainability. Third varied impacts of entrepreneurship on economic development. The literature review also reveals mixed outcomes regarding the influence of entrepreneurship on economic performance. While entrepreneurship is generally viewed positively, impacting economic growth and job creation, the extent of this impact and its sustainability over time remain ambiguous. Some studies suggest that the relationship may differ based on the scale of the enterprise, the region's economic context, and the type of entrepreneurial activity. Fourth limited insight into long-Term dynamics. Most studies focus on short- to medium-term outcomes, with less attention given to the long-term dynamics of the relationship between CO2 emissions, economic development, and entrepreneurship. There's a gap in longitudinal studies that track these relationships over extended periods to capture evolving trends and the impact of technological and policy changes. Fifth the geographical and contextual limitations. The review suggests that research outcomes are highly influenced by the specific geographical and economic context of the study sample. There's a gap in comprehensive studies that compare these dynamics across different economic and environmental contexts, particularly in emerging economies and less-studied regions. And finally, the methodological divergence. The wide range of methodologies and variable definitions used across studies complicates the synthesis of findings and the derivation of universal insights. This methodological diversity indicates a need for more standardized approaches to studying these relationships or meta-analytic studies that reconcile findings across diverse methodologies.

To gain a more profound comprehension of these paradoxes and the assorted array of outcomes found within the existing literature, our pursuit involves addressing two pivotal yet insufficiently explored inquiries as follows:

RQ1: How do various economic activities such as urbanization, trade openness, energy intensity, and resource rent affect the ecological condition, particularly in terms of CO2 emissions?

RQ2: To what extent do overall entrepreneurial activities contribute to ecological degradation?

Firstly, we delve into the repercussions of economic activities, gauged through a diverse spectrum of variables including urbanization, trade openness, energy intensity, and resource rent, on the ecological status of the surrounding environment. This ecological quality is gauged by the metric of CO2 emissions.[3] Secondly, our investigation delves into whether overall entrepreneurial undertakings cascade into ecological deterioration. Furthermore, we scrutinize the cascading impacts of entrepreneurial indices on the efficacy of energy intensity in its mission to curtail CO2 emissions. Additionally, our research probes into the consequences of entrepreneurship indicators on the effectiveness of both the logarithmic GDP and its quadratic expression in mitigating CO2 emissions to offer a comprehensive exploration into the ecological implications of entrepreneurial activities within the context of the environmental Kuznets curve. This multifaceted exploration contributes not only to the theoretical expanse but also to empirical knowledge.

From a theoretical stance, extant literature encompasses a range of entrepreneurship metrics, encompassing facets such as innovative versus imitative entrepreneurship (Ziegler, 1985), public versus private entrepreneurship (Kearney et al., 2009), and individual versus collective entrepreneurship (Makhdoom et al., 2019). Our approach diverges from these precedents as we center our attention on the Entrepreneurship Framework Conditions (EFCs), a multidimensional gauge encapsulating diverse factors like governmental initiatives, education, training, funding, and entry regulations. Our contention rests on the premise that entrepreneurship isn't an isolated individual endeavor; rather, it's influenced by the ecosystem it operates within. Thus, rather than relying on an aggregated metric, the adoption of EFCs empowers us to grasp the multi-faceted essence of entrepreneurship within a global panorama.

Initiating our analysis, we embark on an overview of the core concepts in focus, which encompass total entrepreneurial activity, economic advancement, and the ecological deterioration focalized through CO2 emissions. Subsequently, we delve into the configuration of the empirical model guiding our inquiry, coupled with an exposition of the dataset sources and descriptions.

The rest of the paper organized as follows, Sect. 2 presents a comprehensive rview of related literature, Sect. 3 outloines the empirical model and description of data used in our study, Sect. 4 contains the empirical results and the main findings derived from our research modesl and finally Sect. 5 provdes the discussions and concluding remarks.

2 Review of related literature

The primary driver behind the observed shifts in global climate patterns and the escalation of global temperatures has been pinpointed as the substantial release of carbon dioxide (CO2) into the atmosphere (Caporale et al., 2021). This emission of CO2, a pervasive greenhouse gas, has served as a prominent indicator of the ongoing deterioration of

[3] In his book entitled 'Heat, Greed and Human Need: Climate Change, Capitalism and Sustainable Wellbeing' Gough (2017) argues that CO2 emission is a suitable measure for environmental sustainability. Subsequently, CO2 emission has also been used as a measure of environmental degradation in recent research (see Zamil et al., 2019; Nakamuran and Managi, 2020; Haftor and Climent, 2021; Caporale et al., 2021).

our environment (IPCC, 2015). Projections indicate that the concentration of CO2 in the atmosphere, responsible for a significant portion of total greenhouse gas emissions, is on track to double over this century. This dire trajectory is attributed to the widespread utilization of fossil fuels and holds the potential to raise atmospheric temperatures by a staggering 5 °C by the close of the century (Kraaijenbrink et al., 2017). In the pursuit of identifying the fundamental causes underlying this alarming environmental decline, a considerable body of previous research has endeavored to establish a connection between CO2 emissions and the trajectory of economic development. Nevertheless, the findings within this realm have displayed a degree of inconsistency and incongruity. A comprehensive synthesis of prior literature can be found in Table 1, which provides an overview of the 20 most prominently cited studies, as culled from the expansive repository of the Web of Science database.

Several studies have delved into the intricate relationship between economic growth and CO2 emissions, revealing diverse outcomes. Some research has pointed toward a negative association between these variables, suggesting that as the economy expands, the magnitude of CO2 emissions diminishes (Bamisile et al., 2021; Yaduma et al., 2015; Zanin & Marra, 2012). Conversely, other investigations have showcased a positive connection (Dong et al., 2020; Li et al., 2017; Liimatainen & Pollanen, 2013; Meng et al., 2012; Mohsin et al., 2019). Liu and Hao (2018) and Xie et al. (2020) have both indicated the presence of short-term and long-term bidirectional causality between CO2 emissions and economic growth as measured by GDP. In contrast, the study by Lin et al. (2017) found that augmenting economic growth, encompassing real economic development and urbanization, does not necessarily result in a substantial upsurge in CO2 emissions.

The environmental Kuznets curve (EKC), initially formulated by Kuznets (1955) to elucidate the relationship between income inequality and income levels, has emerged as a pivotal framework in this domain. The EKC posits that during the initial stages of economic growth, the detrimental impact on environmental degradation intensifies; however, beyond a certain income per capita threshold, this impact starts to wane. Espoir and Sunge (2021), Song et al. (2019), and Yaduma et al. (2015) have presented evidence that aligns with the EKC hypothesis, suggesting that attaining a specific income per capita level correlates with improvements in environmental conditions, including CO2 emissions. In contrast, the findings of Azomahou et al. (2006) challenge this hypothesis, and Zanin and Marra (2012) have even identified varied patterns such as L, M, and N-shaped curves across different regions to explain the connection between economic growth and CO2 emissions. Taking a broader global perspective over an extended research span, Yaduma et al. (2015) segregated countries within their sample into OECD and non-OECD categories to discern disparities in economic development levels. They revealed that the OECD group emitted approximately 60 to 369 percent more CO2 compared to non-OECD nations. When comparing countries with equivalent income levels between these groups, non-OECD countries exhibited 26 to 40 percent higher pollution levels than their OECD counterparts. Similarly, Liu and Hao (2018) uncovered unidirectional short-term causality between per capita GDP and renewable energy for energy-importing nations, while the causality reverses in the long run. In the case of energy-importing countries, they identified unidirectional short-term causation between GDP per capita and energy consumption, alongside bidirectional long-term causality between these variables.

Liou and Wu (2011), in a comprehensive global study, scrutinized the nexus between economic growth, energy consumption efficiency, and CO2 emission control efficiency across 57 nations between 1990 and 2005. Their findings underscored the pivotal role of economic development, gauged by per capita GDP, in determining energy usage efficiency

Table 1 Most cited studies on economic development and CO2 emission

References	Variable description	Sample	Method	Findings
Ahmad et al. (2021)	Carbon dioxide emissions (CO2e) according to the IPCC (2014) guidelines, the Added value of the construction industry	China 1999–2018	Dynamic common correlated effects mean group method (DCCEMGM) and Dumitrescu-Hurlin causality	Land urbanization reduces emissions (CO2) via the use of eco-friendly building techniques
Azomahou et al. (2006)	National CO2 emission per capita (Carbon Dioxide Information Analysis Center), GDP per capita	Global 1960–1996	Nonparametric panel model	Estimation findings indicate that the connection is ascending
Bamisile et al. (2021)	Fossil CO2 emissions of a country annually which include sources from fossil fuel use as well as Product use measured in MtCO2/yr. GNI, GDS, Trade, DCPS	Africa 1990–2017	Feasible general least squares (FGLS)	GNI and carbon emissions were shown to be significantly positively associated across all sectors, meaning that as national income in Africa grows, so do carbon emissions
Charfeddine (2017)	CO2 emissions that stem from the burning of fossil fuels, Ecological Footprint is a measure of how much people demand from biologically productive surfaces, income per capita, trade openness, urbanization	Qatar 1970–2015	Markov Switching Equilibrium Correction Model (MS-ECM)	Long-term correlation between environmental deterioration and economic growth
Danish et al. (2019)	Natural logarithm form of carbon dioxide emissions, income, natural resources, renewable energy	BRICS countries 1990–2015	Augmented mean group (AMG) panel algorithm	The influence of natural resources on CO2 emissions in Brazil, China, and India is negligible. Due to the availability of a great variety of natural resources, their abundance aids in reducing pollution in Russia
Dong et al. (2020)	CO2 Emissions from Fuel Combustion, GDP (measured in constant million 2010 US$)	Global 1997–2015	Logarithmic mean Divisia index (LMDI)	CO2 emissions are mostly driven by economic expansion

Table 1 (continued)

References	Variable description	Sample	Method	Findings
Espoir and Sunge (2021)	Co2 as the stock of carbon dioxide emissions per capita; GDP per capita, openness to international Trade, renewable energy consumption, index of governance	Africa 1996–2012	Dynamic spatial panel model	There are major global direct and indirect implications of the CO2 growth nexus
Gardiner and Hajek (2020)	CO2 emissions, and economic development (gross domestic product (GDP), foreign direct investment (FDI), net exports, and employment in industry)	European Union 1990–2015	Variance decomposition and cointegration approach	The findings demonstrate the presence of at least long-run equilibrium linkages between economic growth, energy consumption, CO2, foreign direct investment, and net exports
Li et al. (2017)	Fossil fuel consumption, CO2 emission, GDP, Total factor productivity, energy efficiency, international trade, labor force	China 2007–2013	Dynamic energy-environment-economic CGE	Energy supply limits reduce GDP; by 2050, the negative effect of constrained fossil fuel supplies on GDP may be mitigated
Liimatainen and Pollanen (2013)	CO2 intensity, transport intensity, energy efficiency	Finland 1996–2010	Decoupling	The CO2 intensity of Finnish road freight transit has significantly dropped. The majority of the decline may be traced to the change from delivering big commodities to conveying parcels
Lin et al. (2017)	CO2 emissions, total population, gross domestic product, employed population, urban population, industrial added value, and energy consumption	Global 1991–2013	STIRPAT model	Accelerating urbanization and genuine economic growth will not significantly raise CO2 emissions

Table 1 (continued)

References	Variable description	Sample	Method	Findings
Liou and Wu (2011)	Labor, real capital formation, and total energy use, fossil fuel energy consumption, CO_2 emissions	Global 1950–2005	Fixed effect model (FE) and random effect model (RE)	Enhancing the pure technological efficiency of energy consumption and the scale efficiency of CO_2 emission management is crucial for industrialized nations. In contrast, developing nations must attempt to enhance the pure technological efficiency of CO_2 emission control and energy consumption scale efficiency
Liu and Hao (2018)	Alternative and renewable energy, CO_2 emissions, Energy use per capita, Industry value added, GDP per capita	Global 1970–2013	Vector error correction model (VECM), fully modified OLS (FMOLS) and dynamic OLS (DOLS)	Long-term bidirectional causal relationships between carbon emissions, energy consumption, industrial value added, and per capita GDP
Meng et al. (2012)	CO_2 emissions, population, annual disposable, income per capita, and GDP and Consumer Price Index (CPI)	China 1989–2008	STIRPAT model	There are three crucial areas for CO_2 reduction: (a) lowering the proportion of coal in overall energy consumption and replacing it with non-fossil energies; (b) regulating the use of automobiles in urban areas; and (c) modifying industrial structure
Mohsin et al. (2019)	Carbon dioxide from the transport sector, Energy consumption per capita, Population density, Population in urban agglomerations, GDP per capita, Population growth rate	Pakistan 1975–2015	Hybrid error correction model, regression coefficients, platykurtic distribution, Dickey-Fuller test, and cointegration test	A rise in economic development, urbanization, and energy use exacerbated environmental deterioration resulting from transportation. urbanization

Table 1 (continued)

References	Variable description	Sample	Method	Findings
Song et al. (2019)	GDP and CO_2 emissions	China and US 1965–2016	Two-dimensional decoupling model	The EKC curve of carbon emissions and per capita GDP for China and the United States has an inverted U shape
Wang et al. (2016)	Energy consumption and labor as input variables, GDP as a desirable output, and CO_2 emissions as an undesirable output	Asia Pacific Economic Cooperation 2001–2010	Non-radial efficiency evaluation model	Falling technical efficiency is the primary impediment to enhancing integrated efficiency and CO_2 emissions efficiency
Xie et al. (2020)	CO_2 emission in the power industry, GDP, power generation of fuel, thermal power generation, terminal power consumption, power generation efficiency, transmission and distribution loss, terminal energy consumption intensity	China 1985–2017	Tapio decoupling model	In the electricity sector, the link between CO_2 emissions and economic growth has synchronized during the previous three decades
Yaduma et al. (2015)	Log of per-capita CO_2 emissions, per-capita income,	Global 1960–2007	Quantile fixed effects model	The deconstruction of a statistically significant OECD–non-OECD emissions difference indicates non-income-related variables pushing against the greening of the non-OECD group
Zanin and Marra (2012)	Real GDP and CO_2 emissions	Selected 9 countries 1960–2008	Additive mixed model	With increasing levels of real GDP, the magnitude of CO_2 emission elasticity exhibited a nonlinear decrease

and CO_2 emission management. Examining China, a significant energy consumer with rapid economic growth, Meng et al. (2012) employed the STIRPAT model to elucidate the relationship between CO_2 emissions and various economic development factors from 1989 to 2008. Their results demonstrated a linear relationship between dependent and independent variables, yet with fluctuations throughout diverse stages of economic development. Factors like social and political upheaval, shifts in industrial structure (particularly changes in fossil fuel utilization), and traffic control policies emerged as influential drivers of this dynamic.

Xie et al. (2020) focused on China's power industry, calculating the decoupling state between CO_2 emissions and economic growth. They found fluctuating negative and weak decoupling trends between 1985 and 2007. Long-term strategies involved reducing energy consumption intensity and transmission losses, whereas short-term tactics emphasized increasing clean energy usage and optimizing thermal power generation structures. Shifting the focus to healthcare-related development, Ahmed et al. (2021) unveiled a unilateral connection between urbanization and CO_2 emissions, a health-deteriorating impact of CO_2 emissions on healthcare expenditure, and a reinforcing influence of healthcare expenditure on urbanization. Since early economic examinations of wealth distribution, entrepreneurship's pivotal role has been highlighted, initially championed by Schumpeter (1934). Though various definitions of entrepreneurship exist, the comprehensive framing by Shane and Venkataraman (2000) is widely embraced across disciplines. They portray entrepreneurship as a process involving opportunity evaluation, discovery, and exploitation for introducing novel products, processes, services, or markets. This concept posits that entrepreneurs drive business creation, employment generation, innovation, and consequent development. However, a comprehensive literature review reveals conflicting conclusions regarding this assertion. Refer to Table 2 for a compilation of highly cited studies from the Web of Science database, delving into the link between entrepreneurship and economic development.

The prevailing body of research in the field lends substantial support to the proposition that entrepreneurial endeavors exert a positive influence on economic performance. For instance, in their comprehensive analysis, Audretsch et al. (2015) examined the intricate interplay between entrepreneurship and economic growth across 127 European urban centers spanning the period from 1994 to 2009. Their investigation illuminated an immediate and favorable developmental impact stemming from the emergence of new start-up enterprises, both within small to medium-sized cities and larger metropolitan areas. Furthermore, they unearthed a nuanced U-shaped correlation between variables within the context of major cities over the long term. This correlation indicated a simultaneous occurrence of direct displacement effects, marked by heightened competition prompting the exit of incumbent players, and amplified supply-side spillover effects. However, it's noteworthy that this pattern was not discerned in the context of smaller urban locales. Applying an econometric approach, Dvoulety (2017) subjected the hypothesis to empirical scrutiny by analyzing data from a panel encompassing 13 distinct regions within the Czech Republic over the interval from 2003 to 2015. His analysis revealed divergent outcomes, wherein elevated rates of newly established enterprises and collaborative partnerships corresponded with elevated per capita GDP, while no such correlation was established for newly established self-employed ventures. Nevertheless, both categories of entrepreneurial activity did contribute to the reduction of unemployment rates within the Czech region. Delving into the domain of gender-specific entrepreneurial activities, Terjesen and Amoros (2010) conducted an in-depth exploration of the link between female entrepreneurship and economic progress across 13 Latin American and Caribbean nations during the timeframe 2001 to

Table 2 Most cited studies on entrepreneurship and economic development

References	Variable description	Sample	Method	Findings
Anderson et al. (2006)	Indigenous land rights, entrepreneurship, and economic development	Canada 2006	Case study	Social entrepreneurship has a significant role in the economic prosperity of the indigenous population in Canada
Audretsch et al. (2015)	Entrepreneurship, measured as the number of firm start-ups, urban economic development as the logarithm of GDP per capita in purchasing power parity prices (PPP),	Europe 1994–2009	Linear panel regression model	Validated are the beneficial direct and indirect impacts, as well as the creative destruction, of new firm formation on economic performance
Chrisman et al. (1995)	Faculty entrepreneurship and economic development	Canada 1995	Questionnaire survey and interview	The economic advantages of the faculty's entrepreneurial initiatives are enormous
Dvouletý (2017)	GDP per capita, unemployment rate, rate of newly established business companies and partnership set-ups per capita, rate of newly established self-employed set-ups per capita	Czech Republic 2003–2015	Pooled OLS	Only the higher rates of newly formed business corporations and partnerships were connected with higher levels of GDP per capita in the Czech region, whereas the rate of newly formed self-employed businesses had no effect
Fritsch and Wyrwich (2017)	Regional entrepreneurial culture, employment, number of start-ups, the self-employment rate	Germany 1976–2010	Regression analysis	The regional culture of entrepreneurship is a key resource for regional development
Fuller-Love et al. (2006)	Entrepreneurship and rural economic development	Wales	Case study	Entrepreneurs and encouraging indigenous businesses are critical for economic success in rural regions
Koster and Rai (2008)	Small Scale Industries (SSI), GDP	India	Case study	Recent economic development seems to be substantially influenced by entrepreneurship
Leeson and Boettke (2009)	Two-tiered entrepreneurship and economic development	NA	Conceptual	While private protection technologies permit some investment and trade by safeguarding people's property when the government does not, the efficacy of these technologies may be constrained in a way that prevents investment and exchange from expanding beyond small levels
Liñán and Fernandez-Serrano (2014)	Total Entrepreneurial Activity (TEA), GDP per capita	European Union 2001–2011	Linear regression	Cultural and entrepreneurial characteristics may define nations according to their degree of development, accounting for about 60 percent of the variation in per capita Gross Domestic Product

Table 2 (continued)

References	Variable description	Sample	Method	Findings
Terjesen and Amoros (2010)	Rate of female opportunity-based entrepreneurs, Competitiveness Index, GDP	Latin America 2001–2008	Pooled OLS	The findings highlight the significantly lower industrial productivity of many Latin American new businesses (self-employment) in comparison to their counterparts in affluent nations
Wennekers et al. (2005)	Total entrepreneurial activity, GDP growth in constant prices, unemployment, income disparity	Global 2002	Regression analysis	Improving incentive structures for company start-ups is the most viable public policy strategy for the most developed countries. Developing countries may be better off seeking scale economies, encouraging direct foreign investment, and boosting management education
Szabo and Herman (2012)	Economic development GDP per capita, Competitiveness Index, Total entrepreneurial activity	European Union 2011–2013	Regression analysis	Differences in innovative entrepreneurship may explain variations in economic development levels

2008. Their comprehensive findings pointed to a relatively subdued impact of female-driven entrepreneurial ventures on industrial productivity within the sample countries. Contrastingly, the findings by Fritsch and Mueller (2004) unveiled a significant negative relationship between the establishment of new businesses and regional employment within Germany. This empirical analysis, undertaken on a panel of firms throughout 1983 to 2002, underscored the substantial influence exerted by indirect supply-side effects stemming from new market entrants, a dynamic they asserted to eclipse the mere job creation aspect. Subsequent investigations by Fritsch and Mueller (2008) fortified these observations, corroborating the diminishing positive effect of new business establishment. They attributed this attenuation to the displacement of established incumbents or the subsequent exit of newly established enterprises, both outcomes triggered by heightened market competition.

The observed divergences across the assorted reviewed studies, reflective of the broader literature, could stem from multifaceted determinants including the heterogeneous composition of samples, variations in research durations, idiosyncratic attributes of specific countries, employment of diverse models and econometric methodologies, consideration of distinct metrics for environmental degradation, and even variations in the scope of CO2 emissions. This intricate web of contradictory and inconclusive outcomes compounds the complexity of deriving meaningful insights and informed decision-making, particularly in the context of governmental environmental policies (Işık et al., 2024; Umar Farooq et al., 2023; Mondal, 2023). This challenge is further exacerbated by the heightened awareness of environmental transformations and the resultant calls for proactive measures. Against this backdrop, and fueled by the identified gaps in existing literature, the current research endeavors to contribute robust evidence, as expounded in the subsequent sections.

3 Empirical model and data

Utilizing annual data spanning from 2002 to 2018, the study tracks the evolution of CO2 emissions across fourteen countries.[4] One notable constraint of this investigation is the lack of information regarding entrepreneurial metrics across various periods and geographical locations. Thus, these data constitute the singular dataset available for empirical examination. To assess the influence of various components on CO2 emissions, a total of 45 distinct models were computed. Building upon insights from prior empirical research, multiple potential variables associated with CO2 emissions were validated as control factors. These encompass the natural logarithm of gross domestic product (*lnGDPP*) per capita, along with its squared variant ($lnGDPP^2$), degree of urbanization (*lnURB*), level of trade openness (*lnOPE*), energy intensity (*lnENE*), and resource rent (*LnREN*). These variables are incorporated into the subsequent model for analysis:

$$lnCO_{2it} = \beta_1 + \beta_2 lnGDPP_{it} + \beta_3 lnGDPP^2_{it} + \beta_4 lnURB_{it} + \beta_5 lnOPE_{it} + \beta_6 lnENE_{it} + \beta_7 LnREN_{it} \quad (1)$$

where *ln* represents the logarithmic transformation of the variables, and the obtained coefficients are elasticities. Table 3 displays the results of the estimate of this model using several panel data models. The EKC hypothesis indicates that there is a relationship between economic growth and environmental quality. This hypothesis asserts that there is a positive

[4] Including Argentina, Brazil, Chile, Croatia, Germany, Greece, Ireland, Italy, Slovenia, South Africa, Spain, Switzerland, United Kingdom, United States.

Table 3 Definitions of variables

Variable	Variable constructed	Included in	Source
$lnCO_2$	$= log(CO_2); CO_2 = CO_2$ Emissions (metric tons per capita)		WDI
$lnGDPP$	$= log(GDPP); GDPP=$ GDP per capita (constant 2015 US$)	All models	WDI
$lnENE$	$=$ log(ENE); $ENE=$ Energy intensity level of primary energy (MJ/$2017 PPP GDP)	All models	WDI
$lnURB$	$=$ log(URB); $URB=$ Urban population (% of the total population)	All models	WDI
$lnOPE$	$= log(OPE); OPE=$ Trade Openness (% of GDP)	All models	WDI
$lnREN$	$= log(REN); REN=$ Resource rent (% of GDP)	All models	WDI
$lnGS$	$= log(GS); GS =$ Governmental support and policies	Models A1, B1, C1, D1	GEM
$lnTB$	$= log(TB); TB =$ Taxes and bureaucracy	Models A2, B2, C2, D2	GEM
$lnGP$	$= log(GP); GP =$ Governmental programs	Models A3, B3, C3, D3	GEM
$lnBE$	$= log(BE); BE =$ Basic school entrepreneurial education and training	Models A4, B4, C4, D4	GEM
$lnPE$	$= log(PE); PE =$ Post-school entrepreneurial education and training	Models A5, B5, C5, D5	GEM
$lnRD$	$= log(RD); RD =$ R&D transfer	Models A6, B6, C6, D	GEM
$lnCP$	$= log(CP); CP =$ Commercial and professional infrastructure	Models A7, B7, C7, D7	GEM
$lnMD$	$= log(MD); MD =$ Internal market dynamics	Models A8, B8, C8, D8	GEM
$lnMO$	$= log(MO); MO =$ Internal market openness	Models A9, B9, C9, D9	GEM
$lnPS$	$= log(PS); PS =$ Physical and services infrastructure	Models A10, B10, C10, D10	GEM
$lnCS$	$= log(PS); PS =$ Cultural and social norms	Models A11, B11, C11, D11	GEM

WDI: World Development Indicator; https://datacatalog.worldbank.org/dataset/world-development-indicators

GEM: Global Entrepreneurship Monitor; https://www.gemconsortium.org/data

association between economic development and the quality of the surrounding environment, as represented by an inverted letter U. As the rate of economic growth quickens, the environment first degrades but later starts to improve. As a direct result, the GDP per capita squared coefficient derived in the computation for the CO2 emissions equation must be negative (Grossman and Krueger, 1995). Larger levels of economic activity and GDP lead to higher levels of energy consumption and, as a consequence, increased levels of carbon dioxide emissions. On the other hand, scale effects cause an increase in people's desire for a healthier environment, which in turn leads to stricter regulations. These impacts are referred regarded as "income-induced method effects" (Hübler & Keller, 2010). Moreover, characteristics associated with urbanization and energy usage (Bing et al., 2011; Chakravarty and Tavoni, 2013; Epule, 2012) as well as trade openness (Acheampong et al., 2020; Solarin et al., 2017) are commonly cited as potential factors in the explanation of CO2 emissions:

Viewed through the lens of ecopreneurship, an extensive body of scholarly work has delved into elucidating the correlation between sustainable development and entrepreneurship (Cohen et al., 2008; Sun et al., 2020). Nevertheless, the advent of entrepreneurial endeavors does not automatically ensure the emergence of groundbreaking eco-friendly technologies. The capacity to conceive innovative technologies and ideas that substantiate sustainable development stands out as a prominent characteristic of sustainable entrepreneurs. Entrepreneurs adept at aligning societal and environmental objectives with top-tier, traditionally effective products or processes epitomize the paramount criteria for fostering sustainable advancement within an open-market economy (Schaltegger & Wagner, 2011). However, the pivotal breakthroughs within the market that pave the way for enduring development do not materialize serendipitously; they are rather the result of relentless toil and capital infusion from entrepreneurs who position innovative strides at the core of their corporate strategy and ascribe their paramount importance. Iqbal et al. (2020) posit that green entrepreneurship presents a viable avenue for kindling entrepreneurial spirit, particularly from a standpoint of sustainability. The scholars advocate for the formulation of a green finance blueprint to buttress sustainable economic expansion and nurture sustainable progress.

Sustainable entrepreneurs are those who adopt ecological advancement as their foremost business ethos (Schaltegger & Wagner, 2011). The pivotal contribution of these entrepreneurs lies in the conception of novel, inventive, and sustainable production methodologies that yield products and services that significantly curb the adverse consequences of environmental decline while enriching the overall quality of life (York & Venkataraman, 2010). This vantage point underscores the essentiality of innovation in the realm of environmental entrepreneurship. Investigation into ecological innovation, as well as harnessing human expertise in energy and resource stewardship, constitute pivotal requisites for entrepreneurs aiming to actualize ecological innovation (Li et al., 2018). As technological strides march forward, the potential for augmented productivity could birth environmentally conscious innovations, yet it might also have the converse impact, compromising the environment as industries expand. The outcomes of entrepreneurial pursuits may well aid in rectifying environmental quandaries, yet such ventures might inadvertently employ pollutive energy sources or fossil fuels. Entrepreneurial activities could even hamper the scaling up of production due to the adoption of other manufacturing practices detrimental to the environment. In light of these considerations, it becomes imperative for governments to devise an environmental entrepreneurship blueprint to harness the dividends of entrepreneurial endeavors for environmental betterment.

In the ensuing sections, we shall proffer models for scrutinizing the influence of entrepreneurial indicators on the interplay between energy consumption efficiency and economic growth vis-à-vis ecological footprint. This analysis will elucidate the positive and negative facets of entrepreneurial indicators in shaping these dynamics.

Concurrently with the insertion of control variables, we enter additional variables in the form of three model categories. The inclusion of logarithmic Entrepreneurship Indices (*lnENT*) can be observed in model A. The outcomes of this particular model's estimation are presented in Table 5. To mitigate the potential issue of collinearity, a deliberate separation of the eleven indicators of Entrepreneurship was implemented, leading to distinct estimation models A and B. These separate models were devised to assess the self-reliant impacts of each indicator. To streamline the information presented in Tables 5 and 6 and to reduce unnecessary intricacy, the term *lnENT* is employed as a representation for all Entrepreneurship indicators. For instance, in models 7 and 11, *lnENT* encapsulates the logarithms of Commercial and professional infrastructure and Cultural and social norms. For a comprehensive understanding of which specific Entrepreneurship index is utilized in each estimation methodology, reference Table 1.

$$lnCO_{2it} = \beta_1 + \beta_2 lnGDPP_{it} + \beta_3 lnGDPP_{it}^2 + \beta_4 lnURB_{it} + \beta_5 lnOPE_{it} + \beta_6 lnENE_{it} + \beta_7 LnREN_{it} + \beta_8 lnENT_{it} \tag{2}$$

In addition, the following equation is estimated as Model B in Table 6 to assess the spillover effects of the entrepreneurial indices on the efficacy of energy intensity in decreasing CO2 emissions:

$$lnCO_{2it} = \beta_1 + \beta_2 lnGDPP_{it} + \beta_3 lnGDPP_{it}^2 + \beta_4 lnURB_{it} + \beta_5 lnOPE_{it} + \beta_6 lnENE_{it} + \beta_7 LnREN_{it} + \beta_8 lnENT_{it} + \beta_9 \left(lnENT_{it} \times lnENE_{it}\right) \tag{3}$$

The coefficient of the interaction term, $\left(lnENT_{it} \times lnENE_{it}\right)$, reveals the interaction between the entrepreneurial indices and energy intensity. To study the marginal impacts of energy intensity on CO2 emissions, the derivate of Eq. (3) about $lnENE_{it}$ is computed as follows:

$$\frac{d(lnCO_{2it})}{d(lnENE_{it})} = \beta_7 + \beta_9 lnENT_{it} \tag{4}$$

Also, relations 5 and 6 have been estimated in the form of the C and D models to investigate the effects of entrepreneurship indicators on the effectiveness of the logarithm of GDP and its quadratic form on CO2. The estimation results for these models are reported in Tables 7 and 8.

$$lnCO_{2it} = \beta_1 + \beta_2 lnGDPP_{it} + \beta_3 lnGDPP_{it}^2 + \beta_4 lnURB_{it} + \beta_5 lnOPE_{it} + \beta_6 lnENE_{it} + \beta_7 LnREN_{it} + \beta_8 lnENT_{it} + \beta_9 \left(lnENT_{it} \times lnGDPP_{it}\right) \tag{5}$$

$$lnCO_{2it} = \beta_1 + \beta_2 lnGDPP_{it} + \beta_3 lnGDPP_{it}^2 + \beta_4 lnURB_{it} + \beta_5 lnOPE_{it} + \beta_6 lnENE_{it} + \beta_7 LnREN_{it} + \beta_8 lnENT_{it} + \beta_9 \left(lnENT_{it} \times lnGDPP_{it}\right) + \beta_{10} \left(lnENT_{it} \times lnGDPP_{it}^2\right) \tag{6}$$

To investigate the effect of GDP on CO2, we take a derivative from these equations concerning the logarithm of GDP. Equations 7 and 8 are obtained respectively:

$$\frac{d(lnCO_{2it})}{d(lnGDP_{it})} = (\beta_2 + \beta_9 lnENT_{it}) + 2 \times \beta_3 \times InGDPP_{it} \tag{7}$$

$$\frac{d(lnCO_{2it})}{d(lnGDP_{it})} = (\beta_2 + \beta_9 lnENT_{it}) + 2 \times \left(\beta_3 + \beta_{10} lnENT_{it}\right) \times InGDPP_{it} \tag{8}$$

Hence, by computing the aforementioned equations, we can discern how the indicators of entrepreneurial activity contribute to altering the trajectory and inclination of the Environmental Kuznets Curve.

Table 4 Statistics summary (2002–2018)

	Mean	Median	Maximum	Minimum	Std. Dev	Observations
$lnCO_2$	1.837	1.902	2.975	0.536	0.500	252
lnGDPP	10.045	10.095	11.390	8.540	0.764	252
lnENE	1.260	1.234	2.291	0.278	0.366	252
lnURB	4.286	4.340	4.522	3.929	0.164	252
lnREN	− 0.897	-1.083	2.846	− 4.755	1.902	252
lnOPE	4.145	4.104	5.531	3.096	0.557	252
lnGS	1.425	1.440	1.855	0.916	0.193	252
lnTB	1.297	1.306	1.820	0.788	0.261	252
lnGP	1.472	1.470	1.821	0.986	0.195	252
lnBE	1.166	1.157	1.595	0.788	0.152	252
lnPE	1.527	1.526	1.869	1.147	0.126	252
lnR&D	1.394	1.381	1.828	1.040	0.160	252
lnCP	1.621	1.614	1.949	1.316	0.115	252
lnMD	1.559	1.569	1.864	1.115	0.136	252
lnMO	1.458	1.457	1.753	1.109	0.137	252
lnPS	1.807	1.803	2.069	1.520	0.128	252
lnCS	1.510	1.488	2.035	0.993	0.184	252

Table 5 Estimation results of Eq. 1

	Pooled OLS	Spatial fixed effects	Time-period fixed effects	Spatial and time-period fixed effects	Panel EGLS (Cross-section random effects)
constant	− 27.036				
	(0.000)				
lnGDPP	4.647	1.679	4.661	2.001	2.332
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
$lnGDPP^2$	− 0.198	− 0.018	− 0.198	− 0.033	− 0.054
	(0.000)	(0.432)	(0.000)	(0.181)	(0.030)
lnENE	1.362	1.303	1.373	1.197	1.142
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
lnURB	− 0.057	− 0.739	− 0.060	0.014	− 0.290
	(0.677)	(0.000)	(0.662)	(0.950)	(0.173)
lnREN	− 0.011	0.003	− 0.012	− 0.002	0.007
	(0.390)	(0.594)	(0.336)	(0.763)	(0.351)
lnOPE	0.185	− 0.046	0.183	− 0.051	− 0.071
	(0.000)	(0.092)	(0.000)	(0.055)	(0.009)
$Log-Lik$	46.489	487.408	47.324	510.515	
R^2	0.837	0.995	0.838	0.996	
$LR-test$		46.214	926.384		
		(0.000)	(0.000)		
HausmanTest					43.300
					(0.000)

Table 6 Diagnostic tests for choosing the optimal panel model

	Spatial fixed effects		Time-period fixed effects		Hausman test-statistic	
Model A1	52.231	(0.000)	930.018	(0.000)	29.160	(0.000)
Model A2	49.486	(0.000)	927.827	(0.000)	646.444	(0.000)
Model A3	53.180	(0.000)	930.747	(0.000)	897.297	(0.000)
Model A4	46.614	(0.000)	922.300	(0.000)	271.146	(0.000)
Model A5	45.400	(0.000)	923.205	(0.000)	279.652	(0.000)
Model A6	44.620	(0.000)	926.438	(0.000)	360.592	(0.000)
Model A7	46.223	(0.000)	921.310	(0.000)	258.232	(0.000)
Model A8	48.243	(0.000)	911.123	(0.000)	192.483	(0.000)
Model A9	46.159	(0.000)	918.862	(0.000)	522.492	(0.000)
Model A10	47.484	(0.000)	888.898	(0.000)	379.463	(0.000)
Model A11	53.488	(0.000)	881.155	(0.000)	132.574	(0.000)
Model B1	54.361	(0.000)	916.517	(0.000)	184.191	(0.000)
Model B2	55.443	(0.000)	929.490	(0.000)	280.420	(0.000)
Model B3	54.175	(0.000)	891.109	(0.000)	541.350	(0.000)
Model B4	50.194	(0.000)	941.335	(0.000)	87.324	(0.000)
Model B5	49.031	(0.000)	927.802	(0.000)	150.264	(0.000)
Model B6	44.833	(0.000)	927.159	(0.000)	283.948	(0.000)
Model B7	50.860	(0.000)	929.205	(0.000)	161.598	(0.000)
Model B8	42.565	(0.001)	914.885	(0.000)	171.256	(0.000)
Model B9	49.852	(0.000)	917.142	(0.000)	233.752	(0.000)
Model B10	47.387	(0.000)	880.105	(0.000)	442.045	(0.000)
Model B11	53.961	(0.000)	881.608	(0.000)	156.141	(0.000)
Model C1	49.551	(0.000)	899.228	(0.000)	857.346	(0.000)
Model C2	47.554	(0.000)	894.080	(0.000)	313.841	(0.000)
Model C3	52.535	(0.000)	931.644	(0.000)	322.454	(0.000)
Model C4	48.333	(0.000)	920.184	(0.000)	93.770	(0.000)
Model C5	44.700	(0.000)	905.682	(0.000)	156.659	(0.000)
Model C6	44.321	(0.001)	892.552	(0.000)	211.564	(0.000)
Model C7	50.646	(0.000)	922.657	(0.000)	3.042	(0.963)
Model C8	48.826	(0.000)	903.368	(0.000)	180.800	(0.000)
Model C9	49.102	(0.000)	925.981	(0.000)	108.210	(0.000)
Model C10	47.220	(0.000)	855.726	(0.000)	439.923	(0.000)
Model C11	53.272	(0.000)	877.954	(0.000)	137.188	(0.000)
Model D1	47.235	(0.000)	892.556	(0.000)	2409.913	(0.000)
Model D2	47.154	(0.000)	908.932	(0.000)	72.745	(0.000)
Model D3	52.463	(0.000)	925.335	(0.000)	367.133	(0.000)
Model D4	38.121	(0.004)	936.316	(0.000)	151.153	(0.000)
Model D5	43.156	(0.001)	903.700	(0.000)	131.065	(0.000)
Model D6	43.935	(0.001)	878.664	(0.000)	215.581	(0.000)
Model D7	50.046	(0.000)	916.934	(0.000)	133.732	(0.000)
Model D8	44.086	(0.001)	913.110	(0.000)	114.924	(0.000)
Model D9	47.757	(0.000)	924.454	(0.000)	97.292	(0.000)
Model D10	47.832	(0.000)	840.801	(0.000)	357.583	(0.000)
Model D11	48.863	(0.000)	867.202	(0.000)	175.754	(0.000)

Table 7 Estimation results of Eq. 2

	Model A1	Model A2	Model A3	Model A4	Model A5	Model A6	Model A7	Model A8	Model A9	Model A10	Model A11
lnGDPP	1.955	2.034	1.855	2.052	1.995	1.998	1.983	1.984	2.005	2.051	1.964
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
$lnGDPP^2$	− 0.031	− 0.035	− 0.027	− 0.035	− 0.032	− 0.032	− 0.032	− 0.031	− 0.033	− 0.035	− 0.032
	(0.197)	(0.148)	(0.268)	(0.154)	(0.187)	(0.184)	(0.199)	(0.202)	(0.180)	(0.148)	(0.181)
lnENE	1.174	1.181	1.192	1.193	1.197	1.197	1.198	1.201	1.196	1.186	1.214
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
lnURB	0.176	0.059	0.172	0.030	0.013	0.021	0.018	0.029	0.010	0.016	0.157
	(0.459)	(0.800)	(0.465)	(0.897)	(0.956)	(0.927)	(0.937)	(0.899)	(0.965)	(0.944)	(0.496)
lnREN	− 0.001	− 0.001	− 0.001	− 0.002	− 0.002	− 0.002	− 0.002	− 0.003	− 0.002	− 0.003	0.001
	(0.847)	(0.883)	(0.847)	(0.801)	(0.760)	(0.783)	(0.762)	(0.634)	(0.753)	(0.682)	(0.842)
lnOPE	− 0.044	− 0.051	− 0.038	− 0.052	− 0.052	− 0.051	− 0.052	− 0.047	− 0.051	− 0.049	− 0.040
	(0.103)	(0.057)	(0.164)	(0.054)	(0.055)	(0.060)	(0.055)	(0.081)	(0.060)	(0.067)	(0.129)
lnENT	0.045	0.037	0.069	0.014	− 0.003	0.006	− 0.009	0.040	− 0.007	− 0.040	0.086
	(0.015)	(0.073)	(0.008)	(0.507)	(0.904)	(0.800)	(0.794)	(0.157)	(0.811)	(0.265)	(0.001)
$Log-lik$	513.539	512.156	514.043	510.742	510.523	510.548	510.550	511.540	510.545	511.153	515.826
R^2	0.996	0.996	0.996	0.996	0.996	0.996	0.996	0.996	0.996	0.996	0.996

Table 8 Estimation results of Eq. 3

	Model B1	Model B2	Model B3	Model B4	Model B5	Model B6	Model B7	Model B8	Model B9	Model B10	Model B11
lnGDPP	2.431	2.427	2.074	2.408	2.187	2.111	2.230	2.110	2.288	2.059	2.140
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
$lnGDPP^2$	− 0.055	− 0.055	− 0.038	− 0.054	− 0.042	− 0.038	− 0.045	− 0.039	− 0.047	− 0.036	− 0.041
	(0.023)	(0.025)	(0.153)	(0.027)	(0.083)	(0.131)	(0.072)	(0.109)	(0.059)	(0.149)	(0.114)
lnENE	1.479	1.416	1.296	1.459	1.475	1.283	1.558	0.854	1.419	1.170	1.298
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
lnURB	− 0.131	0.144	0.194	− 0.096	− 0.080	0.063	0.054	− 0.164	0.020	0.013	0.136
	(0.590)	(0.528)	(0.412)	(0.672)	(0.728)	(0.789)	(0.813)	(0.492)	(0.929)	(0.956)	(0.557)
lnREN	0.003	0.002	− 0.001	− 0.001	0.000	− 0.001	0.002	− 0.003	0.000	− 0.003	0.002
	(0.650)	(0.763)	(0.926)	(0.935)	(0.962)	(0.908)	(0.798)	(0.643)	(0.979)	(0.671)	(0.753)
lnOPE	− 0.036	− 0.055	− 0.040	− 0.051	− 0.051	− 0.053	− 0.055	− 0.050	− 0.050	− 0.048	− 0.039
	(0.165)	(0.036)	(0.138)	(0.050)	(0.056)	(0.051)	(0.039)	(0.061)	(0.060)	(0.084)	(0.140)
lnENT	0.328	0.265	0.170	0.287	0.248	0.092	0.300	− 0.215	0.199	− 0.053	0.157
	(0.000)	(0.000)	(0.086)	(0.000)	(0.009)	(0.339)	(0.009)	(0.028)	(0.036)	(0.640)	(0.058)
$lnENT \times lnENE$	− 0.225	− 0.175	− 0.076	− 0.230	− 0.190	− 0.065	− 0.236	0.209	− 0.154	0.009	− 0.059
	(0.000)	(0.002)	(0.324)	(0.000)	(0.006)	(0.357)	(0.005)	(0.007)	(0.023)	(0.908)	(0.367)
$Log - lik$	521.878	517.123	514.544	520.261	514.398	510.986	514.540	515.283	513.169	511.160	516.246
R^2	0.996	0.996	0.996	0.996	0.996	0.996	0.996	0.996	0.996	0.996	0.996

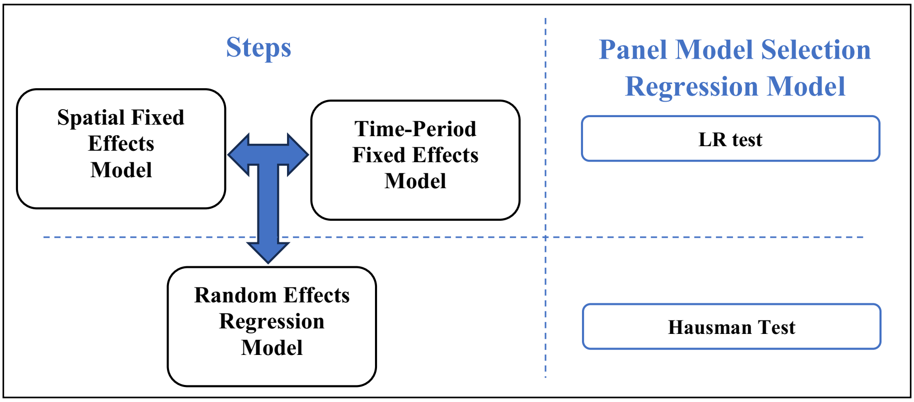

Fig. 1 The calculation procedure used to construct a panel regression model

4 Empirical results

Table 4 provides a summary of the data for the years 2002 to 2018. Because the standard deviations are less than the mean for the bulk of the variables, this indicates that there are no outliers and that there is minimal volatility in the model's variables over an extended period.

Equation 1 was calculated through an array of panel data models, as elucidated in the initial table (Table 5), which exclusively encompasses control models. To illustrate the process of selecting the most appropriate panel model, an array of conventional diagnostic assessments was employed. These tests enable a comprehensive comparison of diverse models, leading to the identification of the optimal model for the given context. Figure 1 illustrates the calculation method used in this study. The flowchart depicts the process of developing a panel regression model.

The initial step involves a comparative analysis between the fixed effects model and the random effects model, executed using the Hausman test. This test serves as a foundational tool for model selection. The outcome hinges on the alternative and null hypotheses: if the alternative hypothesis is upheld, the fixed effects (FE) model is favored, while the null hypothesis encourages the adoption of the random effects (RE) model. Scrutiny of the test outcomes, showcased in Table 5, indicates a consistent rejection of the null hypothesis across all estimated models. As a result, the analytical focus converges on the fixed effects model as the preferred choice for scrutinizing the dataset. After establishing the presence of fixed effects within the model, the analysis proceeds to determine whether these effects are temporally or spatially oriented. This inquiry extends to exploring the feasibility of incorporating time-period and geographically fixed effects. The comparison of models entails the execution of two distinct independent likelihood ratio (LR) tests. The objective of these tests is to determine the effectiveness of models featuring concurrent time-period and spatial fixed effects concerning models where these effects are isolated. A notable observation emerges from these tests, as indicated by a considerably low p-value, resulting in the rejection of the null hypothesis. The significance of the test outcomes, detailed in Table 5, unequivocally advocates for the dismissal of the null hypothesis. This, in turn, emphasizes the necessity of encompassing both time-period and geographic fixed effects concurrently within the model. Furthermore, an analogous methodology is applied to other estimation models and diagnostic examinations, as expounded upon in Table 6.

The results from the estimation reveal a noteworthy relationship: a mere one percent increase in GDP per capita is linked to a notable 2% upswing in CO2 emissions. Simultaneously, the quadratic coefficient linked to GDP per capita stands at − 0.033. Interestingly, this negative coefficient holds little significance, effectively debunking the original postulation of the environmental Kuznets hypothesis within the confines of the countries examined in this study. Examining the factors influencing greenhouse gas emissions, the intensity of energy usage emerges as a key player. The coefficient's value unveils a compelling connection: each percentage hike in energy intensity translates to a substantial 1.197 percent surge in CO2 emissions. This variable's significance lies in its portrayal of energy consumption efficiency. The findings underscore that heightened energy consumption per unit of output triggers an augmentation in CO2 emissions alongside a dip in energy consumption efficiency. Urbanization also merits consideration as a control variable, albeit with marginal implications for CO2 emissions. Given the advanced stage of urbanization in the majority of the sampled countries, any additional urbanization during the study period fails to yield noteworthy outcomes. Meanwhile, the impact of natural resource rental on CO2 emissions proves to be inconsequential. Contrary to initial expectations, the rental of natural resources doesn't wield a substantial influence on greenhouse gas emissions. The concept of trade openness surfaces as another pivotal factor, surprisingly linked to a reduction in greenhouse gas emissions. Strikingly, every percentage point of growth in trade between nations corresponds to a noteworthy 0.05 percent decrease in CO2 emissions. This counterintuitive relationship underscores the intricate dynamics at play in the global trade-environment interplay.

Following the initial model estimation incorporating control variables, the analysis in Table 7 delves into the primary effects of various entrepreneurship metrics on the emissions of greenhouse gases. The results reveal that the coefficients derived for most of the entrepreneurial metrics lack significance, except for four distinct indicators. The study's outcomes suggest that factors such as Governmental support and policies, Taxes and bureaucracy, Governmental programs, and Cultural and social norms wield a noteworthy and affirmative impact on levels of CO2 emissions.

In delving into the intricate environmental ramifications of entrepreneurial indicators, our study delves into their spill-over consequences with a particular focus on curbing energy consumption. The dataset depicted in Table 8 empowers us in our pursuit of this goal. By incorporating the interaction coefficient between the entrepreneurship index and the energy usage intensity, we have enhanced the pertinence of the discoveries when compared to the preceding table's results. As the data in Table 8 illustrates, the immediate influences of entrepreneurial indicators on CO2 emissions (referred to as the *lnENT* coefficient) exhibit predominantly positive and statistically significant associations across the majority of variables. These effects manifest as statistically insignificant only in the context of R&D transfer, and physical and service infrastructure, while revealing an adverse influence on internal market dynamics. Building upon these positive outcomes, the interaction term ($lnENT \times lnENE$) ushers forth noteworthy adverse consequences. Consequently, entrepreneurial indicators yielding indirect impacts contribute substantively to diminishing CO2 emissions, enhancing the environmental landscape by bolstering energy consumption efficiency.

Upon scrutinizing the information in Table 7, it becomes evident that for specific variables, such as Post-school entrepreneurial education and training, Basic school entrepreneurial education and training, Commercial and professional infrastructure, Internal market openness, and Internal market dynamics, the juxtaposition of direct positive and indirect negative effects results in nullification of their collective impact, culminating in a net effect of zero. In contrast,

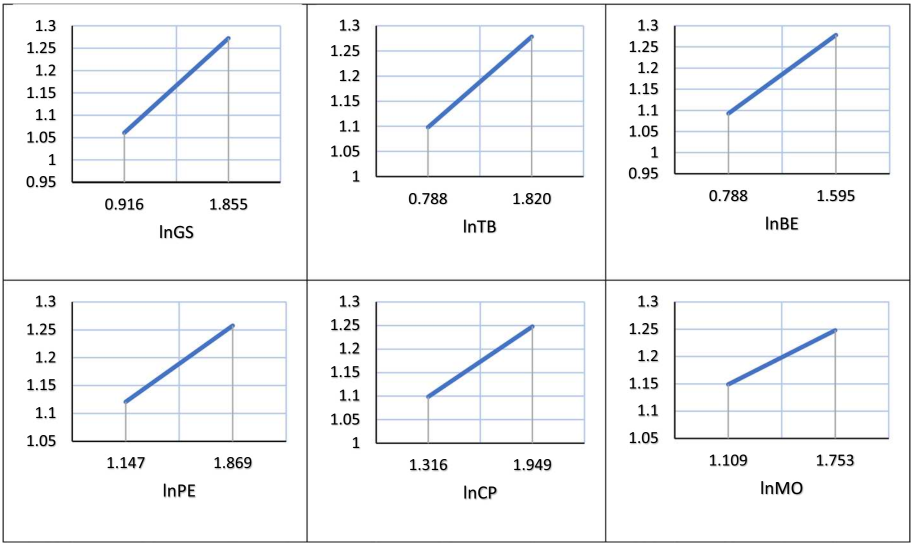

Fig. 2 Effects of energy use intensity on CO2 emissions at different levels of entrepreneurship indicators

for other variables, the ultimate outcomes are affirmative, wherein the CO2 emission-amplifying effects overshadow their CO2 emission-reducing counterparts. To quantitatively express the conclusive ramifications of energy usage intensity on CO2 emissions, we invoke Eq. 4. Ergo, the repercussions of entrepreneurial indicators exhibiting noteworthy direct and indirect effects can be succinctly encapsulated as follows:

$$\frac{d(lnCO_{2it})}{d(lnENE_{it})} = 0.328 - 0.225 \times lnGS_{it} \tag{9}$$

$$\frac{d(lnCO_{2it})}{d(lnENE_{it})} = 0.265 - 0.175 \times lnTB_{it} \tag{10}$$

$$\frac{d(lnCO_{2it})}{d(lnENE_{it})} = 0.287 - 0.230 \times lnBE_{it} \tag{11}$$

$$\frac{d(lnCO_{2it})}{d(lnENE_{it})} = 0.248 - 0.190 \times lnPE_{it} \tag{12}$$

$$\frac{d(lnCO_{2it})}{d(lnENE_{it})} = 0.300 - 0.236 \times lnCP_{it} \tag{13}$$

$$\frac{d(lnCO_{2it})}{d(lnENE_{it})} = -0.215 + 0.209 \times lnMD_{it} \tag{14}$$

$$\frac{d(lnCO_{2it})}{d(lnENE_{it})} = 0.199 - 0.154 \times lnMO_{it} \tag{15}$$

These equations are shown in Fig. 2, which illustrates that the intensity of energy use has a positive impact on CO2 emissions. In addition, these positive impacts diminish with an increase in entrepreneurial indicators, except for the internal market dynamics shown in Fig. 4.

Below is an exploration of the impact of indicators related to entrepreneurship on the correlation between GDP and CO2 emissions. The results obtained from the computations in Eqs. 5 and 6 can be observed in Tables 9 and 10. Upon comparing the information presented in Tables 9 and 10, it becomes evident that the inclusion of the quadratic expression of GDP per capita yields a more substantial influence on numerous variables. As a result, we ground our analysis of Table 10 on the interpretation of the outcomes. Commencing our examination, we initially assess Eq. 8 concerning factors displaying significant spillover repercussions. Utilizing the data sourced from Table 10, we formulate the subsequent equation concerning seven distinct variables associated with entrepreneurship:

$$\frac{d(lnCO_{2it})}{d(lnGDP_{it})} = (-1.770 + 2.667 \times lnTB_{it}) + 2 \times \left(0.155 - 0.132 \times lnTB_{it}\right) \times InGDPP_{it} \tag{16}$$

$$\frac{d(lnCO_{2it})}{d(lnGDP_{it})} = (-2.068 + 3.386 \times lnBE_{it}) + 2 \times \left(0.163 - 0.163 \times lnBE_{it}\right) \times InGDPP_{it} \tag{17}$$

$$\frac{d(lnCO_{2it})}{d(lnGDP_{it})} = (-0.835 + 1.812 \times lnPE_{it}) + 2 \times \left(0.103 - 0.087 \times lnPE_{it}\right) \times InGDPP_{it} \tag{18}$$

$$\frac{d(lnCO_{2it})}{d(lnGDP_{it})} = (-5.736 + 4.440 \times lnCP_{it}) + 2 \times \left(0.338 - 0.212 \times lnCP_{it}\right) \times InGDPP_{it} \tag{19}$$

$$\frac{d(lnCO_{2it})}{d(lnGDP_{it})} = (6.068 - 2.836 \times lnMD_{it}) + 2 \times \left(-0.233 + 0.139 \times lnMD_{it}\right) \times InGDPP_{it} \tag{20}$$

$$\frac{d(lnCO_{2it})}{d(lnGDP_{it})} = (0.082 + 1.586 \times lnMO_{it}) + 2 \times \left(-0.430 - 0.075 \times lnMO_{it}\right) \times InGDPP_{it} \tag{21}$$

$$\frac{d(lnCO_{2it})}{d(lnGDP_{it})} = (-1.295 + 2.053 \times lnENT_{it}) + 2 \times \left(0.129 - 0.101 \times lnENT_{it}\right) \times InGDPP_{it} \tag{22}$$

Exploring the impact of entrepreneurial indices on per capita GDP involves the formulation of Eqs. 16–22, as depicted in Fig. 3. The connection between economic expansion and CO2 emissions is apparent, with the potential for both positive and negative effects. The fluctuation of these impacts is influenced by changes in entrepreneurial activity indices. As illustrated in Table 8's previous findings, the novel outcomes about internal market dynamics follow a similar inverse pattern, visually represented in Fig. 4.

The findings underscore the intricate interplay between economic growth, development, and CO2 emissions, revealing distinct patterns contingent on per capita GDP levels.

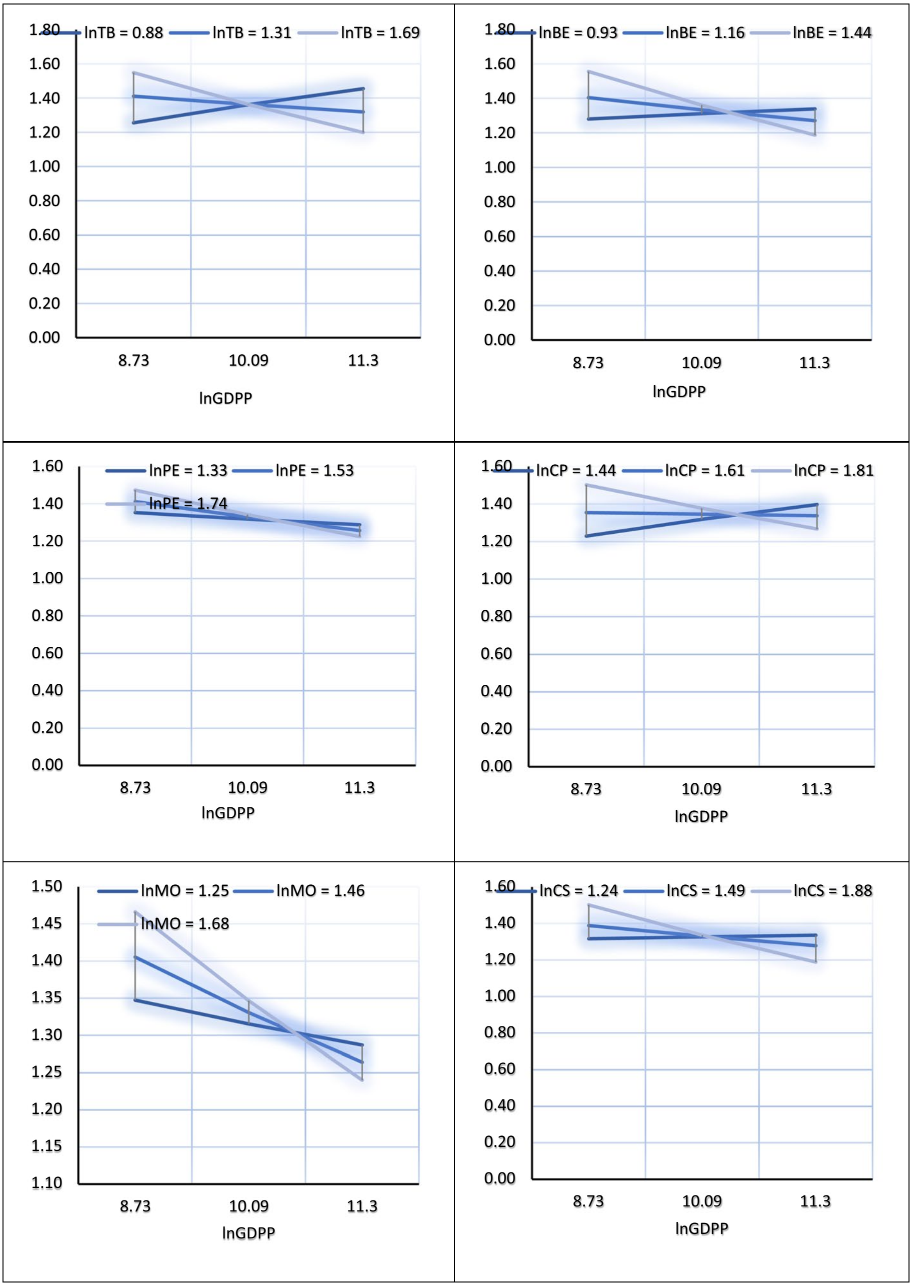

Fig. 3 Effects of GDP per capita on CO2 emissions at different levels of entrepreneurship indicators

Table 9 Estimation results of Eq. 5

	Model C1	Model C2	Model C3	Model C4	Model C5	Model C6	Model C7	Model C8	Model C9	Model C10	Model C11
lnGDPP	1.992	2.069	1.980	2.047	1.832	1.989	1.369	2.054	1.928	2.000	1.984
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.005)	(0.000)	(0.000)	(0.000)	(0.000)
$lnGDPP^2$	− 0.035	− 0.038	− 0.036	− 0.040	− 0.030	− 0.035	− 0.016	− 0.032	− 0.036	− 0.034	− 0.034
	(0.151)	(0.119)	(0.160)	(0.099)	(0.214)	(0.156)	(0.506)	(0.186)	(0.137)	(0.166)	(0.173)
lnENE	1.170	1.185	1.182	1.185	1.197	1.194	1.183	1.189	1.191	1.184	1.213
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
lnURB	0.102	0.049	0.138	− 0.013	− 0.065	0.024	0.110	− 0.010	0.067	0.015	0.150
	(0.679)	(0.833)	(0.562)	(0.953)	(0.778)	(0.918)	(0.627)	(0.967)	(0.769)	(0.948)	(0.519)
lnREN	− 0.002	− 0.001	− 0.002	− 0.003	− 0.002	− 0.003	− 0.002	− 0.004	− 0.003	− 0.003	0.001
	(0.824)	(0.891)	(0.791)	(0.669)	(0.749)	(0.704)	(0.717)	(0.572)	(0.653)	(0.717)	(0.848)
lnOPE	− 0.047	− 0.053	− 0.045	− 0.049	− 0.051	− 0.058	− 0.060	− 0.046	− 0.055	− 0.050	− 0.041
	(0.081)	(0.049)	(0.105)	(0.066)	(0.058)	(0.037)	(0.023)	(0.086)	(0.040)	(0.064)	(0.126)
lnENT	− 0.261	− 0.218	− 0.321	− 0.848	− 0.781	− 0.410	-1.758	0.390	− 0.914	− 0.193	− 0.006
	(0.315)	(0.452)	(0.382)	(0.001)	(0.034)	(0.254)	(0.000)	(0.261)	(0.004)	(0.675)	(0.986)
$lnENT \times lnGDPP$	0.031	0.025	0.040	0.084	0.078	0.041	0.174	− 0.034	0.091	0.015	0.009
	(0.238)	(0.378)	(0.286)	(0.001)	(0.034)	(0.245)	(0.000)	(0.311)	(0.004)	(0.740)	(0.784)
$Log - lik$	514.257	512.556	514.629	516.057	512.813	511.243	518.577	512.068	514.764	511.210	515.864
R^2	0.996	0.996	0.996	0.996	0.996	0.996	0.996	0.996	0.996	0.996	0.996

Table 10 Estimation results of Eq. 6

	Model D1	Model D2	Model D3	Model D4	Model D5	Model D6	Model D7	Model D8	Model D9	Model D10	Model D11
lnGDPP	0.769	-1.770	1.821	− 2.068	− 0.835	1.338	− 5.736	6.068	− 0.430	3.976	-1.295
	(0.520)	(0.095)	(0.210)	(0.043)	(0.610)	(0.365)	(0.011)	(0.000)	(0.771)	(0.114)	(0.364)
$lnGDPP^2$	0.026	0.155	− 0.028	0.163	0.103	− 0.002	0.338	− 0.233	0.082	− 0.134	0.129
	(0.662)	(0.004)	(0.701)	(0.001)	(0.209)	(0.976)	(0.003)	(0.000)	(0.268)	(0.291)	(0.070)
lnENE	1.175	1.223	1.182	1.198	1.190	1.196	1.202	1.202	1.207	1.178	1.212
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
lnURB	− 0.038	0.023	0.134	− 0.441	− 0.230	0.006	0.041	− 0.073	0.012	0.050	0.014
	(0.889)	(0.918)	(0.575)	(0.066)	(0.360)	(0.980)	(0.854)	(0.751)	(0.960)	(0.833)	(0.951)
lnREN	− 0.001	− 0.002	− 0.002	− 0.001	− 0.001	− 0.003	− 0.005	− 0.004	− 0.003	− 0.002	0.002
	(0.836)	(0.744)	(0.787)	(0.902)	(0.849)	(0.690)	(0.490)	(0.539)	(0.694)	(0.835)	(0.746)
lnOPE	− 0.044	− 0.058	− 0.045	− 0.041	− 0.049	− 0.058	− 0.058	− 0.049	− 0.053	− 0.049	− 0.038
	(0.101)	(0.026)	(0.107)	(0.105)	(0.068)	(0.036)	(0.023)	(0.065)	(0.048)	(0.073)	(0.151)
lnENT	− 4.356	-13.431	− 0.827	-17.498	− 9.376	− 2.604	-23.069	14.397	− 8.322	5.016	-10.271
	(0.238)	(0.000)	(0.849)	(0.000)	(0.064)	(0.581)	(0.001)	(0.001)	(0.060)	(0.441)	(0.015)
$lnENT \times lnGDPP$	0.853	2.667	0.141	3.386	1.812	0.479	4.440	− 2.836	1.586	-1.046	2.053
	(0.248)	(0.000)	(0.871)	(0.000)	(0.076)	(0.611)	(0.001)	(0.001)	(0.075)	(0.430)	(0.015)
$lnENT \times lnGDPP^2$	− 0.041	− 0.132	− 0.005	− 0.163	− 0.087	− 0.022	− 0.212	0.139	− 0.075	0.054	− 0.101
	(0.266)	(0.000)	(0.907)	(0.000)	(0.089)	(0.641)	(0.001)	(0.001)	(0.093)	(0.423)	(0.015)
$Log - lik$	514.898	520.688	514.636	526.135	514.304	511.356	523.813	517.521	516.219	511.543	518.899
R^2	0.996	0.996	0.996	0.996	0.996	0.996	0.996	0.996	0.996	0.996	0.996

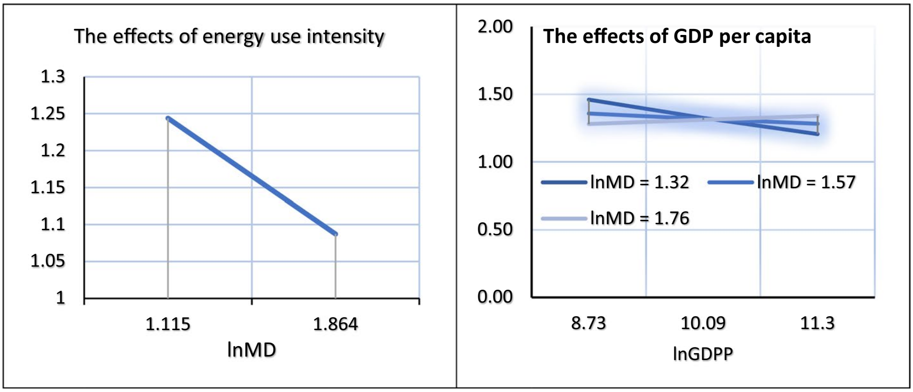

Fig. 4 The effects of energy use intensity and GDP per capita on CO2 emissions at different levels of Internal market dynamics

Within nations exhibiting higher entrepreneurial indicators yet lower GDP per capita, the correlation between economic advancement, development, and CO2 emissions is conspicuously more pronounced. However, this correlation wanes as economies progress into more advanced stages. Significantly, the internal market dynamics indicator deviates from this overarching trend.

The results demonstrate that nations with lower entrepreneurship levels experience an ascending trajectory on the Kuznets curve, characterized by increasing effects of economic growth on CO2 emissions. Conversely, in countries with elevated entrepreneurship indicators, the amplification of these positive effects is mitigated. Consequently, the outcomes of this present study challenge the notion of a uniform Kuznets curve as an explanatory framework for the environmental consequences of economic growth. Instead, there exists a shift from the increasing slop segment (concave upward) to its increasing slop counterpart (concave downward) of the upward Kuznets curve with an increase in entrepreneurship levels.

5 Discussions and conclusion

As society becomes more attuned to the profound ramifications of environmental deterioration on various dimensions of human well-being, it becomes imperative for researchers to illuminate the factors that either contribute to or hinder this process. While scholarly literature has long recognized the influence of entrepreneurial activities on diverse socio-economic metrics, recent attention from both scholars and policymakers has been directed toward its connection with environmental shifts. This study endeavors to enrich this ongoing discourse by delving into the spill-over repercussions of entrepreneurial elements on CO2 emissions. This investigation takes into account an array of variables such as GDP per capita, energy intensity, urban population, trade openness, and resource rent, across 14 countries spanning from 2002 to 2018.

The outcomes reveal that energy usage intensity, included as a control parameter, exerts a positive influence on CO2 emissions. Furthermore, the expansion of the economy and higher GDP per capita is linked to increased CO2 emissions. This contradicts the findings of Bamisile et al. (2021), Yaduma et al. (2015), and Zanin and Marra (2012), who noted a decrease in CO2 emissions magnitude with progressive economic growth. Conversely, this aligns with the conclusions of Dong et al. (2020), Li et al. (2017), Liimatainen and Pollanen (2013), Meng et al. (2012), and Mohsin et al. (2019), who identified a positive correlation. It's important to note, however, that these positive impacts might fluctuate, influenced by the rise in entrepreneurial indices.

Based on our empirical observations, it becomes evident that the direct ramifications of entrepreneurial metrics on CO2 emissions are generally of negligible statistical consequence. The noteworthy impact is discernible solely within domains encompassing governmental backing and regulations, fiscal obligations and administrative complexities, state-initiated initiatives, and prevailing cultural and societal norms. Consequently, the repercussions of entrepreneurial gauges subject to direct manipulation by governmental directives manifest as positive, considerable, and potentially deleterious to the ecological milieu. These outcomes run counter to the conclusions drawn from some of the preceding inquiries. The exploration conducted by Nakamura and Managi (2020) delved into the interrelation between entrepreneurship and the marginal expenses associated with CO2 emissions, whereas He et al. (2020) asserted that entrepreneurship rooted in opportunities fosters a favorable influence on the environmental facets of sustainable progress. Conversely, these results align with the conclusions drawn by Neumann (2022), suggesting that while environmentally conscious entrepreneurial pursuits bolster economic and societal advancement, they do not exhibit a noteworthy correlation with environmental advancement. Furthermore, the authors underscored that economies boasting an elevated ratio of entrepreneurs per capita exhibit a diminished ratio of CO2 emissions per capita, and vice versa.

Moreover, the results spotlight how certain entrepreneurship indicators, possessing both direct and indirect ramifications, yield a reduction in CO2 emissions and an enhancement of the environment through heightened energy efficiency. Interestingly, for specific variables like Post-school entrepreneurial education and training, Basic school entrepreneurial education and training, Commercial and professional infrastructure, Internal market dynamics, and Internal market openness, the opposing direct positive and indirect negative effects effectively nullify each other, resulting in a net effect of zero. Conversely, other factors exhibit positive ultimate outcomes, as their CO2 emission-amplifying consequences overshadow their CO2 emission-mitigating advantages. This shift in impact is attributed to the varying trajectories of entrepreneurial activity. Countries with lower entrepreneurship levels follow an ascending path on the Kuznets curve, exhibiting an augmentation in the influence of economic growth on CO2 emissions. On the other hand, nations with heightened entrepreneurship indicators experience a tempering of these positive effects. Thus, the outcomes of this study challenge the conventional understanding of a uniform Kuznets curve as the explanatory framework for environmental consequences stemming from economic growth. Rather than adhering to a consistent slope, the Kuznets curve showcases a dynamic pattern. With a positive slope, a transition occurs from the upwardly sloped segment (U-shaped) to its inverted counterpart (inverted U-shaped) on the Kuznets curve. This alteration is closely tied to the escalation in entrepreneurship levels.

The findings unveil specific facets of how entrepreneurship indicators influence the environment. When delving into the analysis of the outcomes, one can posit that the sharp increase witnessed in the entrepreneurship metric signifies a significant rise in commercial operations and inventive undertakings on a national scale. In contexts where the GDP figures are relatively lower, this pronounced expansion of entrepreneurial ventures can exert a more pronounced influence on the levels of CO2 emissions. This phenomenon is potentially linked to the earlier phases of industrialization experienced by these countries, coupled with their limited array of resources and technologies aimed at mitigating environmental repercussions. The elevation of entrepreneurship frequently acts as a precursor to processes such as industrialization, urbanization, and a sharp rise in energy consumption. Consequently, this sequence of events often translates to an escalated output of CO2 emissions. The association between heightened business undertakings, economic progress, and entrepreneurship invariably contributes to an augmentation in CO2 emissions. In sharp contrast, nations characterized by elevated GDP values are more likely to have already embraced advanced technologies and environmental policies. This proactive approach tends to mitigate the ecological impact typically associated with economic advancement. Consequently, the relationship between GDP and the ecological footprint of CO2 becomes less pronounced as entrepreneurial activities gain momentum. This trend could potentially be attributed to the phenomenon of diminishing marginal returns concerning environmental sustainability in more developed economies. Moreover, the latitude extended to fledgling enterprises in infiltrating established markets plays a crucial role in curbing CO2 emissions for a multitude of reasons. To begin with, these emerging businesses often introduce innovative and sustainable technologies and practices that are inherently more energy-efficient and environmentally conscious when juxtaposed with their more established counterparts. Fueled by the imperative to distinguish themselves and gain a competitive edge, these nascent players prioritize the reduction of carbon emissions and wholeheartedly embrace renewable energy sources. Furthermore, in economies characterized by lower GDP values, the intensification of market activities might be steered by industries that are less carbon-intensive (such as agriculture or services) or by the adoption of greener technologies. The net result is a dampened influence of GDP on the ecological footprint of CO2. On the flip side, economies with higher GDP values frequently exhibit more mature industrial sectors that heavily lean on fossil fuels, consequently resulting in higher volumes of CO2 emissions. Consequently, as internal market dynamics become more pronounced, the nexus between GDP and the CO2 ecological footprint tends to be magnified for these high-GDP countries.

The findings of this current research yield a diverse array of implications for policymaking. the governmental strategies for fostering green entrepreneurship in the researched nations have shown limited effectiveness in achieving desired outcomes. Despite endeavors such as incentivizing and amplifying the operations of small and medium-sized enterprises (SMEs), these initiatives have fallen short of realizing the objectives of sustainable business advancement. Furthermore, they have not adequately counteracted the adverse environmental impacts associated with escalated production scales. To actualize the aspirations of sustainable development, policymakers must reconsider not only tax structures and legal frameworks but also the efficacy of programs directly supporting SMEs. The degree to which training in establishing or managing SMEs integrates into educational systems at various tiers emerges as a pivotal factor in eco-friendly entrepreneurship. Building upon the insights from previous research by Cortese (2003) and Shumba et al. (2008), a correlation between elevated educational attainment and reduced carbon emissions becomes apparent. Consequently, enhancing entrepreneurship education across educational levels could emerge as a cornerstone strategy for governments striving to nurture green entrepreneurship. Additionally, directing attention towards fortifying property rights, accounting practices, commercial operations, and legal and evaluative institutions that bolster or promote SMEs engenders positive ripple effects for a country's endeavors in fostering green entrepreneurship. This observation holds for regulations governing the unfettered entry of new entrepreneurial ventures into markets. Findings indicate that expanding the market for environmentally friendly products might pave the way for sustainable progress (Mohsin et al., 2019). Consequently, enacting new legislative frameworks could facilitate an environment conducive to the proliferation of environmentally conscious enterprises (Işık et al., 2024; Mondal, 2023; Umar Farooq et al., 2023). In regions undergoing development, the formidable challenges of attaining Sustainable Development Goals emerge due to resource and technological constraints (Anbumozhi et al., 2018). In light of this context, nations could streamline bureaucratic hurdles for environmentally conscious startups. By enacting financial regulations that secure funding for ecological innovations, governments could catalyze the progression of environmentally beneficial products. An imperative in this pursuit involves promoting the utilization of eco-friendly commodities, including diverse renewable energy sources. Placing paramount importance on environmental concerns and instigating initiatives for entrepreneurial education becomes essential.

This study provides insightful analysis into the intricate linkages between entrepreneurship and CO2 emissions across a selection of countries, yet it is not devoid of certain constraints. Primarily, the investigation's coverage is restricted to 14 countries over the span from 2002 to 2018, limiting the extrapolation of its findings to other geographical areas or temporal contexts. The chosen countries, despite their diversity, may not fully represent specific national policies or economic conditions that could affect the results. These constraints pave the way for future research opportunities. Broadening the research framework to encompass a more extensive variety of countries with different economic and environmental settings could enhance our comprehension of the interactions involved. Further research could also gain from the inclusion of alternative metrics for entrepreneurship and environmental impact. This might involve qualitative evaluations of the sustainability orientation of entrepreneurial ventures or the employment of advanced measures to quantify the carbon footprint associated with entrepreneurial endeavors. Delving into the role of technological innovation in moderating the link between entrepreneurship and CO2 emissions could illuminate the avenues through which entrepreneurship either supports or undermines environmental sustainability. Furthermore, an in-depth investigation of the mechanisms underlying the observed effects—such as the influence of government policies, cultural norms, and market dynamics on entrepreneurial activities and their environmental implications—would augment our understanding. Comparative analyses across different sectors within economies or the effects of particular forms of entrepreneurship, like social or green entrepreneurship, could offer detailed insights into the ways entrepreneurial activities impact environmental outcomes.

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Data availability The data that support the findings of this study are available from the corresponding author, [Mohammad Sharif Karimi], upon reasonable request.

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