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The influence of economic complexity processes and renewable energy on CO_2 emissions of BRICS. What about industry 4.0?

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ABSTRACT

This study analyses the relationship between carbon dioxide emissions per capita, the economic complexity index, renewable energy, and inward foreign direct investment using panel data for the BRICS countries from 1995 to 2020. Empirical results confirm that the environmental Kuznets curve is fulfilled, with a positive but decreasing contribution of economic development on environmental deterioration, to the point that neutrality on CO2 emissions can be achieved in the long term. In addition, the results confirm, in this case, the Pollution Haven Hypothesis, that is, the set of BRICS economies chooses to apply regulations that do not respect the environment. The results of other econometric studies support this study, pointing to long-run cointegration. The unit root tests and the variance inflation test also point to stationarity at the first difference and a lack of multicollinearity, respectively.

Finally, given the scarcity of empirical studies, this study adopts an incipient methodology to approximate the impact of the technologies associated with Industry 4.0 on carbon emissions, obtaining evidence that their effect on environmental deterioration is very moderate. In addition, the results suggest that, in the long term, these technologies can contribute to achieving the neutrality of polluting emissions.

1. Introduction

The extreme behaviour of the climate, increasingly frequent in recent decades, has caused international organizations such as the World Meteorological Organization (WMO) or the OECD to consider the problem generated as a global emergency, encouraging developed and less developing nations to adopt anti-pollution measures to stop the environmental deterioration (OECD Green Growth Papers, 2019; WMO, 2021). According to these reports, reducing carbon emissions should be an inexcusable priority for all governments, which implies reducing the use of polluting energy sources, increasing the use of renewable energies, and controlling this energy substitution process.

The impact of carbon emissions on pollution levels has made them a primary global concern in recent decades. Industry, agriculture, and human activity are the main drivers of climate change in developing and developed nations, with CO_2 being the primary cause of global greenhouse gas emissions. Regardless of a nation's level of economic development, CO_2 is frequently cited as a significant driver of environmental degradation (Khezri et al., 2022a). In our analysis, we chose BRICS countries because they have similar levels of development and are highly dependent on fossil energy due to their industrial nature (Khezri et al., 2022a; Iwaro and Mwasha, 2010).

According to Intergovernmental Panel on Climate Change-IPCC (Reay et al., 2007), in the last fifty years, human activity has been the most critical factor in the increase in pollution, contributing around 70%. Different analyses include the BRICS countries due to their significant contribution to environmental deterioration (Azam and Haseeb, 2021; Chen et al., 2022a; Cheng et al., 2022; Khezri et al., 2022b; Usman

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and Makhdum, 2021). Therefore, the present study examines CO_2 emissions and the relationship between Foreign Direct Investment, the Economic Complexity Index and Renewable Energy. Our differential contribution to the body of existing literature focuses on the fact that the selected variables have not been used simultaneously by the panel of BRICS countries.

Indeed, some studies have included BRICs in their research but have not measured the influence of foreign direct investment on CO_2 emissions. Different authors have estimated the impact of foreign direct investment on carbon emissions (Azam and Haseeb, 2021; Azevedo et al., 2018; Jahangir Alam et al., 2012; Khattak et al., 2020), and other authors have found that renewable energy diminishes carbon emissions (Leitão et al., 2021; Ortiz et al., 2021; Rahman et al., 2022).

On the other hand, the analysis of the economic complexity index (ECI) includes the consideration of productive resources, available infrastructure, knowledge, and human capital, that is, a country's production elements, which reflect production sources, existing infrastructures, knowledge, and human capital (Albeaik et al., 2016; Doğan et al., 2021).In this sense, economic expansion, natural reserves, and many private and public infrastructures are viewed as negatives for greener sustainability development, but on the other hand, economic complexity and trade are viewed as positives (Breitenbach et al., 2021; Buhari et al., 2020; Caglar et al., 2022; Romero and Gramkow, 2020; Usman et al., 2022). As a result of this research, several BRICS economies could develop fresh perspectives on sustainability.

Finally, this study also tries to answer two questions to which the economic literature barely contributes empirical works: how does Industry 4.0 influence CO_2 emissions? Does this relationship behave as a non-linear inverted U shape?

Our work is developed in five sections in addition to this introduction. Section 2 is "Literature Review," which analyses the relevant literature. Section 3 is "Data and Methods," which includes appropriate econometric and empirical methods and data. Section 4 addresses the empirical results discussion, and Section 5 does the same with the conclusions and recommendations for future research.

2. Literature Review

This section explains the relationship between per capita Carbon Dioxide Emissions, Economic Complexity Index, Renewable Energy, and Inward Foreign Direct Investment using the most significant research available. The research on BRICS countries is plentiful (Chen et al., 2021, 2022b), being amongst fossil energy dependence, trade (Ibrahim and Ajide, 2021) and renewable energy, and CO_2 emissions (Danish et al., 2019). The abundance of studies on CO_2 emissions is due to its impact on environmental degradation, and this is one of the most relevant topics in today's research literature (Emre Caglar, 2020; Leitão, 2014; Sinha et al., 2017; Shahbaz et al., 2018; Nathaniel et al., 2020; Wang, 2022). Some studies analyzed emissions from several perspectives in BRICS, and other developing economies, ranging from electricity consumption (i.e., energy intensity), trade openness, financial development and renewable energy under the EKC perspective (Acheampong, 2019; Acheampong et al., 2019; Ganda, 2019; Jiang et al., 2021; Pata, 2018; Rana and Sharma, 2019; Rout et al., 2022; Zafar et al., 2019). These studies traditionally have inferred a U-shape connection between ecological degradation and economic growth, i.e., ecological degradation rises as income reaches a limit and it decreases (see Fig. 1).

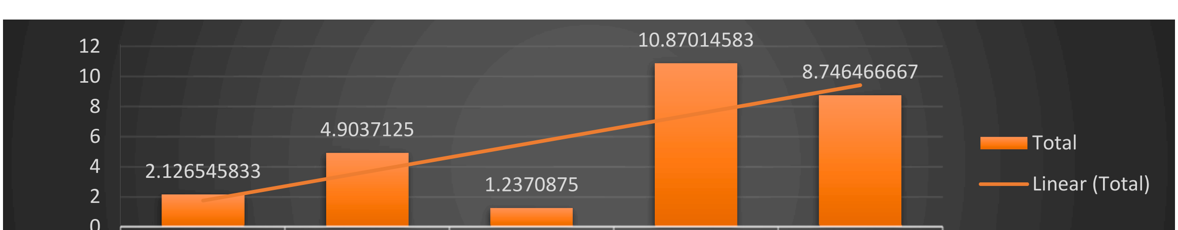
CO_2 per capita is also used as a relevant variable under EKC (Environmental Kuznets Curve) (Altintaş and Kassouri, 2020; Duro and Padilla, 2008; X Li et al., 2021; Parker and Bhatti, 2020), ranging from policy indicators, income differences, energy intensity and consequent rise in Carbon Dioxide Emissions per capita.

Fossil fuel dependence is concurrently referred to as a significant contributor to environmental degradation (Chen et al., 2022b; Li and Haneklaus, 2022a, 2022b; Martins et al., 2021), implying CO_2 emissions are extrapolated due to fossil fuel consumption and production.

Most EKC studies refer to the primary ecological quality indicator as it can affect a greener environment (CO_2 emissions, waste, etc.); as our globalized world is facing rapid growth, renewable energy is seen as the right path to achieve Carbon Dioxide neutrality. Some activities such as agriculture, population, technology, economic development and trade balance are seen as aggravators to ecologic footprint and interfere with greener sustainability and increase degradation. Most of these studies have confirmed the EKC hypothesis for the nations under analysis (Balsalobre-Lorente et al., 2022; Chang and Fang, 2022; Huang et al., 2022a,b; Pata, 2021a; Rout et al., 2022; Saqib, 2022; Usman and Makhdum, 2021), validating the primary ecological quality indicator (such as CO_2 emissions and waste).

The Economic Complexity Index can be used to predict the expected income level of countries and economic growth (Hidalgo and Hausmann, 2009) and greenhouse emissions (Hartmann et al., 2017). An essential element of the calculation methodology is the *principle of affinity*, that is, compatibility between an economy (or territory) and an activity (Hidalgo, 2018). Therefore, the Economic Complexity Index (ECI) is a measure of the capacity of an economy that can be inferred from data connecting locations with the activities present in them. ECI methodology measures production, exports, knowledge and quality and has, for the past decades, been subject to various studies implying its impact on environmental degradation as a first approach (Hausmann and Hidalgo, 2011). However, environmental quality, culture and GDP infer a reduction of environmental degradation in the long run (Can and Gozgor, 2017; Lapatinas et al., 2021; Leitão et al., 2021; Neagu, 2020; Sun et al., 2022). The Economic Complexity Index has been studied under the DOLS and FMOLS methods (Can and Gozgor, 2017; Neagu and Teodoru, 2019), demonstrating that low levels of the index are associated with a greater presence of CO_2 emissions, in addition to a high level of energy consumption and greenhouse emissions correspond to less economic complexity.

According to Pollution Haven Hypothesis (PHV), Inward Foreign Direct Investment (FDI) has also been proven to play an important role in CO_2 emissions. In this sense, some nations prefer less stringent environmental rules resulting in higher pollution levels, although countries are accepting foreign investment with stricter environmental regulations leading to environmental improvements (Pollution Halo



	Brazil	China	India	Russia	South Africa
Total	2.126545833	4.9037125	1.2370875	10.87014583	8.746466667

Fig. 1. Linear Trend on per capita Carbon emissions in BRICS.

Hypothesis - PHH) (Aliyu and Ismail, 2015a, 2015b; Balsalobre-Lorente et al., 2019; Kisswani and Zaitouni, 2021; Mcnally, 1999; Singhania and Saini, 2021; Yilanci et al., 2020).

The selected panel of countries under study have been subject to different econometric approaches. Some studies use ARDL cointegration, Westerlund's cointegration and PMG – Pooled Mean Group and second-generation and heterogeneity panel (Pata, 2021b; Rout et al., 2022).

Other econometric approaches include both long-run and short-run analysis using FMOLS (Fully Modified Ordinary Least Squares), DOLS (Dynamic Ordinary Least Squares) or ARDL to measure long-run elasticity for different sets of countries and variables (Balsalobre-Lorente et al., 2022; Khan et al., 2019; Leitão et al., 2021). ARDL method was used to study the Foreign Direct Investment, negative impact on Renewable Energy and consequently on Environment degradation (Bello et al., 2018; Hussain and Rehman, n.d.; Ibrahiem, 2015; Teng et al., 2021; Wan et al., 2022). The results of the empirical studies do not coincide with the expected impact of foreign direct investment (FDI) on CO_2 emissions, which may affect the countries represented in the same data panel in different ways (Aydin, 2023). Even FDI could have positive effects on CO_2 emissions in the short term but negative ones in the long term, behaving in a non-linear way.

On the other hand, industry 4.0 is a concept that today represents a new era in industrial development characterized by the purpose of obtaining more efficient production using new technologies (i.e., IoT and cybernetic systems) that represent an extreme advance in the digitization of companies and in the interconnection of external and internal networks. All this new strategy is subject to a series of restrictions (Smit et al., 2016; Manoukian, 2018; Environmental Defense Fund, 2018), such as improving energy efficiency, reducing emissions of polluting particles and waste, the reduction of the intensity of use of non-renewable natural resources and the adaptation in the educational and professional training system to orient it to the new demand for required jobs.

This idea took shape with the initiative of the German government in 2011 to gain competitiveness in the world (Kagermann et al., 2011; Wahlster, 2011; Pereira and Romero, 2017; Müller et al., 2018; Slusarczyk, 2018). The intensification of various climatic catastrophes in the last decade and, above all, the emergence of the pandemic caused by COVID'19 and its health, economic and security of supply consequences has had the consequence of redesigning a set of restrictions that must require Industry 4.0 in Europe. Of all of them, for this work, we are interested in two: the need to preserve the environment and the need to reduce the weakness of large economies to guarantee a stable supply of certain raw materials, especially those that constitute the base of the main sources of primary energy. In short, the security of supply cannot be separated from the strategic security of nations and environmental security threatened by increasingly frequent natural catastrophes. For this reason, the paradigm of sustainable development today is based on three pillars: environmental protection, social justice, and economic development (Koilo, 2019).

Regarding environmental sustainability, it is still not clear what the impact of the new industry 4.0 will be on the environment, for example, in terms of additive manufacturing (Ford et al. 2016). There is also no unanimity about how it will impact the job market (Jelonek and Urbaniec, 2019) or what the final impact of 3D printing will be. Burritt and Christ (2016) argue that a positive impact is expected if the industry can achieve complete digitalization that further improves products and services and if it is possible to interact with the environment outside the company in real-time. Tim et al. (2018) makes a regulatory approach on how production processes could contribute to sustainable use of natural resources and the elimination of polluting waste; many qualitative studies and few quantitative ones (Li et al., 2021).

The recent and progressive implementation of Industry 4.0 prevents us from having regular statistics on its implementation and evolution in today's world, so the databases cannot integrate a historical sequence that affects all the technologies involved. Oláh et al. (2020) contain a graphic synthesis that lists six technologies that could form the hard core of industry 4.0: the Internet of Things (IoT), Big Data Analytics, Cloud Computing, 3D Printing, Augmented Reality and Robotic Systems, while Blanco et al. (2017) another three are added, cybersecurity, additive manufacturing, and 3D simulation. Through the appropriate processes, it is expected to obtain three types of sustainable results: economic, improved automation processes and their safety, and greater environmental protection. In addition, these results must be harmonized with the 17 Sustainable Development Goals (SDGs) proclaimed by the UN, a challenge to achieve Society 5.0 (United Nations, 2015).

As stated in section 1, the BRICS countries constitute the leading group that contributes to CO_2 emissions worldwide. Not in vain do they group 40% of the world's population. However, it cannot be said that they share a similar structure to their economies. From the point of view of the objectives of this study, the two largest BRICS countries in terms of per capita pollution, Russia, and South Africa, in that order, maintain very different economic growth strategies: Russia bases it on the abundance of sources of Fossil energy, and South Africa has specialized in mining, metallurgical, automobile, chemical, and fertilizer industries, which are highly polluting. Fig. 2 shows the different positions of each of the BRICS countries in ICT technologies and polluting emissions. Along with the two countries mentioned, the case of South Africa stands out for its high level of polluting emissions per capita and the low weight of its ICT industry, while India maintains relatively low levels of CO_2 emissions and low levels of ICT industry, a situation like Brazil. Five realities must be considered when concluding the industry 4.0 - CO_2 emissions relationship.

3. Data and Methods

Table 1 lists the variables and their sources, as well as the expected signs. This panel of countries was chosen due to their rising CO_2 emissions trend. The dependent variable chosen is Carbon Dioxide Emissions per Capita (LCOPC), and the independent variables are Renewable Energy (LREW), Economic Complexity Index (ECI), and Economic Complexity Index squared (ECI^2), which measures the turning point of the increasing phase of the variable. Using the Environmental Kuznets Curve empirical evidence approach, it is intended to evaluate the behaviour of the variables towards carbon dioxide emissions per capita and their relationship with different development stages for BRICS countries.

Regarding the econometric approach, FMOLS and DOLS are used to test panel data cointegration and first and second-generation unit roots (Kao, 1999). In addition, variance inflation factor (VIF) proofs assess the multicollinearity problems of our sample.

3.1. Empirical methodology

In this section, we present the model specification and the hypotheses to be tested.

$$LCOPC = \alpha_0 + \alpha_1 LREW + \alpha_2 ECI + \alpha_3 ECI^2 + \alpha_4 LFDI + \mu it \quad (1)$$

The following hypothesis has been formulated using the EKC (Environmental Kuznets Curve) arguments.

H1. The composition effect (in EKC) negatively relates economic complexity to CO_2 emissions.

In the short term, the economic complexity index has a positive impact on carbon dioxide emissions; however, in the long term, the opposite occurs, expecting a negative correlation between both variables, that is, a turner point is produced in the function from which the increase in economic complexity produces a reduction in CO_2 emissions. Graphically, an inverted U is observed (See Fig. 3). Previous studies also support this (Can and Gozgor, 2017; Antonietti and Franco, 2021;

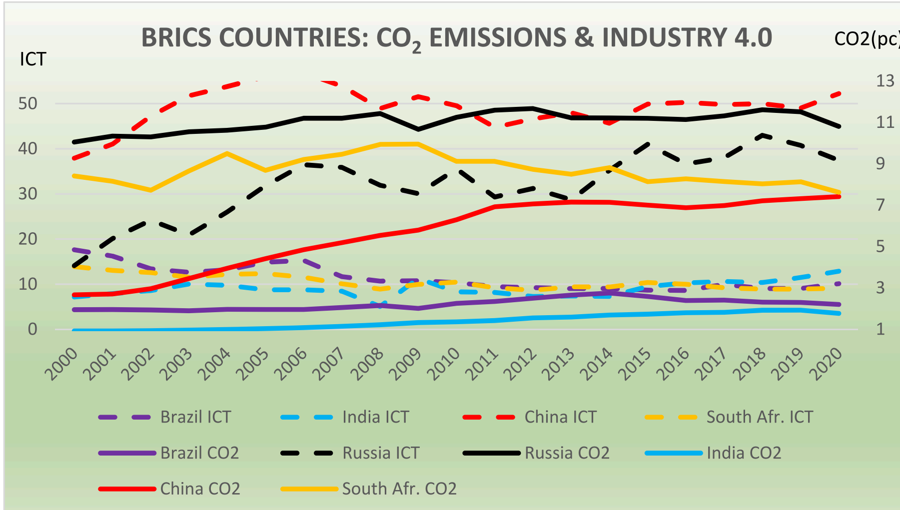


Fig. 2. CO_2 & Industry 4.0 in BRICS
Source: *World Bank. ICT: (ICT goods imports/Total imports) + (ICT goods exports/Total exports).*
CO2(pc): Carbon dioxide emissions per capita.

Table 1a
Variables description.

Variable	Expected Sign	Source
LCOPC (Logarithm of Carbon Dioxide Emissions per capita		World Bank 2023
LREW (Logarithm of Renewable energy)	(−) Impact on LCOPC	World Bank 2023
ECI (Economic Complexity Index)	(+) Impact on LCOPC	World Bank 2023
ECI^2 (Economic Complexity Index Squared)	(−) Impact on LCOPC	World Bank 2023
LFDI (Logarithm of Inward Foreign Direct Investment)	(±) Impact on LCOPC	World Bank 2023

Table 1b
Variables used to represent Industry 4.0 in BRICS countries.

Variable	Descriptor	Expected sign
lcopc	Logarithm of per capita carbon dioxide emissions	
lexpictpc	Logarithm of per capita ICT services exports (BoP, current US$)	(+) Impact on *lcopc*
$lexpictpc^2$	*lexpictpc* square	(−) Impact on *lcopc*
%icte	Percentage of ICT services exports/total exports of services, BoP	(+) Impact on *lcopc*
$\%icte^2$	*%icte* square	(−) Impact on *lcopc*
%ictgei	(Exports ICT goods/exports goods) + (imports ICT goods/import goods) (%)	(+) Impact on *lcopc*
$\%ictgei^2$	*%ictei* square	(−) Impact on *lcopc*

Source of dates: World Bank 2023

Balsalobre-Lorente et al., 2022).

The following hypothesis is based on Pollution Haven – PHV and Pollution Halo PHH.

H2. CO_2 emissions can present a negative/positive correlation with Foreign Direct Investment (FDI).

The Pollution Haven Hypothesis (PHV) supports that Foreign Direct Investment increases environmental degradation. By contrast, other studies consider that FDI reduces environmental degradation, validating the Pollution Halo Hypothesis (Rezza, 2013; Baek, 2016; Piao et al., 2021).

H3. Renewable energy stimulates improvements in the environment**.**

Green energy use contributes to minimizing the environmental footprint (Ibrahiem, 2015; Bello et al., 2018; Teng et al., 2021; Wan et al., 2022), and renewable energy is seen as the right path to achieve Carbon Dioxide neutrality. The use of renewable energy and other sources of clean energy reduces pollution levels.

3.2. Empirical methodology: Pollution emissions and industry 4.0

We have also carried out an empirical study to obtain evidence of the role that industry 4.0 is playing in the CO_2 emissions of the BRICS countries. Few possibilities for obtaining representative variables of industry 4.0 in the large databases of international organizations that can cover these countries. We have used some variables from the World Bank (2023), and we have verified that the variables available in the UNCTAD database are not adequate to capture the impact of Industry 4.0 on polluting emissions, in addition to having a shorter time sequence.

Table 1b presents the variables used to estimate the impact of Industry 4.0 on CO_2 emissions. Many authors have pointed out services linked to information and communication technologies (ICT) as one of the main supports of this industry (Peraković et al., 2019; Oláh et al., 2020; H. Li et al., 2021; Mourtzis et al., 2022).

Since the length of these data series is significantly shorter than those used for the regressions in Table 9, it is not appropriate to use them in a joint analysis of equation (1).

We want to confirm two hypotheses:

H1'. ICT technologies increase CO_2 emissions.

H2'. It is expected that, in the long term, ICT technology can help reduce polluting emissions and contribute to the neutrality of environmental impact. We expect the pollutant emissions function derived from these variables can be an inverted U shape.

This is the simplified model to be estimated:

$$lCOpc = \alpha'_0 + \alpha'_1\, ict + \alpha'_2\, ict^2 + \mu' it \qquad (2)$$

where the *ICT* variable represents the weight of ICT technology in the economy of each BRICS country and will be defined in three different ways, as indicated in Table 1b.

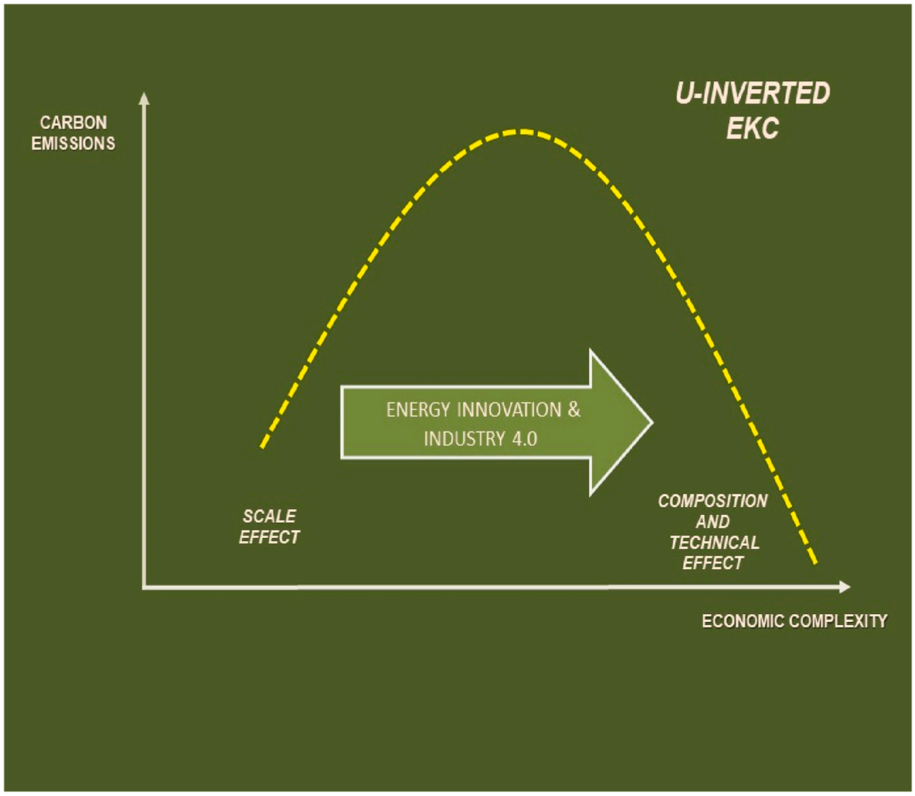


Fig. 3. U-inverted economic Complexity-EKC.

4. Empirical results and discussion

Descriptive statistics for the variables involved in equation (1) are presented in Table 2. The variables also present a positive Kurtosis (leptokurtic), and Renewable Energy and Inward Foreign Direct Investment present the highest maximum values.

The correlation matrix is presented in Table 3.

LFDI (Inward Foreign Direct Investment) is positively correlated with LCOPC (Carbon Dioxide Emissions). On the contrary, LREW, ECI and ECI^2 (Renewable Energy, Economic Complexity, and Economic Complexity squared) are negatively correlated with LCOPC (Carbon Dioxide Emissions).

To test first difference integration, we performed the traditional first generation of unit root tests for panel data (Im et al., 2003; Levin et al., 2002; Phillips and Perron, 1988), expressing that all variables used are integrated at the first difference, also Augmented Dickey-Fuller - Fisher and Philips Perron tests infer the same conclusion, and the results are presented in Table 4.

Pesaran CD Test (Pesaran, 2007) to control independence between individuals is presented in Table 5.

CIPS-Test, second-generation Unit Root t (Pesaran, 2007), was performed due to cross-section dependence between the variables.

Table 2
Descriptive statistics.

Description	LCOPC	LREW	ECI	ECI^2	LFDI
Mean	0.589	1.249	0.337	0.155	6.421
Median	0.505	1.404	0.300	0.090	9.399
Maximum	1.066	1.736	0.860	0.739	10.873
Minimum	−0.102	0.502	−0.050	0.000	−0.299
Std. Dev.	0.386	0.435	0.205	0.177	4.672
Skewness	−0.174	−0.594	0.746	1.750	−0.568
Kurtosis	1.525	1.892	3.136	5.379	1.369
Probability	0.004	0.002	0.005	0.000	0.000
Observations	112	112	112	112	112

Table 3
Correlation matrix.

Description	LCOPC	LREW	ECI	ECI^2	LFDI
LCOPC	1.000				
LREW	−0.904	1.000			
ECI	−0.052	−0.033	1.000		
ECI^2	−0.034	−0.042	0.955	1.000	
LFDI	0.315	−0.480	−0.303	−0.280	1.000

Table 6 shows our results showing that the variables are stationary according to the second-generation unit root tests.

Before continuing the econometric estimation model, the subsequent step was to test multicollinearity. In the presence of multicollinearity, the values of the coefficients are affected by other variables in the model, and the p-values are unreliable. Table 7 presents VIF (variance inflation factor) test, showing that variables LREW and LFDI do not present multicollinearity.

In the case of the ECI and ECI^2 variables, with test values higher than 5, they present multicollinearity with each other, so only the size of these two coefficients is affected, but it does not affect the predictive capacity of the model or the statistics on the goodness of fit. These are two variables related by a quadratic function, where the only important thing is to verify that the coefficients have opposite signs, and multicollinearity is not a problem here.

In Table 8, we present the results for long-run cointegration between variables (Kao, 1999), comprehending all the variables. LCOPC, LREW, ECI, and LFDI present long-run cointegration.

The FMOLS and DOLS estimates are presented in Table 9, and it is confirmed that the signs of the variables are those that prevail in the reviewed literature, but later we will discuss the sign obtained for the variable LFDI.

These tests also validate that Economic Complexity Index and it square confirm the EKC hypothesis with 1% statistical significance (see

Table 4
Unit root tests.

	Level		First Difference	
	Statistic	P-Value	Statistic	P-Value
Method	*LCOPC*		*DLCOPC*	
Levin Lin & Chu t*	−1.729**	(0.042)	−2.055**	(0.020)
Im. Pesaran and Shun W-stat	−1.836**	(0.033)	−3.589***	(0.000)
ADF-Fisher Chi-Square	24.722***	(0.006)	32.805***	(0.000)
PP – Fisher Chi Square	20.301**	(0.027)	50.640***	(0.000)
Method	*LREW*		*DLREW*	
Levin Lin & Chu t*	1.075	(0.859)	−2.194***	(0.014)
Im. Pesaran and Shun W-stat	1.929	(0.973)	−3.664***	(0.000)
ADF-Fisher Chi-Square	5.961	(0.819)	34.869***	(0.000)
PP – Fisher Chi Square	5.641	(0.845)	48.737***	(0.000)
Method	*ECI*		*DECI*	
Levin Lin & Chu t*	1.295	(0.902)	−0.638	(0.262)
Im. Pesaran and Shun W-stat	1.316	(0.906)	−5.700***	(0.000)
ADF-Fisher Chi-Square	4.285	(0.934)	49.579***	(0.000)
PP – Fisher Chi Square	8.651	(0.566)	350.412***	(0.000)
Method	*ECI^2*		*$DECI^2$*	
Levin Lin & Chu t*	−1.212	(0.012)	−4.444***	(0.000)
Im. Pesaran and Shun W-stat	−2.039**	(0.020)	−7.202***	(0.000)
ADF-Fisher Chi-Square	22.692**	(0.011)	65.630***	(0.000)
PP – Fisher Chi Square	17.904*	(0.056)	96.031***	(0.000)
Method	*LFDI*		*DLFI*	
Levin Lin & Chu t*	−3.774***	(0.000)	−2.483***	(0.006)
Im. Pesaran and Shun W-stat	−1.328*	(0.092)	−6.019***	(0.000)
ADF-Fisher Chi-Square	22.166**	(0.014)	53.678	(0.000)
PP – Fisher Chi Square	8.887	(0.543)	99.014***	(0.000)

* Statistically significant at 10% ** Statistically significant at 5% *** Statistically significant at 1%.

Table 5
Cross-section dependence: Pesaran (CD test).

Variable	Statistic	P-Value
LCOPC	89.579***	(0.000)
LREW	130.372***	(0.000)
ECI	4.041***	(0.000)
ECI^2	7.798***	(0.000)
LFDI	2.698***	(0.000)

*** Statistically significant at 1%.

Table 6
Unit root test: second generation (CIPS) with constant.

Variable	T-Statistic	P-Value
LCOPC	−2.909***	(0.000)
LREW	−2.268**	(0.050)
ECI	−2.264**	(0.050)
ECI2	−3.119***	(0.000)
LFDI	−2.206**	(0.050)

** Statistically significant at 5% *** Statistically significant at 1%.

Table 7
VIF test on multicollinearity.

Variables	VIF	1/VIF
LREW	1.32	0.75
ECI	10.58	0.09
ECI2	10.36	0,09
LFDI	1.25	0.79
Mean VIF	5.87	0,44

Table 8
Panel cointegration Test results with intercept and trend.

	t-Statistic	Prob.
ADF	−1.388[a]	(0.082)
Residual Variance	0.00035	
HAC Variance	0.000326	

[a] Statistically significant at 10%.

Table 9
Fully modified least squares (FMOLS) and dynamic least squares (DOLS).

Variables	FMOLS		DOLS	
ECI	0.635***	(0.000)	0.503***	(0.007)
ECI^2	−0.767***	(0.000)	−0.6295***	(0.002)
LREW	−0.902***	(0.000)	−0.370**	(0.027)
LFDI	0.035**	(0.050)	0.017	(0.464)
S.E. of regression	0.047		0.030	
Long-run variance	0.003		0.000	
Mean dependent var	0.593		0.592	
S.D. dependent var	0.383		0.384	
Sum Squared Resid	0.218		0.025	
Observations	107		97	

** Statistically significant at 5% *** Statistically significant at 1%.

Fig. 3), as has been observed in other findings (Can and Gozgor, 2017; Laverde-Rojas and Correa, 2021; Neagu, 2019; Sadeghi et al., 2020). The expected sign is also obtained in the parameter that represents renewable energy, demonstrating that it contributes to the achievement of neutrality of polluting emissions by human activity (see Fig. 4).

In addition, when we use the FMOLS method, the present study also demonstrates that inward foreign direct investment increases carbon dioxide emissions per capita to statistically significant levels, consistent with the PHV-Pollution Haven Hypothesis, as some authors have recently obtained empirical evidence, i.e., Huang et al. (2022) for G20 economies and Balsalobre-Lorente et al. (2022) for BRICS countries. However, other recent studies have also obtained evidence favourable to the Pollution Halo hypothesis, i.e., Ochoa-Moreno et al. (2021) for 20 Latin American countries and Chaouachi and Balsalobre-Lorente (2022) for MINT countries. Even a recent study by Ahmad et al. (2021) supports one hypothesis and the opposite, depending on the Chinese province. This evidence supports that in the selected panel, there is an attraction of dirty industry in host countries, revealing the necessity of changes in regulation aimed at attracting high-tech industry to the BRICS. In this sense, advances in Industry 4.0 would enhance an environmentally friendly industry, attracting foreign business.

Regarding the tasks carried out to estimate Equation (2), unfortunately, in international databases, there are neither sufficiently comprehensive nor long enough variables to measure ICT activity. Moreover, the environmental impact of Industry 4.0 is not only due to the provision of services (which is a minor issue) but also to the production of goods that support ICT services and the rest of automation of industrial processes, networks and durable consumer goods that incorporate high technology. In this study, we have tested three variables to measure the environmental impact of industry 4.0 (see Table 2): the export of ICT services per capita (*lexpictpc*), the percentage that the export of these services represents over the total exports (*%icte*), and the sum of the relative weights representing exports and imports of ICT goods (*%ictgei*). Table 10 summarizes the results of the estimations made using four different methods.

The first observation from Table 10 is that only one parameter (*$lexpictpc^2$*) is not statistically significant in one estimation when the DOLS method is used with the explanatory variable "logarithm of ICT services per capita". Second, in all cases, the parameters obtained when the square of the variables is used show a minus sign, indicating that it is very probable that the positive contribution of 4.0 technologies to CO_2 emissions reaches a maximum, from which manufacturing and the use of

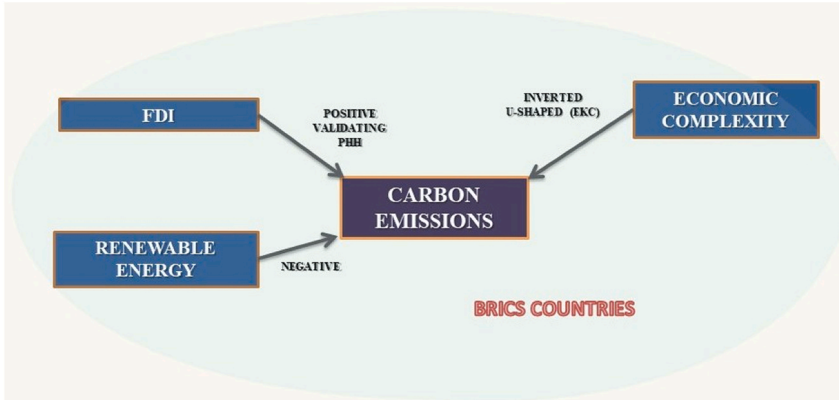


Fig. 4. Graph absract.
Source: Prepared by authors.

Table 10
Impact of Industry 4.0 on CO_2 emissions (lcopc) in BRICS countries.

Variables	Panel Least Squares	Panel FMOLS	Panel DOLS	Panel Quantile Regr. Median	Average Coef.
Proxy variable for Industry 4.0: *lexpictpc*					
lexpictpc	0.87843***	0.14456***	0.07591**	1.81497***	0.7449
lexpictpc^2	−0.29844***	0.03309***	0.033526	−0.93435***	−0.3248
Proxy variable for Industry 4.0: *%icte*					
%icte	0.14099***	0.16416***	0.22238*** −0.004724	0.15741***	0.1712
%icte^2	−0.00298***	−0.00349***	−0.00472***	−0.00332***	−0.0036
Proxy variable for Industry 4.0: *%ictgei*					
%ictgei	0.06498***	0.06814***	0.06883***	0.04831***	0.0626
%ictgei^2	−0.00099***	−0.00104***	−0.00105***	−0.00064***	−0.0037

** Statistically significant at 5% *** Statistically significant at 1%.
lexpictpc: Logarithm of exports of ICT services per capita (BoP, current US$).
%icte: Percentage of exports of ICT services over total exports of services, BoP.
%ictgei: Exports ICT goods/total exports + imports ICT goods/total imports (%).

ICT goods and services will push down polluting emissions. Third, the parameters obtained using the logarithm of ICT services exports per capita-*lexpictpc* and *lexpictpc*^{2} variables are considerably higher than those obtained with the rest of the variables, and the size of the parameters obtained with these two variables are very sensitive to the estimation method used.

All these considerations lead us to affirm that the use of the percentage of ICT services exports over total services exports-*%ictgei* variable is more appropriate to approximate the impact of industry 4.0 on CO^2 emissions: the parameters obtained are significant at 1%, they are not very sensitive to the change in estimation method. They are smaller than the other parameters. An increase of 1 point (in a scale of 0–200) in the value of the variable results in an increase of 0.06% in CO^2 emissions. In this case, given that the variables used are mere approximations of the accurate measurement of Industry 4.0 and that the model is very simplified, it makes no sense to calculate the turning point of each variable.

5. Conclusion and implications

Our study asses the linkage between per capita Carbon Dioxide Emissions, Renewable Energy, Economic Complexity Index and Foreign Direct Investment in BRICS nations for 1995–2018. The choice of these countries regards the similarity of their development level due to their reliance on unclean energy sources strongly impacting Carbon Dioxide Emissions (Azam and Haseeb, 2021; Iwaro and Mwasha, 2010). However, they maintain essential differences in the level of polluting emissions per capita and the level of introduction of information and communication technologies (ICT) (see Fig. 2).

The estimates of the environmental Kuznets function (EKC) based on the impact of the economic complexity index on CO^2 emissions leave no room for doubt. There is a positive impact, although, in the long term, there is a turning point from which the Economic complexity contributes to reducing polluting emissions. This evidence is similar to the evidence obtained when the GDP variable is used to study the impact on CO_2 emissions.

In addition, the empirical findings suggest that renewable energy contributes negatively to carbon dioxide emissions, while foreign direct investment increases these emissions, confirming the Pollution Haven Hypothesis (PHV). This empirical evidence suggests that authorities should promote the use of cleaner energy if they intend to reduce environmental pollution, while a long-term improvement in the economic complexity index does not contribute to increasing pollution. In short, the results are compatible with sustainable growth under these parameters. It is also possible to conclude that Pollution Haven – PHV is present in BRICS nations, where Inward Foreign Direct Investment (FDI) has been shown to impact CO_2 emissions significantly, and nations prefer less stringent environmental regulations.

This study also includes a novel empirical methodology to obtain an approximate estimate of the environmental impact that the set of technologies known as Industry 4.0 is causing. Despite the absence of more adequate statistics and the short sequences of data available, the contribution of information and communication technologies to environmental deterioration seems moderate (less than 0.1% for each point of increase in the weight of these technologies), and the results show that they may have a turning point from which they put downward pressure on carbon emissions.

Future research should study the fit of variables such as trade, the human development index, the quality of democracy or the level of financial development, among others that have impacted pollution levels worldwide. For example, the application of intra-industry trade indicators (static or dynamic) appears essential for understanding whether the BRICS case is based on a monopolistic competition structure associated with an innovation factor or whether it will be explained by the theory of comparative advantages (Balogh and Leitão, 2019; Chaouachi and Balsalobre-Lorente, 2022; Balogh and Leitão, 2019; Chaouachi and Balsalobre-Lorente, 2022). In the same way, it is necessary to know in greater depth the environmental impact of the new technologies associated with Industry 4.0. To do this, international organizations must provide adequate databases that compare countries' efforts to achieve emissions neutrality of these thriving technologies.

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Authors contributions

All authors contributed to the study's conception and design.

Ethics declarations

Not applicable.

Ethical approval and consent to participate

Not applicable.

Consent for publication

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Credit author statement

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Declaration of competing interest

The authors declare no competing interests.

Data availability

Data will be made available on request.

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