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The Impact of Entrepreneurship and Education on the Ecological Footprint: Insights from the G-20 States

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Abstract: Environmental impairment has become a critical global issue. Therefore, identifying the drivers of environmental degradation is essential for addressing environmental challenges worldwide. This research article employs the Westerlund and Edgerton (2007) bootstrap cointegration test and the causality test of Juodis, Karavias, and Sarafidis (2021) to examine the interplay among entrepreneurial activities, education, renewable energy utilization, and ecological footprint in selected G-20 countries during 2002–2020. The causality analysis reveals a unidirectional causal relationship between entrepreneurial activities and education to ecological footprint, along with a feedback loop between ecological footprint and renewable energy utilization. Additionally, the cointegration analysis indicates that education, renewable energy utilization, and entrepreneurial activities generally reduce the ecological footprint in the long term for most of the countries studied. In conclusion, entrepreneurship, education, and renewable energy usage are significant factors in determining the ecological footprint in both short- and long-term scenarios. Hence, countries could leverage education, sustainable entrepreneurship, and renewable energy to enhance environmental quality.

Keywords: entrepreneurial activities; education; renewable energy; environment; panel data analysis; G-20 states

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1. Introduction

The environment has markedly deteriorated worldwide as a consequence of industrialization, economic growth, population expansion, urbanization, deforestation, and significant increases in fossil energy and chemical use since the Industrial Revolution, becoming one of the top global threats for current and future generations [1]. Consequently, combating environmental degradation has emerged as a primary goal for countries, regional and economic unions, and the United Nations (UN). Nearly half of the sustainable development goals (SDGs) set forth by UN members, such as climate action, affordable and clean energy, clean water and sanitation, responsible consumption and production, sustainable cities and communities, and lives on land and below water, aim to improve environmental quality either directly or indirectly [2].

This notable increase in environmental awareness has also led researchers to explore the drivers of environmental impairment globally and in various regions of the world. Empirical studies examining the nexus between economic, institutional, social, legal, and demographic factors and the environment—often proxied by CO_2 emissions, greenhouse gas emissions, and various types of ecological footprints—have identified that factors such as GDP per capita economic growth, sectoral composition, population growth, financial sector development, trade openness, globalization, foreign direct investment inflows, institutions, democratization, economic freedom, human capital development, education, entrepreneurship, innovation, productivity, health expenditures, information and communication technology penetration, renewable and non-renewable energy use, energy intensity, and urbanization play significant roles [3–9].

This article investigates the impact of entrepreneurial activities and education, along with renewable energy, on the ecological footprint. Both entrepreneurial activities and education have been prominent drivers of economic growth and development in recent years, yet the relationship between entrepreneurial activities, education, and ecological footprint remains underexplored. Entrepreneurship, suggested as a key driver of economic growth and development [10–12], has been supported by empirical literature linking it to economic growth [13]. However, the environmental impacts of entrepreneurial activities have not been sufficiently studied. Entrepreneurial activities may affect the environment directly or indirectly through economic growth and development driven by increases in production and consumption. The net effect of entrepreneurial activities on the environment depends on the nature of entrepreneurship and country-specific characteristics such as economic development level, human capital, and education. Entrepreneurial activities can enhance environmental quality if entrepreneurs opt for environmentally friendly products and low-carbon energy sources or develop energy-efficient products and green technologies [14]. Conversely, entrepreneurs may harm the environment by increasing production and consumption, especially if environmental regulations are weak and the country is in the early stages of economic development [15]. Thus, the composition of entrepreneurial activities and country characteristics play a critical role in the connection between entrepreneurship and the environment.

Education influences the environment through various negative and positive aspects. As a key component of human capital, education can impact economic growth directly or through competitiveness and innovation [16,17], thereby affecting the environment either negatively or positively according to the environmental Kuznets curve hypothesis [15]. Additionally, education can contribute to environmental improvement through the development of energy-efficient technologies, abatement technologies, and energy competence via human capital [18,19]. Lastly, improvements in environmental and sustainability awareness through education can positively affect the environment [20]. In conclusion, the impact of education on the environment can vary depending on which factors dominate the nexus between education and the environment.

Fossil fuels are closely associated with significant environmental problems, such as air, thermal, and water pollution, climate change, and solid waste. Approximately 75% of greenhouse gas emissions and nearly 90% of CO_2 emissions globally result from the use of fossil fuels [21]. Consequently, transitioning to low-carbon energy sources such as wind, solar, hydro, and nuclear power is critical for addressing these environmental challenges. In this context, developing renewable energy, known for its substantially lower greenhouse gas and air pollutant emissions, can be an effective strategy for improving environmental quality.

This research article examines the impact of entrepreneurial activities, education, and renewable energy use on the ecological footprint in selected G-20 economies. This paper aims to contribute empirically to the literature in two key aspects. First, as highlighted in the literature review section, there is no theoretical and empirical consensus on the nexus between entrepreneurship, education, and environmental impairment. Therefore, this article seeks to contribute to this sparse area of literature by analyzing this nexus both at the individual country and panel levels. Second, this paper is among the first to investigate the influence of entrepreneurship and education on the ecological footprint in selected G-20 economies, including China, the United States, India, Russia, Japan, and Germany, which are among the top ten CO_2-emitting countries [22].

In the remaining sections of the research, the findings of the related empirical literature are presented, and the data and methods used are introduced. Section 3 discusses the results of causality and cointegration tests, while Section 4 delves into a discussion about these results. The final section of the article summarizes the conclusions, offers policy recommendations, and suggests directions for future research.

2. Literature Research

The drivers of environmental impairment have been extensively studied in the empirical literature. However, the impact of entrepreneurial activities and education—two crucial components of economic growth and development—on environmental impairment has only recently begun to attract researchers' attention.

2.1. Empirical Literature on the Environmental Effects of Entrepreneurship

Empirical studies on the relationship between entrepreneurial activities and the environment, as summarized in Table 1, have shown varied outcomes. For instance, Omri [23], Dhahri and Omri [24], Ben Youssef et al. [25], Omri and Afi [26], Kövendi et al. [27], and Philip et al. [28] revealed a positive impact of entrepreneurial activities on environmental degradation. Conversely, recent studies by Philip et al. [29], Chen et al. [30], and Hussain et al. [31] found a negative impact of entrepreneurial activities on the environment. Additionally, Venâncio and Pinto [32] and Kövendi et al. [27] reported an insignificant relationship between entrepreneurship and environmental indicators.

Table 1. Empirical literature on the environmental effects of entrepreneurship.

Study	Sample; Period	Method	Impact of Entrepreneurship on Environmental Impairment
Omri [23]	69 countries; 2001–2011	Pedroni cointegration test	Positive
Dhahri and Omri [24]	20 developing countries; 2002–2012	Pedroni cointegration test	Positive
Ben Youssef et al. [25]	17 African states; 2001–2014	Cointegration and regression	Positive
Omri and Afi [26]	32 developing countries; 2001–2015	Regression	Positive
Kövendi et al. [27]	67 countries; 2006–2016	Regression	Positive in the developed countries but insignificant in the whole panel
Philip et al. [28]	Turkey; 1985–2016	NARDL	Positive
Philip et al. [29]	Malaysia; 1992–2019	Time series analysis	Negative and bilateral causality
Chen et al. [30]	China; 1999–2018	Time-varying difference-in-differences	Negative
Hussain et al. [31]	China; 2002–2019	NARDL	Negative and bilateral causality
Venâncio and Pinto [32]	67 countries; 2015–2018	Regression	Insignificant

Omri [23] analyzed the interaction between entrepreneurship, sectoral output, and environmental impairment in 69 countries with varying income levels from 2001 to 2011 using the Pedroni cointegration approach. His findings indicated that entrepreneurial activities positively affected environmental degradation, although the impact was relatively lower in high-income countries. Furthermore, entrepreneurship initially had a negative effect on the environment, but this turned positive after crossing a certain threshold. Dhahri and Omri [24] also researched the impact of entrepreneurship on key components of sustainable development in developing countries, revealing a positive influence of entrepreneurship on CO_2 emissions and a bilateral causal relationship between entrepreneurship and CO_2 emissions.

Ben Youssef et al. [25] examined the impact of entrepreneurship on CO_2 emissions in 17 African countries using cointegration and regression analyses. They found that both formal and informal entrepreneurship increased CO_2 emissions, with the latter having a greater effect. Nakamura and Managi [33] studied the relationship between entrepreneurial activities, CO_2 emissions, and economic development in 62 countries from 2002 to 2010.

They discovered that entrepreneurship developed up to a certain threshold in countries with low marginal costs of CO_2 emissions but decreased in places where these costs were high. However, increases in the marginal costs of CO_2 emissions were accompanied by increases in entrepreneurial activities.

Omri and Afi [26] investigated the impact of entrepreneurship and public educational expenditures on the environment in developing countries, finding a negative effect of entrepreneurship on the environment. Neumann's literature survey [34], which included 102 publications, also highlighted the negative impact of entrepreneurship on environmental quality. In a similar vein, Philip et al. [28] reported a negative impact of entrepreneurial activity on the environment in Turkey for the period 1985–2016, using the NARDL approach.

On the other hand, Philip et al. [29] investigated the impact of entrepreneurship, renewable energy, financial sector development, and technological innovation on CO_2 emissions in Malaysia from 1992 to 2019 using time series analysis techniques. They found that positive shocks in entrepreneurial activities decreased CO_2 emissions and identified a bilateral causal relationship between entrepreneurship and environmental quality. Chen et al. [30] explored the role of entrepreneurship in the relationship between CO_2 emissions and high-speed rail in China, revealing that entrepreneurship mediated the reduction in CO_2 emissions linked to high-speed rail. Lastly, Hussain et al. [31] examined the interplay among entrepreneurial activity, technological innovation, energy use, and carbon emissions in China from 2002 to 2019 using the NARDL and Granger bootstrap causality tests. They discovered that entrepreneurial activities reduced carbon emissions and established a bilateral causal relationship between entrepreneurial activities and environmental quality.

Venâncio and Pinto [32] analyzed the impact of different types of entrepreneurship on SDGs in 67 countries between 2015 and 2018. Their results indicated an insignificant influence of entrepreneurship on climate action, sustainable cities and society, life on land, life below water, and responsible production and consumption. Kövendi et al. [27] assessed the effect of entrepreneurship, innovation, and technology on CO_2 emissions in 67 countries with varying economic development levels from 2006 to 2016 using a regression analysis. They found that entrepreneurship had an insignificant effect on CO_2 emissions across the entire panel. However, in developed economies, entrepreneurship was associated with an increase in CO_2 emissions.

2.2. Empirical Literature on the Environmental Effects of Education

Recent studies have begun to explore the relationship between education and environmental impairment. The majority of these studies, as listed in Table 2, have revealed the negative impact of various education indicators on environmental impairment. Research by Omri and Afi [26], Uddin [35], Sahoo and Sethi [36], Li and Ullah [37], Özbay and Duyar [38], Sart et al. [39], Wang et al. [40], and Xin et al. [41] has demonstrated a negative effect of different education indicators on environmental degradation. However, studies by Li and Zhou [42] and Zafar et al. [43] have shown a positive impact of education on environmental impairment. Additionally, Khan [44] identified an inverted U-shaped relationship between CO_2 emissions and education.

In their empirical work, Omri and Afi [26] found that tertiary education and public education expenditures reduced CO_2 emissions in models incorporating necessity and opportunity entrepreneurship. However, only tertiary education was significant in the models considering formal and informal entrepreneurship. Uddin [35] also examined the impact of education on CO_2 emissions in Bangladesh from 1974 to 2010 using a cointegration test and revealed that education decreased CO_2 emissions by improving environmental awareness.

Table 2. Empirical literature on the environmental effects of education.

Study	Sample; Period	Method	Impact of Education on Environmental Impairment
Omri and Afi [26]	32 developing countries; 2001–2015	Regression	Negative
Uddin [35]	Bangladesh; 1974–2010	Cointegration	Negative
Li and Ullah [37]	BRICS states; 1991–2019	NARDL	Negative
Özbay and Duyar [38]	OECD states; 1997–2019	Cointegration	Negative (higher education), positive (lower education), and bilateral causality
Sart et al. [39]	EU states; 2000–2018	Causality	Bilateral causality
Wang et al. [40]	146 countries; 2000–2016	Regression	Negative in the whole panel and high-income countries but insignificant in low- and middle-income states
Xin et al. [41]	China; 1991–2020	ARDL	Negative
Li and Zhou [42]	Chinese provinces; 1996–2015	Pedroni cointegration test	Positive
Zafar et al. [43]	22 top remittance-receiving economies; 1986–2017	Cointegration	Positive

Li and Ullah [37] investigated the environmental implications of education in BRICS countries from 1991 to 2019 using the NARDL approach. They discovered a negative impact of education on CO_2 emissions. Özbay and Duyar [38] analyzed the effect of different education levels on environmental quality in 20 OECD countries from 1997 to 2019, finding that higher education reduced CO_2 emissions, whereas lower-level education increased them. They also identified a bilateral causal relationship between higher education, lower-level education, and CO_2 emissions.

Sart et al. [39] explored the causal relationship between tertiary education and CO_2 emissions in EU countries from 2000 to 2018, finding a bilateral causal link. Wang et al. [40] examined the relationship between education level, population structure, income, and ecological footprint in 146 countries from 2000 to 2016 using a regression analysis. They reported a negative impact of education on the ecological footprint in the overall sample and in high-income countries, but this relationship was insignificant in low- and middle-income countries. Xin et al. [41] studied the connection between unemployment, education, and CO_2 emissions in China from 1991 to 2020 using the ARDL approach and found a negative long-term impact of schooling years and literacy rate on CO_2 emissions.

Conversely, Li and Zhou [42] investigated the impact of demographic factors and higher education on CO_2 emissions in China using a regression approach and found a positive impact of higher education on CO_2 emissions in eastern China. Similarly, Zafar et al. [43] examined the drivers of CO_2 emissions in 22 top remittance-receiving countries from 1986 to 2017 using a cointegration test and reported a positive impact of education on CO_2 emissions.

2.3. Empirical Literature on the Environmental Effects of Renewable Energy

The relationship between renewable energy use and environmental impact has been extensively studied in the empirical literature. The majority of research articles listed in Table 3, including works by Philip et al. [29], Sahoo and Sethi [36], Nathaniel et al. [45], Usman et al. [46], Wang et al. [47], Rej et al. [48], Abid et al. [49], Raza et al. [50], Nan et al. [51], Wang et al. [52], and Abban et al. [53], have demonstrated a negative impact of renewable energy use on environmental impairment. However, studies by Raghutla et al. [54] and Karadağ Albayrak et al. [55] identified a positive impact of renewable energy utilization on environmental impairment, while Tiwari et al. [56] reported an insignificant relationship between ecological footprint and renewable energy use.

Table 3. Empirical literature on the environmental effects of renewable energy.

Study	Sample; Period	Method	Impact of Renewable Energy Use on Environmental Impairment
Philip et al. [29]	Malaysia; 1992–2019	Time series analysis	Negative
Sahoo and Sethi [36]	36 developing economies; 1990–2016	Causality and cointegration tests	Negative and unilateral causality from renewable energy use to the ecological footprint
Nathaniel et al. [45]	MENA states; 1990–2016	Causality and cointegration tests	Negative in Israel and Jordan and insignificant causality
Usman et al. [46]	15 countries with the highest emissions; 1990–2017	Causality and cointegration tests	Negative and bilateral causality
Wang et al. [47]	N-11 states; 1990–2018	CS-ARDL	Negative
Rej et al. [48]	India; 1970–2017	ARDL	Negative
Abid et al. [49]	Saudi Arabia; 1980–2017	ARDL	Negative and bilateral causality
Raza et al. [50]	G-20 states; 1990–2021	CS-ARDL	Negative
Nan et al. [51]	China; 2000–2019	VAR and quantile regression	Negative and insignificant causality
Wang et al. [52]	OECD states; 1995–2028	Causality and cointegration tests	Negative and bilateral causality
Abban et al. [53]	29 European countries; 1990–2019	Regression	Negative
Raghutla et al. [54]	N-11 states; 1980–2018	Regression	Positive
Karadağ Albayrak et al. [55]	Turkey; 1980–2016	ARDL	Positive
Tiwari et al. [56]	6 European developing economies; 1994–2018	Causality and cointegration tests	Insignificant
Nathaniel and Khan [57]	ASEAN economies; 1990–2016	Causality and cointegration tests	Insignificant in the long run and bilateral causality

Nathaniel et al. [45] analyzed the connection between the ecological footprint, renewable energy use, and urbanization in MENA countries from 1990 to 2016 using causality and cointegration tests. They found a negative impact of renewable energy on the ecological footprint only in Israel and Jordan and an insignificant causal relationship between the ecological footprint and renewable energy utilization. Similarly, Sahoo and Sethi [36] explored the relationship among non-renewable and renewable energy, human capital, natural resources, globalization, and ecological footprint in 36 developing economies from 1990 to 2016. They discovered a negative impact of renewable energy on the ecological footprint and a unilateral causal relationship between renewable energy utilization and the ecological footprint.

Usman et al. [46] investigated the effects of non-renewable and renewable energy use, along with financial development, on the ecological footprint in 15 high-emission countries from 1990 to 2017. Using causality and cointegration tests, they uncovered a negative impact of renewable energy utilization on the ecological footprint and a bilateral causal relationship between renewable energy use and the ecological footprint. Philip et al. [29] also found that positive shocks in renewable energy reduced carbon emissions in Malaysia.

Wang et al. [47] examined the impact of several factors, including renewable energy, on the ecological footprint in N-11 countries between 1990 and 2018 using the CS-ARDL approach. They reported that renewable energy use negatively influenced the ecological footprint. Rej et al. [48] studied the relationship between industrialization, renewable energy utilization, exports, and ecological footprint in India from 1970 to 2017 using the ARDL approach, finding a negative impact of renewable energy utilization on the ecological footprint.

Furthermore, Abid et al. [49] analyzed the determinants of the ecological footprint in Saudi Arabia from 1980 to 2017 using the ARDL approach. They discovered a negative impact of renewable energy utilization on the ecological footprint and a bilateral causal relationship between renewable energy utilization and the ecological footprint. Raza et al. [50] also reported a negative influence of renewable energy utilization on the ecological footprint and a bilateral causal relationship between the two variables in G-20 countries from 1990 to 2021 using the CS-ARDL approach.

Nan et al. [51] researched the impact of renewable energy use on China's energy ecological footprint using VAR and quantile regression. They found a negative effect of renewable energy utilization on the energy ecological footprint and an insignificant causal relationship between the energy ecological footprint and renewable energy. Wang et al. [52] investigated the determinants of the ecological footprint in 36 OECD countries from 1995 to 2028 using causality and cointegration tests, revealing a negative impact of renewable energy utilization on the ecological footprint and a bilateral causal relationship between the ecological footprint and renewable energy use. Lastly, Abban et al. [53] demonstrated the negative impact of renewable energy on CO_2 emissions in European countries through a regression analysis.

Raghutla et al. [54] explored the impact of renewable energy use on the ecological footprint in N-11 countries from 1980 to 2018 using quantile regression and cointegration tests, uncovering a positive impact of renewable energy utilization on the ecological footprint. Karadağ Albayrak et al. [55] investigated the relationship between non-renewable and renewable energy utilization, economic growth, trade openness, and ecological footprint in Turkey from 1980 to 2016 using the ARDL approach, finding a positive impact of renewable energy on the ecological footprint in Turkey.

Tiwari et al. [56] discovered an insignificant relationship between ecological footprint and renewable energy in six developing European countries based on causality and cointegration analyses. Finally, Nathaniel and Khan [57] examined the impact of urbanization, economic growth, and non-renewable and renewable energy use on the ecological footprint in ASEAN countries from 1990 to 2016 using causality and cointegration tests. They reported an insignificant impact of renewable energy utilization on the ecological footprint but a bilateral causal relationship between the ecological footprint and renewable energy utilization.

In light of the reviewed theoretical and empirical literature, the following three hypotheses are proposed for this research:

The following three hypotheses of the research are identified as a consequence of reviewing the related theoretical and empirical literature:

Hypothesis 1. *There is a significant relationship between entrepreneurship and the ecological footprint.*

Hypothesis 2. *There is a significant relationship between education and ecological footprint.*

Hypothesis 3. *There is a significant relationship between renewable energy use and the ecological footprint.*

3. Data and Methods

This article examines the interplay among entrepreneurship, education, renewable energy consumption, and the ecological footprint in the G-20 states. The study's variables are detailed in Table 4. We use the ecological footprint as an environmental proxy because it encompasses various environmental factors, making it one of the most comprehensive environmental indicators [57]. The ecological footprint (ECOFT) is proxied by the ecological footprint of consumption, which includes the ecological footprint of production and the ecological footprint of net trade, as calculated by the Global Footprint Network [58]. The ecological footprint of production reflects the biocapacity use from a country's production processes, while the ecological footprint of net trade indicates biocapacity use due to international trade [59]. The explanatory variables are entrepreneurship (ENTR), education

(EDU), and renewable energy consumption (RENEW). Entrepreneurship is represented by early-stage entrepreneurial activity (the rate of entrepreneurs to the population aged 18–64), as calculated by the Global Entrepreneurship Monitor [60], reflecting early-stage entrepreneurial activities. Education is proxied by the education index (the average of indices of expected and mean schooling years), calculated by the UNDP [61,62], representing the overall education level and considering not only current schooling years but also expected schooling years. Renewable energy use (RENEW) is depicted by the renewable energy share in total final energy use, as calculated by the World Bank [63], due to its widespread use in the empirical literature.

Table 4. Dataset description.

Variable Symbols	Variable Definition	Resource
ECOFT	Ecological Footprint	Global Footprint Network
ENTR	Early-stage Entrepreneurial Activity	Global Entrepreneurship Monitor
EDU	Education Index	UNDP
RENEW	Renewable Energy Use	World Bank

The G-20 states form the research sample, because G-20 economies include China, the United States, India, Russia, Japan, and Germany, which are among the top ten CO_2-emitting economies [22]. However, seven countries were excluded due to insufficient entrepreneurship data. Thus, the sample comprises Brazil, China, France, Germany, India, Italy, Japan, Mexico, Russia, South Africa, South Korea, the United Kingdom, and the United States. Entrepreneurship data spans from 2002 to 2021, while renewable energy use data are available until 2020. Hence, the study period is 2002–2020. Empirical analyses were conducted using EViews 13.0 and Stata 17.0.

Table 5 presents the summary statistics of ECOFT, ENTR, EDU, and RENEW. The mean values for the overall sample are 4.094 gha (global hectares) per person, 8.771%, 0.754, and 13.692%, respectively. RENEW, ENTR, and ECOFT show high volatility from 2002–2020, while EDU appears more stable over this period.

Table 5. Summary statistics of the variables.

Summary Statistics	ECOFT	ENTR	EDU	RENEW
Mean	4.094	8.771	0.754	13.692
Median	4.197	7.590	0.793	9.460
Maximum	10.482	24.010	0.942	50.050
Minimum	0.084	1.480	0.380	0.700
Std. Dev.	2.241	4.743	0.134	13.019
Skewness	0.280	0.786	−0.709	1.552
Kurtosis	3.295	3.053	2.619	4.214

The study explores the short- and long-term relationships among entrepreneurial activities, education, renewable energy, and ecological footprint in the selected G-20 states using the Westerlund and Edgerton [64] bootstrap cointegration test and the Juodis, Karavias, and Sarafidis (JKS) [65] causality test. The cointegration analysis assesses whether variables move together or exhibit a common long-term trend. Specifically, two variables with stochastic trends are cointegrated if their linear combination eliminates these trends or becomes I(0) [66]. The Westerlund and Edgerton [64] cointegration test, utilizing an LM bootstrap process, is expressed in Equation (1):

$$y_{it} = \alpha_i + x_{it}^{'}\beta_i + z_{it} \quad (1)$$

where $z_{it} = u_{it} + \sum_{j=1}^{t} \eta_{ij}$. η_{ij} is an error term with a zero mean and σ_i^2. The hypotheses for this test are as follows:

$$H_0: \ \sigma_i^2 = 0 \ (\text{indicating a cointegration relation for each cross-section})$$

$$H_0: \ \sigma_i^2 > 0 \ (\text{suggesting no cointegration relation for each cross-section})$$

The Westerlund and Edgerton [64] test is advantageous as it accounts for cross-sectional dependence, autocorrelation, and heteroscedasticity in the cointegration equation, and it is robust for small panel datasets.

Granger causality analysis tests, whether one time series, are useful in forecasting another series [67]. Put differently, a variable x Granger-causes another variable y if predictions of y are more accurate using past values of both x and y, rather than solely using past values of y [68]. The JKS [65] causality test offers several advantages over the traditional Granger causality test. First, it is applicable to both heterogeneous and homogeneous panels. Second, it eliminates dynamic panel bias through the use of the split panel jackknife method. Additionally, the test produces robust results for panels where T < N, unlike the Dumitrescu and Hurlin causality tests. Lastly, the JKS [65] causality test surpasses the Dumitrescu and Hurlin test in terms of power, as demonstrated by an extensive Monte Carlo experiment.

4. Results and Discussion

In this study's application section, the cross-sectional dependency among the ECOFT, ENTR, EDU, and RENEW series is investigated using Breusch and Pagan's [69] LM test, Pesaran's [70] LM CD test, and Pesaran et al.'s [71] LM adj. test. The findings are presented in Table 2. The tests reject the null hypothesis of cross-sectional independence, confirming the existence of cross-sectional dependency among these series.

Homogeneity is then examined using Pesaran and Yamagata's [72] delta tilde tests, with the results shown in Table 6. These tests also reject the null hypothesis, indicating the presence of heterogeneity among the variables.

Table 6. Cross-sectional dependency and heterogeneity tests.

Tests of Cross-Sectional Dependency		
Test	**Test Statistics**	***p*-Value**
LM	57.254	0.021
LM CD	64.780	0.000
LM adj.	68.245	0.000
Heterogeneity Tests		
Test	Test Statistics	*p*-Value
$\tilde{\Delta}$	48.128	0.005
$\tilde{\Delta}_{adj.}$	51.376	0.008

The stationarity of the series is assessed using the CADF (Cross-sectional Augmented Dickey–Fuller) test by Pesaran [73] and the SURADF (Seemingly Unrelated Regression Augmented Dickey–Fuller) unit root test by Breuer et al. [74,75], considering cross-sectional dependence and heterogeneity. The results in Table 7 reveal that ECOFT, ENTR, EDU, and RENEW have unit roots at their level values but become stationary when first differenced.

Table 7. Results of stationarity analysis of ECOFT, ENTR, EDU, and RENEW.

	CADF Unit Root Test		SURADF Unit Root Test	
Variables	**Constant**	**Constant + Trend**	**Constant**	**Constant + Trend**
ECOFT	−0.835	−0.981	−0.985	−10.104
D(ECOFT)	−6.453 ***	−7.102 ***	−7.113 ***	−7.674 ***
ENTR	−1.219	−1.311	−1.297	−1.613
D(ENTR)	−7.904 ***	−8.642 ***	−8.466 ***	−9.035 ***
EDU	−0.967	−1.089	−1.056	−1.102
D(EDU)	−8.221 ***	−9.780 ***	−8.980 ***	−9.596 ***
RENEW	−0.714	−0.876	−0.814	−0.905
D(RENEW)	−5.987 ***	−6.599 ***	−6.404 ***	−7.011 ***

Note: Bootstrap critical values of the SURADF test are generated through 10,000 replications. *** It is significant at the 1% level.

Cointegration among ecological footprint, entrepreneurship, education, and renewable energy is analyzed using the Westerlund and Edgerton [64] bootstrap cointegration test, with outcomes including asymptotic and bootstrap probability values presented in Table 8. The significant cointegration interaction among these variables is confirmed, as probability values exceed the 5% significance level.

Table 8. Results of the Westerlund and Edgerton bootstrap cointegration test.

Constant			Constant + Trend		
Test Statistic	**Asymptotic *p*-Value**	**Bootstrap *p*-Value**	**Test Statistic**	**Asymptotic *p*-Value**	**Bootstrap *p*-Value**
8.432	0.584	0.622	9.563	0.613	0.694

Cointegration parameters for cross-sections and the panel are estimated using the augmented mean group estimator by Eberhardt and Teal [76], with the results shown in Table 9. At the panel level, entrepreneurial activities, education, and renewable energy use are found to negatively impact the ecological footprint. Education has the most substantial negative effect, followed closely by renewable energy utilization. Entrepreneurial activities have a slightly lesser negative impact.

Table 9. Cointegration parameters.

Country	ENTR	EDU	RENEW
Brazil	0.113 **	−0.265 **	−0.107 **
China	−0.092 **	−0.178 **	−0.091 **
France	−0.121 *	−0.288 **	−0.115 **
Germany	−0.129 **	−0.291 **	−0.118 **
India	0.084 **	0.114 **	−0.086 **
Italy	−0.117 *	−0.253 **	−0.102 *
Japan	−0.134 **	−0.295 **	−0.113 **
Mexico	0.083 **	0.159 **	−0.097 **
Russia	−0.124 *	−0.263 **	−0.099
South Africa	0.101 **	−0.192 **	−0.087 **
South Korea	−0.105 **	−0.240 **	−0.110 **
United Kingdom	−0.127 **	−0.301 **	−0.120 **
United States	−0.138 **	−0.309 **	−0.123 **
Panel	−0.121 **	−0.274 **	−0.136 **

** and *, respectively, are significant at 1% and 5%.

A country-specific analysis reveals varied impacts. Entrepreneurial activities increase the ecological footprint in Brazil, India, Mexico, and South Africa but decrease it in China, France, Germany, Italy, Japan, Russia, South Korea, the United Kingdom, and the United States. Education reduces the ecological footprint in all countries except India and Mexico. Renewable energy utilization decreases the ecological footprint in all analyzed countries except Russia.

Entrepreneurial activities, education, and renewable energy use may influence the ecological footprint through various direct and indirect aspects. Specifically, entrepreneurial activities can affect the environment either by developing energy-efficient products and green technologies or through economic growth and expansion. Therefore, the net environmental effects of entrepreneurial activities depend on the nature of these activities and the economic development levels of the countries involved. Consequently, existing studies have reported mixed results for different countries or panels.

In this context, studies by Omri [23], Dhahri and Omri [24], Ben Youssef et al. [25], and Omri and Afi [26] revealed a positive effect of entrepreneurial activities on environmental impairment in developing countries. Conversely, Kövendi et al. [29] identified a positive effect of entrepreneurship on environmental impairment exclusively in developed countries. Meanwhile, Philip et al. [28] found a positive impact of entrepreneurship on environmental impairment, but a subsequent study by Philip et al. [29] indicated a negative impact in Malaysia, where entrepreneurs rapidly adapted to changing economic conditions and embraced green and energy-efficient technologies. Similarly, Chen et al. [30] and Hussain et al. [31] observed a negative effect of entrepreneurship on environmental impairment in China.

In summary, our findings for China align with those of Chen et al. [30] and Hussain et al. [31]. Furthermore, the observed positive effect of entrepreneurship on the ecological footprint in Brazil, India, Mexico, and South Africa partially corresponds with the findings of Omri [23], Dhahri and Omri [24], Ben Youssef et al. [25], and Omri and Afi [26] for developing countries. However, our cointegration analysis indicates that entrepreneurial activities reduce the ecological footprint in China, France, Germany, Italy, Japan, Russia, South Korea, the United Kingdom, and the United States.

Based on our findings and the relevant literature, it is evident that entrepreneurial activities can be environmentally beneficial if they focus on developing green and energy-efficient technologies and fostering innovation and productivity. Otherwise, in the absence of stringent environmental regulations, often seen in underdeveloped and developing countries, entrepreneurial activities can exacerbate environmental damage by increasing production and consumption.

Education is a crucial factor that can influence the environment through environmental and sustainability awareness improvements, human capital, human development, innovation, and technological progress. Consequently, the net impact of education on the ecological footprint varies among countries, contingent on country-specific characteristics. However, the majority of the relevant empirical literature, as presented in Table 2, indicates a generally negative impact of education on environmental impairment across different countries and groups. Wang et al. [40] found that education reduced environmental impairment in high-income countries within a panel of 146 countries, but the relationship between education and environmental impairment was insignificant in low- and middle-income states. In contrast, Li and Ullah [37] and Xin et al. [41] identified a negative impact of education on environmental impairment using the ARDL approach, while Li and Zhou [42] observed a positive impact of education on environmental impairment in Chinese provinces through a panel cointegration approach.

This study reveals that, in the long run, education reduces the ecological footprint in 11 countries of the sample but increases it in India and Mexico. Thus, our results align with the findings of Li and Ullah [37] and Xin et al. [41], who examined the relationship between education and the environment for BRICS countries and China on a larger scale.

Therefore, education emerges as a pivotal tool to combat environmental impairment, but its effectiveness is heavily influenced by country-specific characteristics.

Regarding renewable energy, increasing its share in total energy use, especially with low-carbon emissions, is expected to decrease environmental impairment. The studies in Table 3, examining the impact of renewable energy on the environment in various countries and groups, including the G-20 states, generally suggest that renewable energy use significantly reduces environmental impairment. An exception is the findings of Raghutla et al. [54] and Karadağ Albayrak et al. [55], who, respectively, reported a positive impact of renewable energy use on environmental impairment in the N-11 states and Turkey. Raghutla et al. [54] argued that renewable energy use did not decrease environmental impairment due to the predominant use of non-renewable energy.

Our study finds a negative relationship between renewable energy use and environmental impairment, aligning with the findings of Raza et al. [50], who explored this nexus for G-20 states. In conclusion, renewable energy is an effective tool for reducing environmental impairment.

Lastly, the causal relationship among ecological footprint, entrepreneurial activities, education, and renewable energy is examined using the JKS [65] panel causality test, with results shown in Table 10. The test indicates a one-way causal relationship between ENTR and EDU to ECOFT and a bidirectional causal connection between RENEW and ECOFT. In other words, entrepreneurial activities and education significantly impact the ecological footprint, and a feedback loop exists between the ecological footprint and renewable energy utilization.

Table 10. JKS causality test results.

H0	HPJ Wald Test	*p*-Value
ENTR $\nrightarrow$ ECOFT	3.1221	0.0172
ECOFT $\nrightarrow$ ENTR	3.2399	0.1979
EDU $\nrightarrow$ ECOFT	5.5750	0.0182
ECOFT $\nrightarrow$ EDU	0.1823	0.9998
RENEW $\nrightarrow$ ECOFT	7.5316	0.0026
ECOFT $\nrightarrow$ RENEW	6.2864	0.0004

The causal relationship between the ecological footprint, entrepreneurial activities, and education has been the focus of a limited number of studies. In this area, Philip et al. [29] and Hussain et al. [31] each identified a bidirectional causal relationship between entrepreneurship and environmental impairment in Malaysia and China, respectively. Similarly, Özbay and Duyar [38] and Sart et al. [39] found a bidirectional causal relationship between education and environmental impairment in OECD and EU states, respectively. However, our study reveals a unidirectional causal relationship between entrepreneurship and education to environmental impairment in G-20 states, a difference that may stem from the specific samples used in these studies.

Furthermore, the causal relationship between renewable energy and environmental impairment has been more extensively investigated. A number of studies, including those by Usman et al. [46], Abid et al. [49], Wang et al. [52], and Nathaniel and Khan [57] have reported a bidirectional causal relationship between environmental impairment and renewable energy use, aligning with our findings. In contrast, Nathaniel et al. [45], Nan et al. [51], and Tiwari et al. [56] reported insignificant causality between renewable energy use and environmental impairment.

These varying results across different studies highlight the complexity of the relationships among these factors and underscore the importance of considering specific country contexts and samples when interpreting causal relationships in environmental studies.

5. Conclusions

Environmental impairment has emerged as a significant global threat for both current and future generations. Consequently, researchers and policymakers have prioritized environmental issues at the local, regional, and international levels. This focus has notably intensified studies on the drivers of environmental impairment. However, until recent years, the impact of entrepreneurial activities and education on the environment has not been adequately addressed by researchers. This paper examines the relationship among the ecological footprint, entrepreneurial activities, education, and renewable energy utilization in selected G-20 states, which are also the world's top CO_2 emitters, using a panel data analysis. Due to limited entrepreneurship data, the study employs panel datasets and relevant analysis methods despite the advantages of a time-series analysis in understanding dynamics, deepening insights, and handling data. The availability of entrepreneurship and renewable energy data restricts the sample to 13 G-20 states and the study period to 2002–2020.

The causality test results reveal a causal link between entrepreneurial activities and education to the ecological footprint and a feedback loop between ecological footprint and renewable energy utilization. Additionally, the cointegration coefficients indicate that entrepreneurial activities, education, and renewable energy utilization generally have a negative impact on the ecological footprint in most G-20 countries. However, in countries with relatively lower income and human development levels, entrepreneurial activities and education positively affect the ecological footprint. Overall, our empirical findings are largely consistent with the existing theoretical and empirical literature.

Theoretically, renewable energy is an effective tool for reducing environmental impairment in nearly all countries. Education also plays a crucial role in combating environmental impairment, although its effectiveness varies significantly based on country-specific characteristics. Lastly, entrepreneurial activities can contribute to reducing environmental impairment if they promote innovation, productivity, and the development of green and energy-efficient technologies. In contrast, without such a focus, entrepreneurial activities can exacerbate environmental damage by increasing production and consumption, especially in underdeveloped and developing countries with lenient environmental regulations. Future research should investigate the impact of different types of entrepreneurship on environmental impairment in countries with varying environmental regulations.

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