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Room for Improving the Ecological Sustainability Gap in G20 Economies through the Lens of Load Capacity Factor: The Role of Green Energy Initiatives as Moderators

Hossein Ali Fakher[1,*], Ghalieb Mutig Idroes[2]

[1] Department of Business Management, Ayandegan Institute of Higher Education, Tonekabon, Iran; ha_fakher@aihe.ac.ir; imanfakher@yahoo.com.

[2] Department of Energy and Green Economics, Graha Primera Saintifika, Aceh Besar 23371, Indonesia; ghaliebidroes@outlook.com.

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Abstract

With the global imperative to combat climate and environmental challenges, the factors contributing to ecological contamination have received increasing attention in contemporary academic discourse. Meanwhile, the significance of the Green Energy Initiative (GEI) as a moderating factor in this interrelation is often overlooked in the world's leading economies, particularly within the G20-the largest contributor to global carbon emissions-in the context of the Load Capacity Factor (LCF). In this context, this study selected data from 2007 to 2022. It employed the two-step system GMM estimator for the equation to thoroughly shed light on the interrelation between ecological contamination, economic growth, Financial Development (FD), Trade Openness (TRO), and energy consumption. The findings disclose that GDP and its square positively and negatively impact LCF, respectively, confirming the Environmental Kuznets Curve (EKC) hypothesis. Moreover, TRO contributes to increased environmental degradation. Additionally, FD plays a positive role in reducing environmental degradation. Furthermore, the results reveal that GEI has significantly improved the G20's environmental sustainability. More importantly, the moderation effect of GEI and economic growth suggests that GEI can improve the effectiveness of economic growth to shape ecological sustainability. In light of the results obtained, various regulatory actions are proposed to curb ecological contamination, aligning with sustainable development principles.

Keywords: Load capacity factor, Environmental kuznets curve hypothesis, Economic growth, Two-step sys-GMM approach.

1 | Introduction

1.1 | Background

The concept of Sustainable Development Goals (SDGs) focuses on addressing the requirements of people today while ensuring that future generations retain the capacity to fulfill their necessities. Researchers,

Corresponding Author: imanfakher@yahoo.com

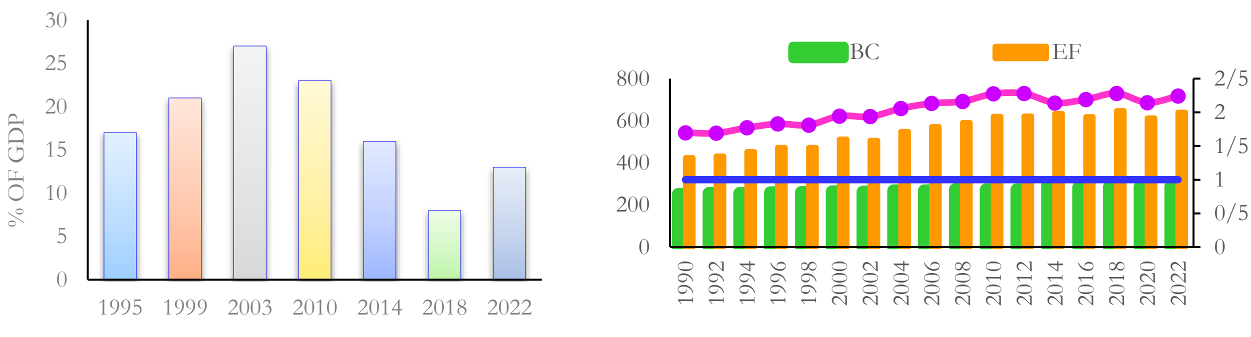
policymakers, and global institutions are widely examining and debating this issue as they strive to balance economic growth, environmental protection, and social well-being [1]. Environmental crises, including climate change, global warming, and ecosystem deterioration, have emerged as the most significant obstacles to fulfilling these goals [2].

As the world's leading economies and a broad representation of both developed and developing nations, G20 economies are the largest contributors to global carbon emissions [3]. In response to these significant contributions, G20 countries have implemented various environmental strategies to mitigate ecological issues [4]. Thus, considering these problems enables policymakers to design strategies that balance economic variables with ecological health in these economies.

1.2 | Selection of Countries and Indicators

The choice to focus on G20 countries is motivated by the fact that these economies, which are responsible for approximately 80% of global gross domestic product and nearly account for 75% of total greenhouse gas emissions, continue to rely heavily on fossil energy resources, leading to significant ecological contamination [5], [6]. On the other hand, this group of economies comprises roughly 60% of the world's population and 75% of global trade [7]. From 2007 to 2022, the Elevated Ecological Footprint (EFI) of G20 countries reflected the overuse of resources and rising carbon emissions, highlighting the urgent need for strategies to address their significant environmental challenges and promote sustainable development. In conclusion, ecological degradation has increased over the years in G20 economies, showing a serious threat to SDGs. The G20 comprises a mix of both advanced and emerging economies, allowing for a comprehensive examination of how ecological footprints affect biocapacity across various nations. As illustrated in *Fig. 1b*, between 1990 and 2022, G20 nations have consistently used natural resources at a rate exceeding nature's ability to regenerate them. This excessive consumption has led to a significant ecological shortfall, highlighting the unsustainable state of their environmental practices.

On the other hand, based on *Fig. 1.a*, the depletion of natural resources in G20 nations showed an upward trend between 1995 and 2003. However, from 2006 to 2018, a steady reduction in resource consumption became evident. This downward trajectory in resource availability across G20 economies may be linked to escalating environmental degradation and its adverse effects on ecosystems. Many G20 nations have either introduced or are considering eco-friendly taxation policies to encourage lower carbon emissions and advance sustainable technologies, driving this ongoing shift. The G20 states encompass a broad spectrum of economies, ranging from highly developed to rapidly growing and less industrialized markets. Each country adopts distinct approaches to environmental regulations and the shift toward renewable energy, reflecting their unique economic conditions and policy priorities (refer to *Fig. 2.c*). Given these critical situations, these countries must implement immediate and effective measures to address the issue.

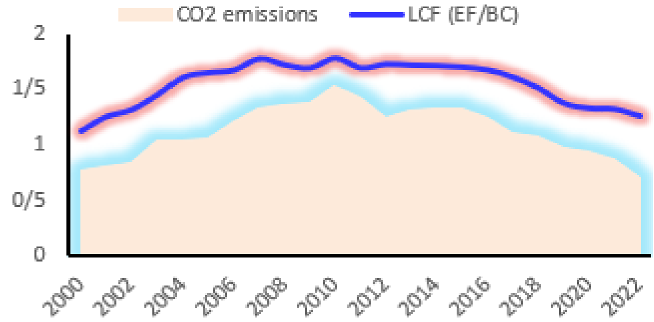


a. b.

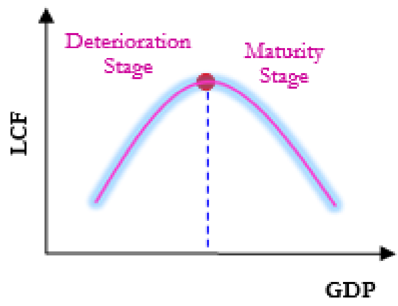
Fig. 1. Progress of ecological contamination (LCF) and natural resources rents in G20 economies; a. Natural resources rents trend, b. Load capacity factor trend [5], [8].

The choice to consider Load Capacity Factor (LCF) as a proxy of ecological contamination is motivated by the fact that the previous literature applied ecological footprint and CO_2 emissions in their environmental models. One of the limitations of these indicators is that they do not pay attention to the supply side of the environment (biocapacity) and only cover the demand side [9]. In contrast to most prior studies that predominantly relied on ecological footprint and CO_2 emissions, this research utilizes the LCF introduced by Siche et al. [10] and Pata [11] to evaluate the ecological conditions of G20 nations. The LCF is determined by calculating the ratio of the ecological footprint to biocapacity, accounting for both the demand and supply sides of ecology [9]. According to the prior literature, ecological contamination rises and eventually declines as economic growth advances. When this relationship is represented graphically, it forms a bell curve or an inverted U-shape, as shown in *Fig. 2.b*. This phenomenon is known as the Environmental Kuznets Curve (EKC) hypothesis [12].

The inverted U-shaped EKC in *Fig. 2.b* is divided into two stages. The first is the deterioration stage, where economic growth expands, leading to increased carbon emissions and demonstrating a direct relationship between growth and environmental degradation. The second is the maturity stage, where economic growth becomes more efficient, reducing environmental deterioration and indicating a shift toward sustainability [13].



a.



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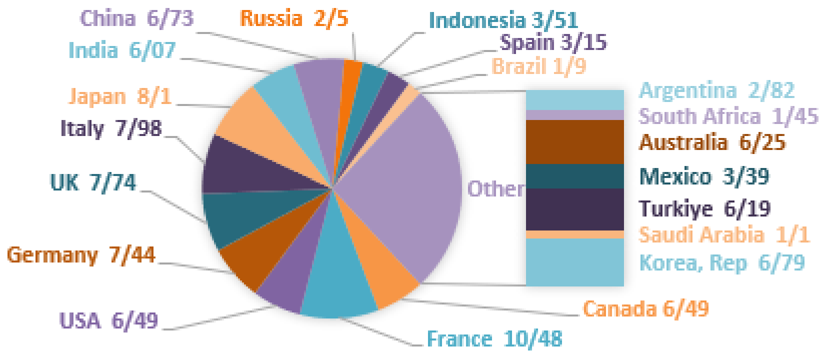


c.

Fig. 2. Trends in the LCF and CO_2 emissions; a. The status of environmental policy stringency for the G20 countries; b. Inverted U-Pattern (EKC assumption), c. Phases of ecological contamination [5], [8].

On the other hand, *Fig. 2.a* illustrates the relationship between CO_2 emissions and ecological degradation, represented by the LCF (EF/BC) indicator, from 2000 to 2022. The initial rise in CO_2 emissions corresponds with increasing ecological stress, as reflected in the upward trend of LCF. In contrast, the subsequent decline in emissions after 2010 aligns with a reduction in ecological degradation. This pattern suggests that policies or advancements aimed at reducing carbon emissions have contributed to mitigating environmental deterioration over time.

1.3 | Novelty of the Study

In light of the explanation above, the contributions of this study to the existing literature can be summarized into five viewpoints: firstly, the current study uses LCF as a proxy for ecological contamination, representing both the supply and demand sides of the environment. Secondly, this study adopts the variable renewable energy research development and demonstration budgets, which proxies for Green Energy Initiatives (GEI) budgetary in the sample of G20 states. Thirdly, this study contributes to bridging a significant research gap in the existing literature on the relationship between economic growth and ecological contamination, particularly regarding the moderating role of GEI. This study takes a distinct approach by focusing on G20 nations, setting it apart from prior research that largely centers on environmental decline in developing regions. The rationale behind this choice lies in the G20's unique position-these countries not only rank among the largest polluters worldwide but also lead significant sustainability initiatives (see *Fig. 2.c*). Lastly, this study employs the two-step system GMM to investigate the drivers of ecological contamination in the context of LCF, enabling us to provide highly robust, comprehensive, and reliable results-particularly when the number of observations exceeds the periods (N > T).

1.4 | Objective, Methodology, and Research Questions

Building on the explanation above, this study attempts to bridge these gaps by exploring the linkages between LCF, Financial Development (FD), Trade Openness (TRO), and economic growth using the two-step system GMM method within the context of the EKC hypothesis in the panel dataset of G20 countries from 2007 to 2022. More importantly, the primary objective of this study is to empirically scrutinize the role of GEI as a moderator in the economic growth-LCF nexus. In line with the objectives discussed above, this research seeks to shed light on the following main research questions:

I. How does LCF respond to economic growth within the framework of the EKC?

II. What role does TRO play in LCF?

III. What are the roles of FD and GEI in LCF?

IV. How does GEI improve the effectiveness of economic growth to shape LCF?

After the current section, the remaining sections of the paper are depicted in *Fig. 3*.

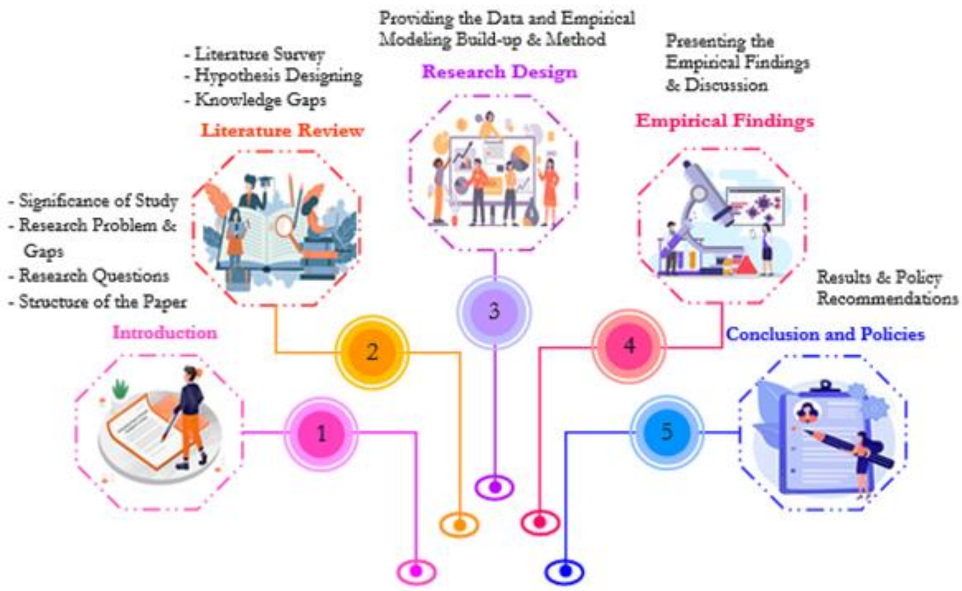


Fig. 3. Path plan for the current paper.

2 | IntSynopsis of Literature, Interaction Analysis, Hypothesis Designing, and Knowledge Gaps

This section is structured into four key areas:

I. A review of relevant literature that examines key factors influencing ecological conditions.

II. The interaction analysis, which highlights the indispensable role of GEI in shaping the impact of economic growth on ecological conditions.

III. The formulation of hypotheses, presenting four core propositions derived from the central research inquiries.

IV. An exploration of knowledge gaps, offering an in-depth evaluation of existing studies to identify areas requiring further investigations.

2.1 | Synopsis of Literature

The parabolic relationship between economic growth and ecological quality is rooted in the theory of the EKC, initially propounded by Kuznets [14]. Many scholars have committed to studying this nexus in terms of its importance. In the previous studies, different environmental pollution indicators were considered. Some applied CO_2 emissions as the dependent variable validating the EKC [12], [15–17]. In addition to these studies, Wang et al. [18] for 147 countries, Pata et al. [15] for Germany, and Georgescu and Kinnunen [19] for Finland have also obtained similar findings using ecological footprint as an environmental pollution indicator. Finally, other studies using the LCF as the dependent variable confirmed the EKC [20], [21].

The role of clean energy investment in promoting ecological sustainability has gained significant attention in recent years. In this regard, many studies have investigated the relationship between renewable energies and the quality of the environment. For example, from the case of the US economy, Sharif et al. [22] assessed the linkage between renewable electricity production and CO_2 emissions, showing that renewable energy helps mitigate the environmental damage caused by CO_2 emissions by incorporating the data of Italy from 1990 to 2019 by deploying the quantile-on-quantile (QARDL) approach. In a similar study, Li et al. [23] evaluated the association between renewable energy and environmental degradation for 1991–2019, indicating that clean energy investment tends to decline CO_2 emissions in Russia and Japan. Furthermore, Pata et al. [15] determined the contributing effect of renewable energy in mitigating CO_2 emissions in Germany using the data from 1974 to 2018.

The literature has two opposing viewpoints on the linkage between FD and ecological sustainability. The first of these claims is that FD enhances ecological sustainability. In this regard, Abbas et al. [24] explored how FD influences CO_2 emissions in the Next-11 emerging economies from 1990 to 2022. They highlighted that FD contributes to diminishing CO_2 emissions. Furthermore, Usman et al. [25] looked at the relationship between FD and greenhouse gas emissions in Arctic economies, showing FD increases ecological sustainability by providing funds/incentives for new eco-friendly technologies. Advocates of the second view state that FD increases environmental pollution. In this view, Boussaidi and Hakimi [26] investigated the impact of FD on CO_2 emissions from 2004 to 2021. According to the findings, FD deteriorates the quality of the environment in the MENA region.

The role of TRO in promoting ecological sustainability has become a significant and controversial area of research. Academic studies on this topic generally fall into three core frameworks. The initial framework argues that TRO poses risks and detrimental effects to ecological systems. For example, Wang et al. [27] revealed the negative role of TRO in environmental quality across 96 developing countries from 2000 to 2018, using the LCF as an indicator of environmental quality. According to the findings reported by Ali et al. [28], a rise in TRO is associated with a corresponding growth in ecological footprint. A different body of literature positively approaches the relationship between TRO and environmental quality, arguing that trade liberalization can contribute to better ecological outcomes by lowering pollution and promoting cleaner practices. For example, Peng and Pu [29] examined the impact of TRO on pollution levels across 31 provinces in China between 2000 and 2015, revealing that TRO effectively lowered emissions and enhanced environmental quality. Iorember et al. [30] determined that increased trade volumes contribute to better ecological outcomes by reducing the ecological footprint. Thi et al. [31] analyzed panel data from 53 countries and found that TRO positively influences environmental quality. Thirdly, research indicates that the environmental effects of TRO vary, highlighting its diverse impact across different contexts. For instance, Pham et al. [32] found no evidence of a statistically significant effect of TRO on environmental pollution in sampled developing countries. Hakimi and Hamdi [33] conducted a study to assess the influence of TRO on environmental quality across 143 nations. Their comprehensive analysis revealed that TRO did not substantially affect ecological health.

2.2 | Interaction Analysis

While the individual influences of GDP and GEI on ecological conditions have been studied, their crucial combined impact within the context of LCF has been largely overlooked, particularly in G20 states, which comprise both advanced and emerging economies and are the largest contributors to global carbon emissions. Investments in green energy innovations are pivotal in promoting sustainable development by stimulating economic growth while addressing environmental challenges [34], [35]. On the one hand, a well-developed green energy industry may play an indispensable role in affecting economic growth through investments in clean energy manufacturing and the deployment of clean power capacity [23], [36]. On the other hand, funding advancements in green energy innovations enhance the development and adoption of cleaner technologies, which contributes to lowering carbon emissions while fostering economic growth [36]. These discussions and empirical evidence suggest that GEI can shape the impact of economic growth on ecological conditions. However, research on how this mutual influence affects the relationship between economic growth and ecological conditions remains limited. Therefore, further studies are essential, particularly within G20 states striving to meet their net-zero commitments.

2.3 | Hypothesis Designing

As discussed in the "introduction" and "literature review" sections, this study sheds light on how load capacity, as a proxy for ecological contamination, is affected by economic growth, FD, and TRO through the lens of EKC assumption. The paper proposes four main hypotheses, including hypothesis 1, based on the main research questions above. FD is associated with lowering environmental deterioration; hypothesis 2. TRO inversely impacts the environmental deterioration; hypothesis 3. The dynamic interactions between economic growth and LCF confirm the EKC theory and hypothesis 4. GEI mitigates the effect of economic growth on environmental deterioration. In light of the above-mentioned explanation, the first set of testable hypotheses in this study can be depicted in *Fig. 4*.

Fig. 4. Graphical representation of the hypotheses in this study.

2.4 | Knowledge Gaps

A review of prior research reveals that many studies have used ecological footprint and CO_2 emissions as environmental proxies, one-sided measures. In contrast, this study considers the LCF a superior measure of ecological contamination, as it captures both ecology's demand and supply sides. More importantly, this study is driven by the lack of existing literature and the necessity to unveil the hidden role of GEI in moderating the effects of economic growth on ecological contamination, ultimately promoting sustainability across G20 states. Additionally, the EKC hypothesis in G20 nations has not been thoroughly examined in previous studies within the context of LCF. Moreover, no studies have examined the interrelation between underlying variables in G20 economies within the framework of the simultaneous equations system using the GMM estimation method. Therefore, this work aims to bridge these gaps by adopting the four key aspects mentioned above and validating hypotheses H_1–H_4.

3 | Research Design

3.1 | Data and Sample Selection

In this study, ecological contamination is the dependent variable proxied by the LCF. This predictive variable is measured as ecological footprint per capita divided by biocapacity per capita. In conclusion, the study also adopted the other variables: economic growth GDP, which is measured as per capita GDP (constant 2015 US$); TRO, which is measured as total trade as a percentage of GDP; FD, which is measured as domestic credit to the private sector as a share of GDP and GEI, which is measured as renewable energy research development and demonstration budgets in million US$. Data for the period 2007 to 2022 is applied for the analysis. The data information, including symbols, measurement, type of variables, and sources, are represented in *Table 1*.

Table 1. Data description.

Variables	Code	Measure	Type of Variable	Source
Load capacity factor	LCF	Ecological footprint per capita divided by biocapacity per capita	Dependent	GFN
Economic growth	GDP	GDP per capita (constant 2015 US$)	Independent	WDI
Square of economic growth	GDP2	The square value of GDP	Independent	Authors' calculation
Trade openness	TRO	Total trade as % of GDP	Independent	WDI
Financial development	FD	Domestic credit to private sector, % of GDP	Independent	WDI
Green energy initiatives	GEI	In a million US$	Independent	IEA

Fig. 5 depicts the geographical locations of the G20 economies, illustrating the distribution of CO_2 emissions (in tCO_2/cap) among the members in 2022. Canada and Saudi Arabia have the highest emissions, while India and Indonesia have the lowest.

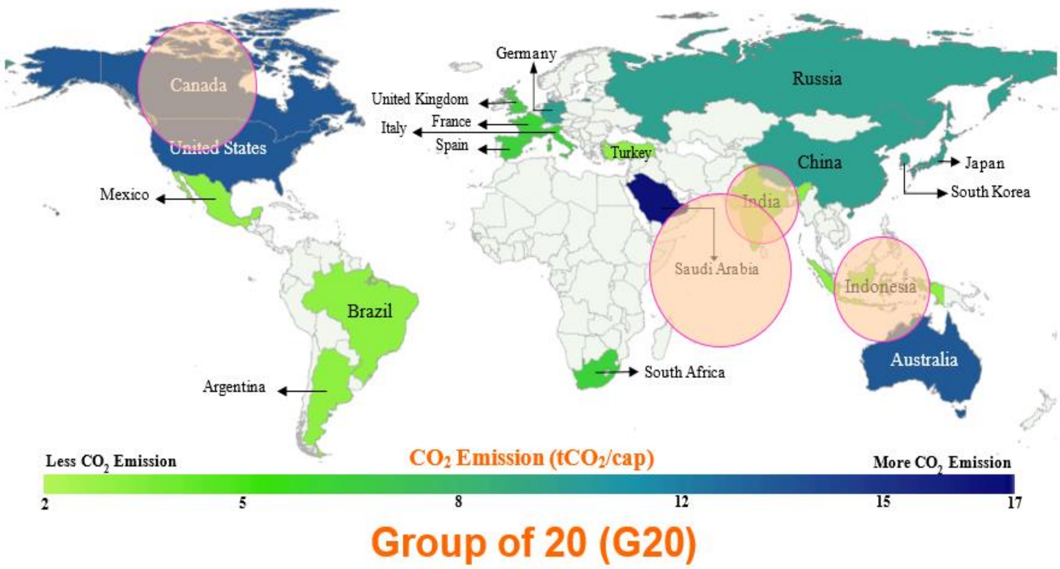


Fig. 5. Geographical location for the G20 economies.

3.2 | Model Specifications

According to the research methodology, this study applies the following model:

$$\mathrm{lnLCF_{it}} = \alpha_0 + \alpha_1 \mathrm{lnLCF_{i,t-1}} + \alpha_2 \mathrm{lnGDP_{it}} + \alpha_2 \mathrm{lnV_{it}} + \varepsilon_{it}, \quad (1)$$

where LCF denotes ecological contamination, and GDP shows economic growth. I indicate the individual country, the time is represented by t, and the error term is shown by ε. Lastly, V connotes a group of variables, other than those mentioned above, that will influence ecological contamination. In exploring how ecological contamination LCF correlates with economic growth GDP, LCF initially rises and then eventually declines as GDP advances [37]. In this context, the next model is derived by adopting a nonlinear approach for evaluating the possible non-linearity of the GDP-LCF nexus under the assumption of the EKC hypothesis. Accordingly, a quadratic term of the variable LnGDP is added to *Eq. (1)* as follows:

$$\mathrm{lnLCF_{it}} = \alpha_0 + \alpha_1 \mathrm{lnLCF_{i,t-1}} + \alpha_2 \mathrm{lnGDP_{it}} + \alpha_3 \mathrm{lnGDP_{it}^2} + \alpha_4 \mathrm{lnV_{it}} + \varepsilon_{it}, \quad (2)$$

where GDP^2 is the square of economic growth, the rationale for evaluating this parabolic linkage is based on the explanation in the "introduction" section.

By incorporating additional variables and the interaction term (GEI×GDP) that influence ecological contamination into the model, *Eq. (2)* is rewritten as *Eq. (3)*.

$$\mathrm{lnLCF_{it}} = \alpha_0 + \alpha_1 \mathrm{lnLCF_{i,t-1}} + \alpha_{2i} \mathrm{lnGDP} + \alpha_{3i} \mathrm{lnGDP_{it}^2} + \alpha_{4i} \mathrm{lnTRO_{it}} + \alpha_{5i} \mathrm{lnFD_{it}} + \alpha_{6i} \mathrm{lnGEI_{it}} + \alpha_{7i} \mathrm{ln(GEI \times GDP)} + \varepsilon_{it}. \quad (2)$$

Eq. (3) postulates that economic growth, the square of economic growth, TRO, FD, GEI, and the interactive effects of GEI and GDP (GEI×GDP) can affect ecological contamination.

Since the number of cross-sectional variables (N) is larger than the number of the periods (T), the Generalized Method of Moments (GMM) is used for the estimation of the above equation *Eq. (3)*. In GMM, a widely used estimation method for panel data modeling, a set of instrumental variables is employed to address the endogeneity problem. Therefore, more useful and reliable information can be provided to policymakers to formulate effective policies to promote long-term economic growth for G20 economies. The study's pictorial estimation strategy is shown in *Fig. 6*.

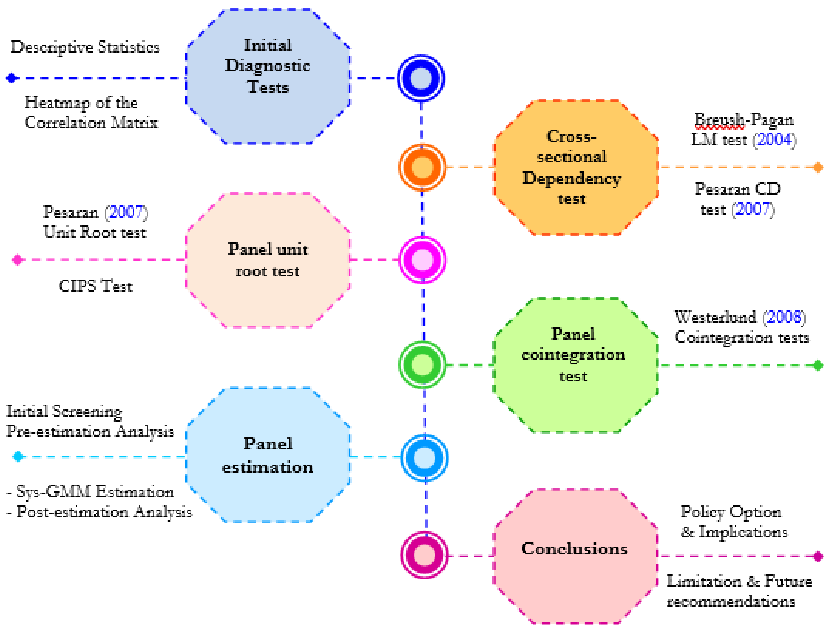


Fig. 6. Diagram of the estimation strategy.

3.3 | Generalized Method Of Moments Technique

This research employs the two-step system GMM estimator, a methodology introduced by Blundell and Bond [38], to analyze the associations among the examined variables across the specified model. Panel data modeling often encounters challenges related to heteroskedasticity and endogeneity in explanatory variables. The system-GMM approach incorporates a lagged dependent variable as an endogenous factor to tackle these concerns. Additionally, this technique accounts for the anticipated correlation between the error term and country-specific fixed effects [39]. Several factors influenced the choice of this methodology. One key consideration is that the total period (T = 16 years, from 2007 to 2022) is shorter than the number of cross-sectional units (N = 20 countries). The system-GMM framework can effectively manage potential issues arising from endogeneity and heterogeneity [40]. The two-step system GMM method yields more efficient estimators than the one-step approach. The Hansen and Sargan tests are employed to assess the instrument's validity. Meanwhile, the Wald test is utilized to evaluate the validity of the model's variables. Given this context, the two-step system GMM technique is implemented in this study due to its ability to generate efficient and reliable estimates.

4 | Empirical Results and Analysis

4.1 | Initial Screening

First, the fundamental statistics for underlying variables are presented in *Table 2*. The first two rows display the average value. The mean values of GDP, FD, TRO, and GEI are greater than their corresponding standard deviation, indicating that all of these variables are unevenly distributed in G20 countries. Regarding the skewness values, LCF, GDP, FD, TRO, and GEI are left skewed. According to the values of Kurtosis, FD and GEI are greater than 3, showing the Leptokurtic distribution. Meanwhile, the kurtosis values of LCF, GDP, and TRO are less than 3, indicating platykurtic distribution. Based on the results of Jarque Bera, nonnormal distribution is confirmed for all variables.

Table 2. Descriptive statistics.

Variables	LCF	GDP	FD	TRO	GEI
Mean	0.730	9.741	4.359	3.923	4.682
Median	0.839	10.081	4.537	3.987	4.745
Std. Dev.	0.923	0.990	0.708	0.345	1.393
Skewness	-0.367	-0.771	-0.820	-0.425	-0.013
Kurtosis	2.236	2.841	3.016	2.555	4.678
Jarque-bera (p-value)	14.982 (0.000)	32.046 (0.000)	35.911 (0.000)	12.287 (0.002)	37.577 (0.000)
Obs.	320	320	320	320	320

On the other hand, *Fig. 7* provides an overview of the variables' statistics, illustrated by the correlation heatmaps *Fig. 7.a* and the RADAR chart *Fig. 7.b*, which visually represent the descriptive statistics and the correlation coefficients, respectively.

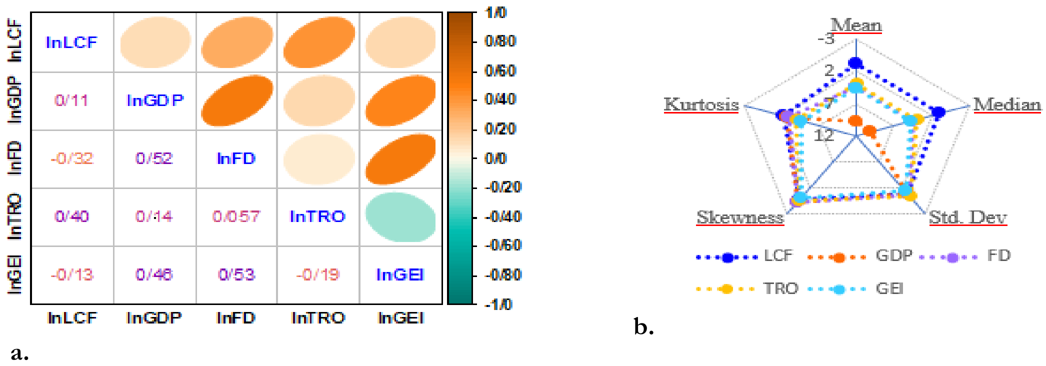
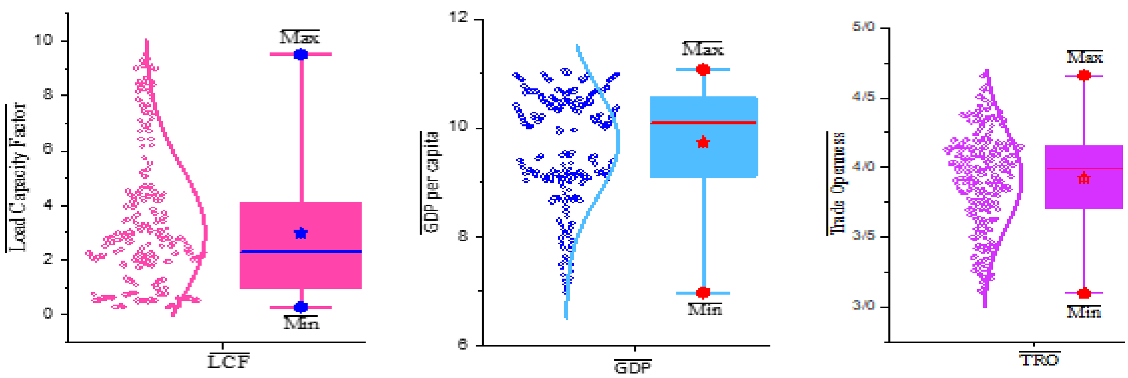


Fig. 7. Correlation heatmap and RADAR chart for studied variables; a. Correlation heatmap, b. RADAR chart.

By looking at *Fig. 7.a* indicates that the absolute values of all pair correlations are less than 0.53, showing the weak issue of multicollinearity in the model. *Fig. 8* illustrates a box-and-whisker diagram for the analyzed variables, highlighting key statistical measures. The star symbol denotes the mean, while a horizontal line within the box marks the median. The lower and upper boundaries of the box correspond to the 25th and 75th percentiles, respectively. The whiskers extend to the 5th and 95th percentiles, with their lower and upper edges representing these values. Additionally, individual dots indicate the minimum and maximum observed values.



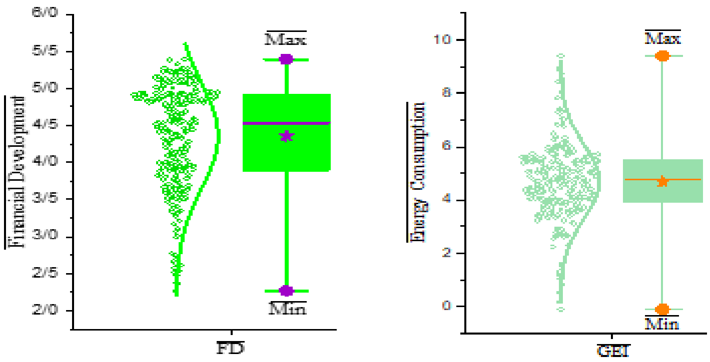


Fig. 8. Box-plot summary statistics of all the variables of a panel of G20 countries (after logarithm) covering the period 2007-2022.

4.2 | Pre-Estimation Analysis

Preliminary tests are conducted to verify the accuracy and reliability of the regression outcomes prior to interpretation. As a preliminary measure, the Variance Inflation Factor (VIF) results, illustrated in *Fig. 9*, indicate that multicollinearity is not an issue, as all mean VIF values are well within the acceptable limit of 2.

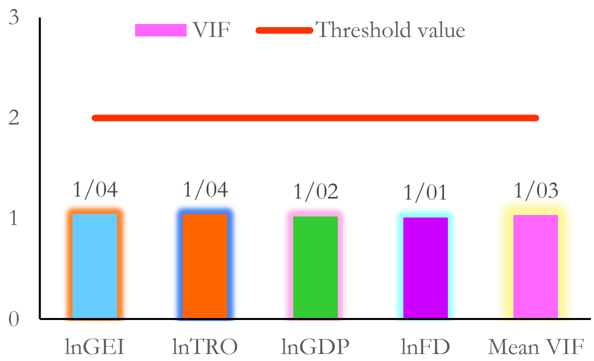


Fig. 9. Visual representation of VIF results.

For the second step, the results of Breusch and Pagan [41] and Pesaran [42] CD tests for Cross Dependence -section (CD) are presented in *Table 2*, disclosing the availability of CD among the study variables. These results lead to applying the second-generation unit root and cointegration tests.

Table 2. CD tests and second-generation unit root test.

Variables	BP-LM Test	Pesaran CD Test	Prob.	CIPS Level	1st Difference
lnLCF	1075.807	6.373	0.000	-1.914	-3.799***
lnGDP	1339.875	28.156	0.000	-1.607	-3.564***
lnTRO	799.707	10.692	0.000	-1.783	-3.372***
lnFD	1334.887	7.155	0.000	-1.821	-3.264***
lnGEI	465.113	11.177	0.000	-3.828***	-4.751***

Notes: *** represents a 1% level of significance. Critical values at level 1%: -2.4, 5%: -2.21, and 10%: -2.1. Critical values at the first difference: 1%: -2.45, 5%: -2.22, and 10%: -2.11.

As a next step, the stationarity of the study variables is examined using the cross-sectional augmented Im, Pesaran, and Shin (CIPS) test developed by Pesaran [42]. The results are displayed in *Table 2*, revealing that the variables exhibit different integration levels, but they all achieve stationarity once their first differences are taken.

The research now progresses to survey whether a cointegration relationship exists among the variables. To achieve this, the study employs the Westerlund [43] cointegration test, which accounts for cross-sectional dependence and heterogeneity while ensuring reliable outcomes. According to the statistics and p-values presented in *Table 3*, the null hypothesis of no cointegration can be rejected in our model. Hence, the variables exhibit a long-term relationship and tend to move in tandem across G20 nations throughout the analyzed timeframe.

Table 2. Westerlund [43] cointegration test.

Model	Statistic	P-Value
Variance ratio	6.0041***	0.0000

Note: *** represents significance levels of 1%.

After confirming the procedures for assessing long-term cointegration, the next step involves analyzing the coefficients that define the relationship among the variables under investigation. The current study employs the two-step system GMM approach to achieve this objective. *Table 5* presents the coefficients estimated for *Eq. (3)* in this context.

4.3 | The Environmental Kuznets Curve Hypothesis Analysis

The estimated outcomes, presented in *Table 5*, unveil critical insights into the impacts of key variables (GDP and its square) on ecological conditions LCF, analyzed through the two-step Sys-GMM approach.

Table 5. Results of two-step system GMM-estimation.

Variables	Coefficients	P-Value
L. dep. var.	0.344***	0.000
lnGDP	0.836***	0.000
lnGDP2	-0.085**	0.018
lnTRO	0.114***	0.000
lnFD	-0.025***	0.001
lnGEI	-0.213***	0.000
Ln (GEI×GDP)	-0.048**	0.021
Diagnostic Tests		
Wald test (p value)	88.70	0.000
AR (1) (p value)	- 2.29	0.028
AR (2) (p value)	-0.15	0.880
Sargan Test (p value)	29.16	0.882
Hansen Test (p value)	14.48	0.271

Note: *** and ** represent 1% and 5% significance levels, respectively. L. dep. var. indicates Lagged-dependent variables.

The positive and highly significant coefficient of the lagged LCF suggests a strong persistence effect, indicating that past values of environmental degradation significantly influence its current state. This reflects the inertia in ecological systems, where environmental degradation tends to persist due to the long-term accumulation of pollutants and delayed policy impacts. In the context of G20 nations, where industrial processes and energy consumption have historically contributed to ecological stress, the result underlines the path-dependent nature of environmental outcomes.

Additionally, the highly positive coefficient of GDP indicates that economic growth, in its initial stages, contributes to an increase in LCF, implying greater environmental degradation. This supports the early phase of the EKC hypothesis, where higher income levels lead to increased pollution due to expanded industrial activity, energy consumption, and urbanization. In G20 economies-many of which are either still growing rapidly or managing legacy industrial infrastructures-this relationship underscores the environmental costs of unchecked economic expansion. On the other hand, the negative and significant coefficient of squared GDP confirms the inverted U shape of the EKC. As GDP increases beyond a certain threshold, the rate of environmental degradation begins to decline, suggesting that higher-income G20 countries may have reached a level where economic growth is associated with better environmental outcomes. This result is consistent with the studies of Pata et al. [15], Mahmood et al. [16], and Naseem et al. [17]. This turning point likely corresponds to adopting cleaner technologies, stricter environmental regulations, and shifting toward service-oriented economies that reduce the ecological footprint.

4.4 | Direct Analysis

Moreover, TRO's positive and significant impact on LCF indicates that increased international trade contributes to environmental degradation in G20 countries. This conclusion, based on estimates, agrees with those of Wang et al. [27] and Ali et al. [28]. This may be attributed to the pollution haven hypothesis, wherein countries specialize in pollution-intensive industries due to comparative advantage or lax environmental regulations. Higher trade volumes may lead to greater transportation emissions and energy use. Despite G20 nations' relatively stringent environmental standards, global trade dynamics may still impose environmental burdens, especially through imports and exports of carbon-intensive goods.

The negative and significant coefficient of FD suggests that improved financial systems are associated with reduced environmental degradation. This outcome corroborates those of prior research, such as that of Sharif et al. [22] and Pata et al. [15], emphasizing financial systems' significance in environmental protection. In G20 economies, deep and efficient financial markets facilitate investments in green technologies, renewable energy, and environmentally friendly infrastructure. Moreover, FD enhances access to capital for sustainable business practices and fosters environmental awareness among investors and firms through green financing and Environmental, Social, and Governance (ESG) frameworks.

GEI has a strong negative and statistically significant effect on LCF, implying that greater emphasis on green energy improves environmental quality. This is intuitive, as green energy reduces reliance on fossil fuels, lowers greenhouse gas emissions, and improves energy efficiency. This outcome aligns with those reported by Sharif et al. [22] and Li et al. [23]. In the G20 context, this reflects the growing policy focus on renewable energy (e.g., solar, wind, hydro) and international commitments such as the Paris agreement, which promote the transition to sustainable energy systems. A summary of the outcomes interpreted above is also illustrated in *Fig. 10*.

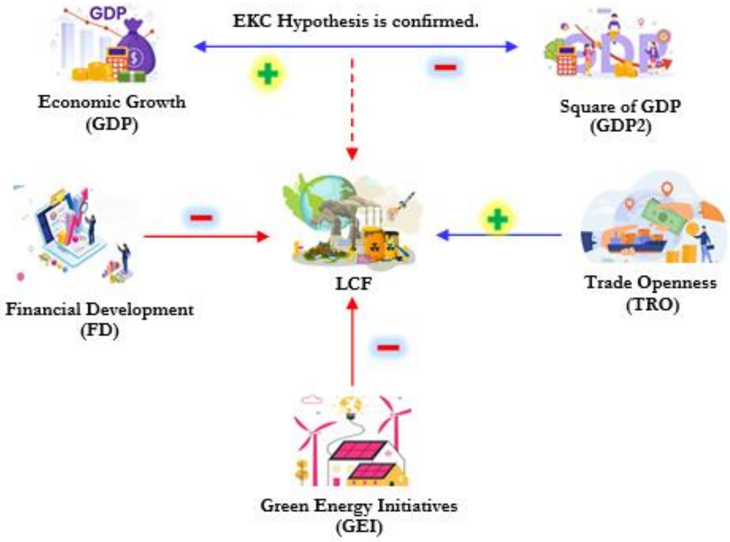


Fig. 10. Graphical presentation of outcomes associated with the EKC and the direct analysis.

4.5 | Interaction Analysis

The interaction term between GEI and GDP is negative and significant, indicating that GEI moderate the adverse environmental effects of economic growth. As countries grow economically, strong green energy policies can help mitigate the environmental damage typically associated with growth. This result is particularly important for G20 economies, often at the forefront of economic expansion and environmental innovation. It implies that the environmental trade-offs of GDP growth can be alleviated when green energy becomes an integral part of the development strategy. *Fig. 11* also provides a visual representation of the interpreted outcomes summarized above.

Fig. 11. Graphical presentation of outcomes associated with the moderating role (GEI×GDP).

4.6 | Post-Estimation Analysis

The findings related to the first and second-order serial correlation validate the instruments deployed in this paper. In addition, the Wald test results provide evidence that the defined instrumental variables in the model are valid and that there is no need to introduce additional instrumental variables. Lastly, the Sargan and Hansen tests demonstrate valid over-identifying restrictions, showing that using numerous instruments does not weaken the model.

5 | Conclusion

The G20 nations, being the primary sources of global carbon emissions, possess robust financial systems, significant economic expansion, and substantial trade activity. Moreover, these countries have experienced a sharp rise in energy consumption and carbon output over the past few years. For these reasons, applying the panel data model, this study investigates how GDP, the square of GDP, TRO, FD, GEI, and the interaction term (GEI×GDP) influence the LCF, a proxy for environmental degradation. The present study explored this linkage from the perspective of LCF, focusing on the G20 economies from 2007 to 2022.

The results of the two-step sys-GMM estimator reveal that GDP and its square have positive and negative impacts on LCF, respectively, confirming the EKC hypothesis. Moreover, TRO contributes to increased environmental degradation in G20 economies. Additionally, FD plays a positive role in reducing environmental degradation. Furthermore, the results reveal that GEI has significantly improved the G20's environmental sustainability. More importantly, the interaction term (GEI×GDP) is negative, indicating that GEI moderates the adverse environmental effects of economic growth in G20 economies.

5.1 | Policy Recommendations

In light of the aforementioned findings, the study offers policy recommendations that are essential for the future of the economies in G20 countries. It recommends that G20 countries leverage income gains to fund climate resilience and adaptation projects. They also need to support green consumption behavior through eco-product subsidies, awareness campaigns, and sustainable procurement policies.

On the other hand, enforcing environmental standards in trade agreements, including carbon border taxes or environmental clauses in FTAs, can work well to discourage the adverse environmental effects of TRO. Additionally, G20 states must encourage green supply chains, promote low-carbon goods and services exports, and develop eco-labeling systems and sustainability certifications for imports and exports.

Moreover, promoting green finance instruments, such as green bonds, ESG-linked loans, and climate funds, can work well to support the environmental benefits of FD in G20 nations.

In addition, GEI has proven helpful to the G20's ecological conditions. Hence, vigorously promoting investment in clean energy R&D, especially in storage, hydrogen, and smart grid systems, which are essential for G20 countries, is crucial. Furthermore, governments need to phase out fossil fuel subsidies and redirect those funds to support green energy infrastructure and jobs.

Importantly, GEI moderates the environmental cost of economic growth. Therefore, it is recommended that governments integrate green energy policies into national development planning to ensure that economic growth does not come at the environment's expense. Also, green industrial policies-e.g., support for green manufacturing clusters and low-carbon industrial parks-should be applied to guide structural transformation.

5.2 | Limitations and Future Recommendations

One major constraint of this research lies in its narrowed scope concerning the factors influencing ecological outcomes. Although the analysis centers on GDP, FD, TRO, and GEI as drivers of ecological conditions, it overlooks other potentially influential elements-such as educational attainment, energy usage behavior, and tourism-related activities-which could offer additional explanatory power. Additionally, employing alternative analytical techniques may lead to divergent findings. Future studies could address these limitations to provide a more holistic understanding of the determinants of ecological conditions.

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Author Contribution

Hossein Ali Fakher: conceptualization, methodology, software, validation, formal analysis, data maintenance, creating the initial design, review, and editing. Ghalieb Mutig Idroes: writing-reviewing and editing, formal analysis.

All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors declare no conflict of interest. Both authors reviewed and approved the final manuscript.

Data Availability

Data will be made available on request.

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