

Research

Growth limits and ecological capacity in developing countries

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Received: 26 October 2025 / Accepted: 23 December 2025

Published online: 29 December 2025

© The Author(s) 2025 [OPEN](#)**Abstract**

This study examines the Load Capacity Factor (LCF) as a comprehensive indicator of environmental sustainability in 61 developing countries from 1992 to 2021. This research provides empirical novelty by combining a broad cross-country coverage with a dynamic SYS-GMM approach to uncover both linear and nonlinear drivers of ecological capacity. The primary objective is to assess the influence of economic, social, and institutional determinants, while also examining the nonlinear relationship between per capita income and ecological capacity through the load capacity curve framework. The results reveal an inverted U-shaped relationship between GDP and LCF. The findings suggest that without sustainable policies in place, the attainment of education, health, and increased living standards will elevate the span of resource use and environmental strain to a greater extent than the development will reduce LCF. The resource rent of natural capital illustrates the extent to which resource endowments aid in the development of biocapacity. The negative, significant impact of industrialization demonstrates that the production systems of developing nations continue to be heavily weighted toward negative environmental impacts. The data shows that political stability, and therefore, good governance, plays a substantial role in alleviating environmental pressure and resource management. This also shows that positive governance plays a substantial role in alleviating environmental pressure and resource management. These findings highlight the importance of integrating economic progress with institutional strengthening and proactive environmental policies to ensure long-term ecological sustainability in developing countries. These findings underscore the urgency of integrating economic growth with institutional quality and proactive environmental governance. Key policy directions include strengthening governance to boost ecological resilience, channeling resource rents into environmental restoration, accelerating the transition to clean energy, and steering industrial and human development toward sustainable pathways.

Keywords Developing countries · GMM · Load capacity factor · Sustainable development**1 Introduction**

In recent decades, attention to environmental sustainability has increased in line with the growing pressure on natural resources due to economic activities. The Load Capacity Factor (LCF) was introduced as a comprehensive indicator by comparing biocapacity with resources use [19]. On the demand side, the Ecological Footprint (EF) indicator measures

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the level of natural resource consumption in various aspects to meet human needs [4]. When this consumption exceeds the regenerative capacity of nature, an ecological deficit occurs, reflecting a global environmental imbalance [50].

Many countries struggle to balance economic growth with environmental protection, particularly developing nations that rely heavily on natural resources [41]. These countries are required to achieve economic progress without neglecting ecosystem integrity [3]. In densely populated developing countries, effective strategic integration is necessary for inclusive economic growth and environmental conservation efforts. Natural resources are often exploited intensively to support economic growth and meet the ever-increasing consumption needs of the population [24, 49].

The importance of economics and human development lie in their ability to improve the relationship between economic growth and environmental sustainability. Economic sector development means having more access to financial services, better resource distribution, and greater macroeconomic efficiency [52]. The enhanced economic development of poorer countries positively impacts the investment of renewable technologies, the efficiency of energy use, and the implementation and support of policies that promote environmental sustainability [9]. Meanwhile, human development (HDI), also contributes to supporting resource efficient practices. HDI provides a comprehensive measure of social achievement through health, education, and living standards [35]. The importance of economics and human development lie in their ability to improve the relationship between economic growth and environmental sustainability. Economic sector development means having more access to financial services, better resource distribution, and greater macroeconomic efficiency [52]. The enhanced economic development of poorer countries positively impacts the investment of renewable technologies, the efficiency of energy use, and the implementation and support of policies that promote environmental sustainability [9].

At the earlier stage of many developing countries' economic growth, there is an influx of urbanization and industrialization, leading to the uptake and consumption of fossil fuels and therefore a rise in emissions and further environmental consequences [14, 47]. One of the major components contributing to this phenomenon is the increase in economic openness [26, 33]. It is true that on a global scale, economic openness can facilitate the more efficient allocation of resources, but at the same time, there is a greater danger of excessive unsustainable natural resource exploitation [15]. In the interplay between a country's economic and environmental parameters, among the other variables, political stability is in itself a factor which can shape the balance of policy coherence, regulatory marginal cost, and the sustainability of the growth pattern [1]. Politically more stable countries have the greater power of fostering environmentally and socially responsible investments and development, and at the same time balancing the regulatory costs of control on environmental quality [8].

While significant, empirical studies on the determinants of LCF remain scarce, especially concerning developing nations. Most investigations focus on adverse environmental impacts, especially carbon emissions or EF [15, 23, 34, 55], and do not consider the ecological equilibrium LCF provides. In general, developing nations have an increased environmental burden due to their resource-dependent economic structure and institutional complexities. In this regard, the sch determinants of LCF are worthy of investigation. However, these studies have not sufficiently explored LCF using dynamic econometric approaches that can address endogeneity, particularly the System GMM framework. Furthermore, empirical research integrating economic, social, environmental, and institutional determinants of LCF. In addition, the nonlinear relationship between income and ecological capacity conceptualized through the Load Capacity Curve (LCC) has received little empirical validation in developing country settings. These gaps highlight the need for a more comprehensive and methodologically robust analysis of LCF.

This study will examine the concept of Life Cycle Cost (LCC) as an extension of the Environmental Kuznets Curve (EKC) [37]. Whereas the EKC describes the inverted U-shaped relationship between income and degradation of environment, the LCC describes a U-shaped curve which indicates the dynamics of sustainability as follows. In the early stages of economic development the Life Cycle Footprint (LCF) falls due to the increased environmental degradation. However, beyond a certain turning point, the LCF will increase as the economy implements improved environmental management [51]. In that sense, LCC becomes critical for understanding the ecological overshoot.

This study aims to: (i) identify the economic, social, environmental, and institutional determinants of the LCF in developing countries; (ii) examine the nonlinear relationship between income and LCF using the Load Capacity Curve LCC framework; and (iii) provide dynamic panel evidence using the two-step System GMM to support policies that strengthen ecological capacity.

This study is grounded in the growing concern that many developing countries are experiencing rapid economic expansion while their ecological capacity continues to deteriorate. Although sustainability indicators have gained prominence in recent research, the load capacity factor remains largely overlooked in cross-country empirical analysis. Understanding its key drivers is crucial because the LCF reflects both ecological resource availability and human demand,

offering a more comprehensive assessment of environmental pressure than conventional measures. The present study also advances the literature by incorporating the load capacity curve framework to examine potential non-linearities in the income environment relationship within developing economies. By integrating multiple dimensions of sustainability and employing a dynamic System GMM approach, this research fills a notable gap in the empirical evidence on LCF and provides policy-relevant insights for countries seeking to reconcile economic growth with ecological resilience.

2 Literature review

Past investigations have suggested that the connection between the economy (economic growth and productivity), the society (living standards and quality of life), and the environment (overexploitation of natural ecosystems) is complicated and contextual. The Load Capacity Factor (LCF) is also a composite measure and facilitates the analysis, yet is still in need of a true multidimensional analysis that includes the multi and transdisciplinary institutional arrangements, socially and economically structural and socio-economic aspects. Determinants of sustainability of the environment have been studied using the Load Capacity Factor indicator in efforts, however this effort assesses unsustainability and unsustainable developing economies with comparatively a wider expanse of analysis and longer timeline. This allows to attain a more realistic potential assessment in the dynamics of sustainability in the unsustainable and unsustainably developing economies with potentially and comparatively diverse structuring and institutional set ups. Most preceding inquiries utilized the ARDL, MMQR, and/or the CS-ARDL methodology, which solely emphasize the longer-term relationships in cross-sectional or time series data. This research particularly differs in the methodology to the utilizing the two-step System GMM, which is more effective in the analysis of panel data with dynamics because of the criticisms that are commonplace in the areas of endogenous variables, heteroscedasticity, and autocorrelation in panel datasets with time dynamics.

To this end, this study thus brings to light the unsustainability of developing nations. The ensuing table (Table 1) presents some of the previously done efforts. These efforts study, in some instances, the variables of prime interest and their sequence of impact, with respect to the LCF, the load capacity factor that proxies the indicator of the environment and sustainability.

2.1 Sustainable development

The dependence of development on the exploitation of natural resources emphasizes the importance of applying sustainable development principles to preserve the environment [53]. Sustainable economic development is not only determined by income growth, but also by a country's ability to maintain a balance between resource consumption and available ecological capacity [28]. In this context, uncontrolled economic expansion can erode natural capital and push ecological systems closer to their biophysical limits. Exceeding the environment's capacity to utilize natural resources can lead to a decline in its natural ability to absorb and assimilate resources [23].

Regarding some of the indicators measured by LCF, of the literature mentions LCF as a more holistic measure than CO₂ emissions or at EF. That said, EF has been critiqued for not considering the ability of the environment to recover. This critique, however, has been measured in the LCF indicator, LCF for biocapacity in Ali et al. [6], Dam and Sarkodie [12], Du et al. [16]. LCF measure the capacity of the environment/the LCF value's burden of resource consumption. The higher the value, the higher the sustainability. The literature justifiably covers the scope of the other facets of sustainability. The EKC model for theory suggests the means of unraveling the paradox of "economic growth and the environment. Dam and Sarkodie [12], Okezie et al. [38] introduces a U shape i.e. the Load Capacity Curve (LCC) hypothesis. LCC aims at demonstrating, for given income ranges, sustainability loss of Ecological Capacity or LCF, but with the potential to recover, the higher the income. This makes it possible to measure biocapacity, ecological footprint, and environmental sustainability [21, 42].

2.2 Economic growth and LCF

Investing in the economy does not guarantee advancements in the environment, and the connection between GDP and LCF differs greatly from country to country and by the level of development. Sharif et al. [48] Associating higher income with lower LCF corroborates the observations of Ali et al. [6] and Zhao et al. [58] in France and the BRICST

Table 1 Empirical literature review

Author	Scope	Period	Variable used	Method	Results
[5, 6]	10 countries with the highest nuclear energy consumption	1995–2020	LCF, nuclear energy, renewable energy, financial globalization, technological innovation, economic growth	Nonparametric MMQR, Granger causality	Nuclear energy, renewable energy, and financial globalization increase LCF. Economic growth decreases LCF. There is a causal relationship between LCF and key variables
[37]	North Africa region	1991–2022	LCF, GDP, Fintech, natural resource rent, globalization	QR, AMG, HPI	Inverse U-shaped relationship between GDP and LCF. Fintech increases LCF, while globalization and resource rents decrease it. There is bidirectional causality between GDP, GDP2, Fintech and LCF
[57]	BRICS countries	1995–2023	LCF, green energy, financial development, environmental regulation	CS-ARDL	Green energy and development finance improved environmental quality. Strict regulations have reduced pollution and promoted sustainability, especially in Russia and South Africa
[12]	Turkey	1965–2018	ILCF (Inverse Load Capacity Factor), real income, renewable energy, trade openness	ARDL, Granger TYGC	Real income and trade openness increase ILCF (positive for sustainability), renewable energy has only a short-term positive impact. There is an inverted-U-shaped relationship between income and ILCF, supporting the ILCC hypothesis. Turkey has not yet reached the per capita income to sustain long-term sustainability
[17]	Turkey	1986–2022	LCF, economic growth, urbanization, fossil energy investment, renewable energy	Augmented ARDL	The LCC hypothesis (U-turn) holds: low income lowers LCF, but increases after the turning point. RR&D increases LCF, FR&D and urbanization decrease it. Urbanization is considered not high quality (less skilled workforce). Policies should focus on clean energy R&D and improving the quality of urban labor
[40]	Turkey	1982–2019	LCF, resource efficiency, renewable energy, globalization	Quantileogram, quantile-on-quantile regression, nonparametric Granger causality	Resource efficiency, renewable energy and globalization have significant positive impacts on LCF across quantiles. The largest effects are seen in the low to middle quantiles. These three variables are considered as important drivers of environmental sustainability in Turkey. Indicates the potential of circular economy and energy efficiency strategies
[11]	ASEAN	1986–2018	LCF, human capital, green energy, GDP, globalization, population	CS-ARDL	LCF increases with income and human capital. Green energy also increases LCF, but globalization and population density worsen environmental quality. The LCC hypothesis is validated

Table 1 (continued)

Author	Scope	Period	Variable used	Method	Results
[25]	South Africa	1990–2019	LCF, renewable electricity, industrialization, GDP, human capital	NARDL, Granger spectral causality	Renewable electricity increases LCF; industrialization and GDP decrease LCF. Human capital increases LCF. All variables affect LCF in the long run
[20]	ASEAN	1984–2018	LCF, natural resources, political risk, urbanization, biomass	ARDL, frequency-domain causality	Biomass increases LCF. Natural resources, political risk, and Urbanization decrease LCF. LCC hypothesis validated
[36]	Sub-Saharan Africa	2006–2020	EF, renewable energy, industrialization	GMM	Renewable energy decreases EF, while industrialization increases it. However, if industrialization is driven by renewable energy, it can support sustainable development and climate change mitigation
[19]	Egypt	1980–2022	LCF, democracy, GDP, energy consumption, trade openness, financial development, urbanization	Fourier ARDL	Democracy reduces LCF, GDP and energy consumption worsen LCF, while trade openness increases LCF. Finance and urbanization are not significant. The need for an integrated strategy is emphasized

economies, positing that economic growth aggravates natural system pressures. Conversely, Emre Caglar et al. [17] reports a U-shaped curve for Turkey, in which case initial development reduces available ecological capacity, but eventually further development leads to ecological capacity restoration once a certain level of growth is reached. Other areas of the world show different dynamics: Okere et al. [37] report inverted U-shaped while [18] reports the absence of evidence for the LCC hypothesis in the African context, suggesting that growth based on natural resource does not lead to enhancement of the ecological support capacity. These divergent results reveal theoretical inconsistencies regarding whether rising income ultimately enhances or depletes environmental support systems. Such contradictions indicate that GDP and LCF nexus may depend on structural conditions, policy regimes, or resource endowments factors not fully addressed in existing studies. However, most prior research has not examined how GDP dynamics operate specifically within developing countries, nor have they applied a dynamic GMM framework capable of correcting for endogeneity in the growth and LCF relationship. This limits the ability to draw robust conclusions about whether the LCC mechanism holds in lower-income contexts.

2.3 Economic factors

Openness to trade (TO) demonstrates divergent impacts across LCF. There are negative correlates [38] versus short-run gains with long-run detriments for Turkey [12]. Eyuboglu and Uzar [19] document positiveness for Egypt, while globalization arguing to aggravate negative impacts Sharif et al. [48], Fang et al. [20]. These are trade dependent for the quality of regulations and structures of the economy. In the same way, the ON also shapes the ecological industrialization capacity. Industrialization (IND) does South Africa's LCF and Jin & Huang side Nulambenh and Jaiyeoba [36] from industrialization to higher EF and weakened it unless renewable reduction supported the resource-encroaching productive activities that sustain ecological capacity to cleaner technologies. According to Kuznets [27], during the early stages of industrialization, increased production and consumption will lead to environmental degradation. However, after reaching a certain income level, people begin to pay more attention to environmental issues, so that environmental quality can improve. Also, financial development (FD) has had outcome patterns, as well. Zhang and Linjin [57] found that FD assists LCF via green financing, where [45] noted that its impact is contingent on directing investments towards sustainable sectors. Accordingly, economic variables consider LCF in particular contexts as opposed to uniformly. However, these studies do not examine how trade, industrialization, and financial development interact with institutional quality in developing countries, leaving unclear why similar economic conditions lead to different sustainability outcomes across contexts.

2.4 Social factors

There exists a social dimension wherein the Human Development Index or the Human Capital Indicator (HCI) displays an affirmative correlation with sustainability. Human capital significantly facilitates LCF within ASEAN countries [11]. Meanwhile, it was shown that education increases the positive aspects associated with environmental improvements, and, along with welfare, strengthens the outcomes further [10]. All these aspects of the social phenomena generalized here indicate the positive engagement of the entire society with the implementation of improvements in sustainability. Increases in HDI tend to improve environmental quality when accompanied by environmental awareness, adequate education, and access to clean technology [10, 39]. However, the effect of HDI on LCF is not always uniform: in developed countries, an increase in HDI usually promotes greater sustainability due to the application of green technological innovations and effective environmental regulations, while in some developing countries, an increase in HDI may not be in line with environmental efficiency, so its impact on the environment is more limited [46].

On the other hand, Urbanization (URB) tends to decrease LCF. Poorly managed urban expansion negatively affects LCF, report Eyuboglu and Uzar [19] and Emre Caglar et al. [17], while Fang et al. [20] corroborates this finding with data from ASEAN. The contradiction here is not with respect to the direction of the effect, most studies showing the urbanization phenomenon has detrimental impact on LCF, but rather with respect to the circumstances under which urban growth may constitute a net negative or positive. However, the existing literature does not examine how social factors particularly HDI and urbanization interact with institutional quality to influence LCF in developing economies. These limits understanding of why similar social conditions produce different sustainability outcomes across countries.

2.5 Natural resources and energy

Research by Okere et al. [37] and Erdogan [18] highlights that reliance on revenues from the exploitation of natural resources, such as oil, forests, and energy, tends to reduce LCF. Du et al. [16] demonstrate that effective governance can enhance the sustainable use of natural resources, improving environmental carrying capacity, particularly in ASEAN countries. These findings show both a consensus that resource exploitation can undermine ecological capacity, and a divergence regarding the role of governance in mediating this effect. Evidence from the Middle east and North Africa countries shows that green financing combined with renewable energy investments mitigates the ecological pressures of trade and industrialization [56]

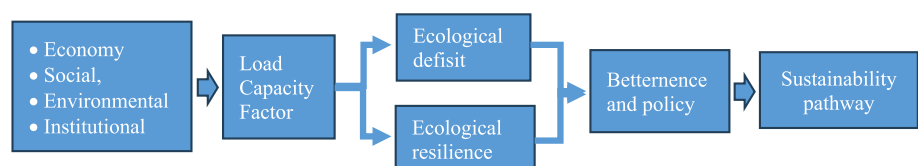
Renewable energy (RE) utilization shows consistent advancement in LCF, as noted in several studies [5, 40, 48] where the consumption of RE has a net positive impact on the environmental sustainability of the countries studied. Adjacent to these studies, focusing on the impact of renewable energy (RE) on short-term LCF (ILCF), Dam and Sarkodie [12] advocates this positively aligns with the energy transition in the world. Moreover, Ali et al., Samour et al., 2025, in the scope of 10 most nuclear energy consuming countries, found positive contributions of RE on LCF, however, Dam and Sarkodie [12] elucidates the short-term contributions of RE, while the long-term consequences are determined by the energy policy and management frameworks in the vicinity, possibly placing RE in a paradoxical situation. Overall, these studies collectively underscore that natural resources and energy are critical determinants of LCF, but their effects are highly contingent on governance, policy, and technological context. Nevertheless, prior studies do not assess how these environmental and energy factors jointly interact with institutional structures in developing countries, leaving open important questions about the mechanisms linking resources, energy policy, and sustainability.

2.6 Institutional and governance dimension

The political environment is profoundly shaped by the quality of institutions and governance. Eyuboglu and Uzar [19] mention how the democratization of Egypt apparently reduced LCF and thus reflects a political trade-off between freedom and environmental protection within the scope of the democracies of the poorer countries. On the other hand, as pointed out by Cavaleiro et al. [10], democracy and public governance in the form of regulatory quality and the rule of law, have a positive impact on the country's environmental performance. The above contrasting findings imply that the impacts of governance, especially of democracy, are contingent upon the level of institutional and civil maturity, policy compliance, and the system of political order.

Overall, the literature suggests that economic and social development interact with institutional factors in complex ways, affecting ecological capacity differently across contexts. While LCF offers a more integrated measure of environmental balance, capturing the multidimensional role of governance remains challenging. Prior studies typically rely on qualitative governance indices and rarely examine how institutional effectiveness moderates the impact of economic drivers on LCF. However, none of these studies investigate whether governance conditions amplify or weaken sustainability outcomes in developing countries, nor do they incorporate dynamic methods that address endogeneity. By using a governance dummy, this study tests whether countries with stronger institutional frameworks systematically achieve higher LCF, helping clarify the mixed evidence observed in earlier research. The flow of analysis can be seen in Fig. 1.

Fig. 1 Sustainability pathways



3 Data and research method

3.1 Data and variable description

This study used secondary data from various institutions, including the World Bank, International Monetary Fund (IMF), Global Footprint Network (GFN), and the United Nations Development Program's (UNDP) Human Development Reports, as well as KOF. The study utilizes panel data from developing countries from 1991 to 2021. Furthermore, the data is analyzed by using Stata. The variable descriptions can be seen in Table 2. This study aims to analyze the economic, social, and environmental determinants of ecological sustainability in developing countries using the LCF indicator as the dependent variable. LCF measures the environmental capacity to support both resource consumption and waste production [45]. Additionally, the GDP variable and its square are used to test the validity of LCC, as demonstrated by the study of Ulussever et al. [51]. To better understand the political factors that may influence ecological carrying capacity, this study incorporates dummy variables to highlight differences among countries in relation to their level of political stability. Therefore, this research examines not only economic and environmental elements but also explores how institutional factors contribute to sustainability.

The selected explanatory variables are supported by prior literature. Economic growth (GDP) is included due to its impact on ecological footprints, consistent with the Environmental Kuznets Curve. Human development (HDI) reflects human capital and environmental awareness. Natural resource rents capture the pressure of resource extraction, while financial development can either intensify or mitigate environmental impact. Renewable energy consumption represents sustainable energy use, and urbanization accounts for changing infrastructure and consumption patterns. Trade openness influences production and energy intensity, and political stability affects environmental policy and governance. These variables have been widely used in empirical studies on other countries [5, 6, 16, 48].

All variables are transformed into their natural logarithmic forms to enhance the robustness of the estimation results and to mitigate potential heteroscedasticity. This study utilizes annual panel data covering 61 developing countries over the period 1992–2021. Prior to conducting empirical analysis using the System GMM approach, the fundamental characteristics of the sample data are examined through descriptive statistics. Table 3 presents the measures of central tendency (mean), dispersion (standard deviation), and the minimum and maximum values for each variable during the 1992–2021 period. This summary provides a comprehensive overview of the average levels and variability of economic, social, and environmental conditions across the 61 developing countries analyzed.

3.2 Model specification

This article aims at discussing how economic, social, and environmental factors affect ecological carrying capacity in the developing countries using LCF indicator. LCF is an essential sustainability indicator in the sense that it shows how much a country can use in ecological consumption and regenerative capacity of the environment. It is expressed as the relationship between the biocapacity and ecological footprint and thus reflects the balance between ecological supply and ecological demand. An increase in LCF is an indicator of sustainability whereby the biocapacity is greater than its consumption, whereas LCF of less than one is ecological deficit. The theoretical background of the present paper is based on the Cobb–Douglas production function, which is an effective model of the relationship between several inputs and a result, which in this case, is the ecological carrying capacity. In line with the hypothesis of the LCC postulates a nonlinear (inverted U-shaped) correlation between economic growth and environmental sustainability, the model uses both GDP and GDP² to empirically model this nonlinear (inversely U-shaped) relationship [51]. Therefore, the econometric model and the theoretical framework can be formulated in the following way:

$$LCF = f(GDP, GDP^2, TO, FD, HDI, TNR, RE, IND, URB, DPS) \quad (1)$$

- GDP and GDP² are the economic growth and the squared expression of economic growth, which shows the non-linear aspect of income and environmental capacity.
- Economic factors are financial development (FD), trade openness (TO), and industrialization (IND), which determine the demand of the resources and efficiency of the resource utilization.

Table 2 Data description and sources

Variable	Symbol	Unit	Source	Definition
Load Capacity Factor	LCF	Global hectares/capita	GFN	Ratio of bio capacity to ecological footprint
Gross domestic product	GDP	Constant 2015 US dollars	WDI	Gross domestic product per capita
Gross domestic product squared	GDP ²	Constant 2015 US dollars	WDI	Square of GDP
Trade openness	TO	Percentage (%) of GDP	WDI	Sum of exports and imports to GDP
Financial development	FD	Index	IMF	Financial sector development index
Human development index	HDI	Index	UNDP	A measure of well-being based on education, income, and health
Urbanization	URB	number of persons (people)	WDI	Population living in urban areas
Total natural resource rent	TNR	Percentage (%) of GDP	WDI	Revenue from natural resource extraction (oil, gas, minerals)
Renewable energy consumption	RE	Percentage (%) of total energy consumption	WDI	Proportion of energy from renewable sources such as wind, water and solar
Industry	IND	Percentage (%) of GDP	WDI	Contribution of the industrial sector to GDP
Political Stability	DPS	Dummy (0/1)	WGI	Indicates the political stability of a country. Values 1 if the country is in a stable state; 0 otherwise

Table 3 Descriptive statistics

Variable	Obs	Mean	Std. Dev	Min	Max
lnLCF	1830	−0.125219	0.8620083	−2.195152	3.18827
lnGDP	1830	7.655273	0.9292597	5.313978	9.561016
lnTO	1830	4.099396	0.4988211	1.417684	5.395475
lnFD	1830	−1.739191	0.6559661	−3.632856	−0.2999731
lnHDI	1830	−0.5705805	0.250658	−1.52326	−0.1589957
lnTNR	1830	1.075874	1.476852	−6.049184	4.089062
lnRE	1830	3.435462	1.081561	−0.5108256	4.577799
lnURB	1830	15.71151	1.792207	10.02571	20.59872
lnIND	1830	3.247701	0.3503834	1.488124	4.278784
DPS	1830	0.1803279	0.3845654	0	1

- Social factors include urbanization (URB) and human development (HDI) which are a reflection of demographic pressure and social development on the ecological resources.
- The renewable energy consumption (RE) and total natural resource rent (TNR) are the indicators of the environmental factor, which reflect both the attempts of resource sustainability and green transition.
- The dummy variable of political stability (DPS) is added because it includes political factors that account institutional quality and governance effectiveness in ensuring environmental balance. To capture differences in political stability levels, a dummy is constructed using a threshold based on the annual median of the political stability index for developing countries. This approach is widely used in governance studies when continuous data are not available for the entire study period. This allows the dummy to reflect structural differences between countries with relatively high and low political stability without compromising the robustness of the instrument and the integrity of the panel data.

This theoretical argument posits that economic growth initially worsens the environment due to emerging industrial activities. However, once a threshold level of income and a mature institutional framework are achieved, environmental quality improves, thereby affirming the LCC hypotheses. This ecological improvement is further promoted by social progress, the increasing use of renewable energies, and enhanced governance systems that implement sustainable policies, facilitated by institutional stability.

Nonetheless, given the dynamic nature of the dependent variable (LCF), where its past values potentially influence current outcomes, employing a simple Ordinary Least Squares (OLS) regression could result in biased estimations due to endogeneity, unobserved heterogeneity, and serial correlation. To address these econometric weaknesses, this study adopts the Generalized Method of Moments (GMM) estimator, following the influential work of Arellano & Bover [7] and other subsequent studies in Turan Koyuncu [59].

There are two primary GMM methods that appear in panel data research, namely Difference GMM (DIF-GMM) and System GMM (SYS-GMM) estimators [13]. Since the dimension of cross-section (number of countries) is greater than the dimension of time, the two-step System GMM approach will be used in this research, where more effective and consistent estimates are obtained through the integration of level and differenced equations [50]. This methodology does not change in cases where a few regressors are endogenous [30]. The overall empirical estimation thus takes the two-step System GMM framework that is effective in dealing with dynamic relationships, endogeneity and country effect, thus providing robust and policy implication on the determinants of ecological carrying capacity in developing countries.

This study aims to assess the determinants of LCF. To achieve this, we also adopt the methodology used by Pata and Kartal who tested LCC in environmental implications in South Korea [42]. As a result, the dynamic panel model can be written in the form of equation as follows:

$$\begin{aligned} \text{LCF} = & \alpha + \beta_1 \text{LCF}_{i,t-1} + \beta_2 \text{GDP}_{i,t} + \beta_3 \text{GDP}_{2i,t} + \beta_4 \text{TO}_{i,t} + \beta_5 \text{FD}_{i,t} + \beta_6 \text{HDI}_{i,t} \\ & + \beta_7 \text{TNR}_{i,t} + \beta_8 \text{RE}_{i,t} + \beta_9 \text{URB}_{i,t} + \beta_{10} \text{IND}_{i,t} + \beta_{11} \text{DPS}_{i,t} + \varepsilon_{i,t} \end{aligned} \quad (2)$$

LCF is the Load Capacity Factor and serves as the dependent variable. $\text{LCF}_{i,t-1}$ indicates the lag of the dependent variable as a dynamic component. i and t represent country and year, respectively, α is the constant term, β is the coefficient of variables ($\beta = 1, 2, 3, \dots, N$) and $\varepsilon_{i,t}$ is the error term. To avoid heteroskedasticity issues, all variables are transformed into

logarithmic form using the natural logarithm scale. In the two-step System GMM framework, $LCF_{i,t-1}$ was treated as endogenous due to the dynamic persistence of ecological capacity. In addition, GDP, IND, HDI, and FD were classified as endogenous because these factors may simultaneously influence, and be influenced by, ecological sustainability. To address the resulting endogeneity, the estimator employs internal GMM-style instruments constructed from the appropriate lagged levels and differences of these variables. Meanwhile, URB, TO, DPS, RE, and TNR were treated as predetermined or exogenous. These variables serve as external IV-style instruments, as their contemporaneous values are theoretically less sensitive to short-run ecological shocks. This combination of internal and external instruments strengthens the identification strategy and ensures consistent estimation of the model parameters.

Pre-estimation procedures include Pesaran's cross-sectional dependence (CD) test and panel unit root tests. The CD test specifically designed for panels with a large cross-sectional dimension (N) and a relatively small-time dimension (T) was introduced by Pesaran [43] and is expressed as Eq. (3) and (4)

$$CD = \sqrt{\frac{2T}{N(N-1)}} \left(\sum_{i=1}^{N-1} \sum_{j=i+1}^{N-1} \hat{\rho}_{ij} \right) \quad (3)$$

where $\hat{\rho}_{ij}$ is the sample estimate of the par-wise correlation of the OLS residuals. The validity of the instruments in the GMM estimation system can be evaluated using the instrument validity test conducted through the Hansen Test, while the assumption of the absence of second-order autocorrelation is tested using the Arellano-Bond test (AR(2)) as suggested by [44]. Testing the validity of the model is done through two main stages, namely the Hansen test and the Arellano-Bond test. Hansen's test aims to identify the possibility of overidentification of the instrument, if the null hypothesis is rejected, then the instrument is considered valid because it is not correlated with the error term [32]. Meanwhile, the Arellano-Bond test is used to evaluate the autocorrelation of the residuals, with the model declared fit if the null hypothesis is accepted on AR(1) but rejected on AR(2), confirming that the moment conditions are appropriately specified and that the instruments are valid at higher orders confirming that the moment conditions are appropriately specified and that the instruments are valid at higher orders confirming that the moment conditions are appropriately specified and that the instruments are valid at higher orders [54].

Robustness checks were applied to ensure that the main estimation results were not sensitive to changes in model specifications or alternative estimators. The testing was conducted using two approaches. First, specification sensitivity was evaluated by replacing the TO variable with the Globalization Index (GI) as an alternative indicator of economic openness, and by removing URB variable to assess the potential for over-specification. Second, the study applied alternative estimators in the form of System GMM one-step and Panel-Corrected Standard Errors (PCSE). The PCSE estimator developed by Beck and Katz [60] is used to address heteroscedasticity, serial correlation, and cross-sectional dependence that commonly arise in cross-country panel data. All these robustness procedures are estimated using the same dataset and model structure as the main estimation, allowing for a direct comparison of the stability of the sign, magnitude, and significance of the coefficients.

4 Result and discussion

Prior to estimating the models, descriptive statistics and correlation analyses were conducted to provide an overview of the data characteristics. Table 3 presents the descriptive statistics of all variables included in the study. These statistics provide insights into the mean, standard deviation, and range of each variable across the sampled countries. Table 4 shows the pairwise correlation coefficients among the variables. The correlation matrix helps to identify potential multicollinearity issues and the strength and direction of relationships between explanatory variables and LCF prior to model estimation.

4.1 Pre-estimation test

In panel data analysis, cross-sectional dependence testing is an important preliminary step before model estimation. This test ensures that the selected unit root test method is appropriate for the characteristics of the data. Therefore, this study first tests cross-sectional independence using CD test developed. A significant CD statistic indicates the presence of cross-sectional dependence, rendering first-generation unit root tests inappropriate. Therefore, this study applies

Table 4 Correlation variables

	LCF	GDP	TO	FD	HDI	TNR	RE	IND	URB	DPS
LCF	1.0000									
GDP	0.0145	1.0000								
TO	-0.0002	0.2637	1.0000							
FD	-0.3144	0.6502	0.1381	1.0000						
HDI	-0.1215	0.8736	0.3078	0.6706	1.0000					
TNR	0.3963	-0.3202	-0.0201	-0.3356	-0.3027	1.0000				
RE	0.3135	-0.4856	-0.2748	-0.4798	-0.6020	0.2614	1.0000			
URB	0.1408	0.4523	0.3584	0.2828	0.4204	0.1902	-0.1902	1.0000		
IND	-0.1786	0.1872	-0.3736	0.4768	0.2788	0.1454	-0.1045	0.2428	1.0000	
DPS	0.1308	0.3915	0.4412	0.1293	0.3171	-0.2789	-0.2459	0.1562	-0.4269	1.0000

the second-generation Cross-Sectionally Augmented IPS (CIPS) test proposed by Pesaran [43], which extends the IPS framework by incorporating cross-sectional averages into the ADF regression to account for unobserved common factors. The IPS test offers precision in capturing heterogeneous dynamics across countries [31]. This approach produces more reliable stationarity results under cross-sectional dependence and ensures that the variables satisfy the assumptions required for dynamic panel estimators such as System GMM. Table 5 presents pre-estimation tests.

4.2 GMM analysis

To prevent instrument proliferation one of the main concerns in System GMM estimation we explicitly compare the number of instruments with the number of cross-sectional units. In this study, the final model employs 32 instruments for 61 groups, meaning the instrument count is safely below the recommended threshold. This indicates that the model does not suffer from excessive instrument accumulation. Instrument reduction was achieved by limiting lag depth, collapsing instruments, and restricting the instrument matrix to ensure parsimony. Therefore, the diagnostic check confirms that the System GMM specification remains robust and free from instrument proliferation.

The results of the dynamic model estimation with the two-step System GMM approach (Table 6) provide empirical evidence that strengthens and at the same time expands the theoretical understanding that has been built in the introduction and literature review regarding the determinants of environmental sustainability, especially in developing countries. This study emphasizes the LCF as a synthetic indicator that measures the balance between ecological capacity (biocapacity) and environmental pressure (ecological footprint), which represents the extent to which development can be considered sustainable.

To ensure the validity of the dynamic model used, autocorrelation and instrument validity in the two-step system GMM estimation are tested. The Arellano-Bond test results as shown in Table 7 show that there is the expected first-order

Table 5 Result of pre-estimation tests

Variables	CD test	CIPS	IPS	
		I(1)	I(0)	I(1)
lnLCF	143.93***	-3.268***	-2.8879***	-25.5394***
lnGDP	148.17***	-2.694***	6.8853	-19.1532***
lnGDP2	148.27***	-2.653***	7.9126	-19.1962***
lnTO	33.08***	-3.109***	-2.9276***	-22.9023***
lnFD	95.81***	-3.445***	-2.5969***	-24.6766***
lnHDI	207.64***	-2.616**	-3.8611***	-11.5911***
lnTNR	51.26***	-3.344***	-5.7194***	-22.8049***
lnRE	86.59***	-2.932***	2.7083	-21.8972***
lnURB	214.02***	-1.789	-9.2306***	-0.4502
lnIND	15.97***	2.683***	-2.2591**	-22.6736***

*** Significant at 1%

** Significant at 5%

Table 6 Result of dynamic panel-data estimate, two-step system GMM

Variable	Coefficient	z	p > z	Std. Err
L1.lnLCF	0.9465***	36.10	0.000	0.0262
lnGDP	0.4447***	2.66	0.008	0.1672
lnGDP2	−0.0252**	−2.53	0.011	0.0100
lnTO	−0.0120	−0.66	0.510	0.0182
lnFD	0.0124	0.60	0.550	0.0207
lnHDI	−0.1697**	−2.01	0.044	0.0845
lnTNR	0.0197***	2.99	0.003	0.0066
lnRE	0.0106	1.15	0.251	0.0092
lnURB	−0.0028	−0.43	0.667	0.0065
lnIND	−0.0782**	−2.21	0.027	0.0355
DPS	0.0354**	2.30	0.022	0.0154
Constant	−1.7169**	−2.58	0.010	0.6659
Number of obs				1769
Number of instruments				32
Number of groups				61

*** Significant at 1%

** Significant at 5%

Table 7 Test of instrument validity

Uji Statistik	Statistic	p-value
Arellano-Bond AR(1)	−4.48	0.000
Arellano-Bond AR(2)	1.04	0.297
Hansen J-Test	18.41	0.560
Sargan Test	17.32	0.632
Wald Chi ²	50,428.94	0.000

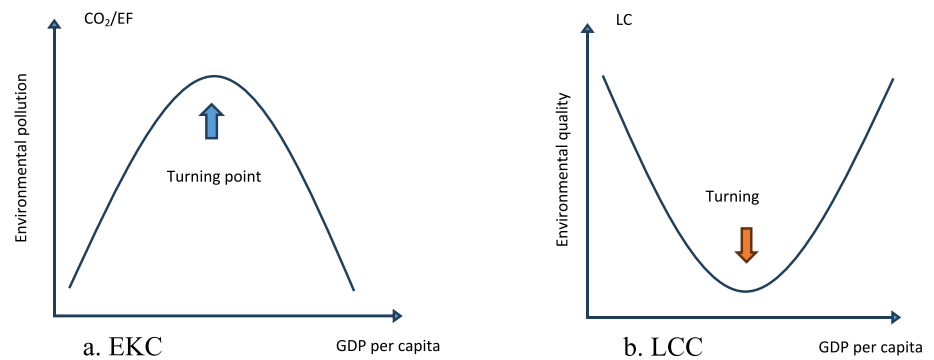
autocorrelation (AR(1)) in the difference model, but there is no second-order autocorrelation (AR(2)), which indicates that the model specification is appropriate and does not contain higher residual correlation. Furthermore, the Hansen and Sargan tests yielded p-values of 0.560 and 0.632 respectively. In addition, the significant Wald Chi² value ($p < 0.01$) indicates that the model as a whole is able to explain the variation in LCF well. This indicates the presence of first-order autocorrelation expected in a first-difference model, but no second-order autocorrelation, which is an important assumption in GMM models [54]. These results indicate that the estimates obtained are robust and can be used to draw empirical conclusions about the determinants of environmental sustainability in developing countries.

4.2.1 Hypothesis proving: relationship between income and LCF

This study tests the validity of the LCC hypothesis that predicts a U-shaped relationship between income and environmental sustainability, as measured by LCF. In the LCC framework, it is expected that income growth initially reduces LCF before eventually improving it once economies reach a sufficiently advanced stage. Because LCF is a “higher-is-better” indicator, an upward-sloping trajectory reflects improving ecological sustainability. Economic growth will encourage improvements in environmental capacity through the adoption of green technology, institutional improvements, and changes in consumption behavior.

However, estimation results using the two-step system GMM method show that the relationship between income and LCF in developing countries does not follow the LCC pattern. The positive coefficient of GDP and negative coefficient of GDP², indicate an inverted U relationship in which LCF first rises but later declines, meaning that sustainability deteriorates after surpassing a certain income threshold. For a better understanding of the differences between the EKC and LCC hypotheses, the two curves are illustrated in Fig. 2 which compares the inverted U shape of the Environmental Kuznets Curve (EKC) with the inverted U-shape observed for the LCF in this study. In the EKC, emissions are a “higher is worse” indicator, so an inverted-U reflects environmental improvement after the turning point. In contrast, because LCF

Fig. 2 Hypotheses the EKC and LCC Hypotheses

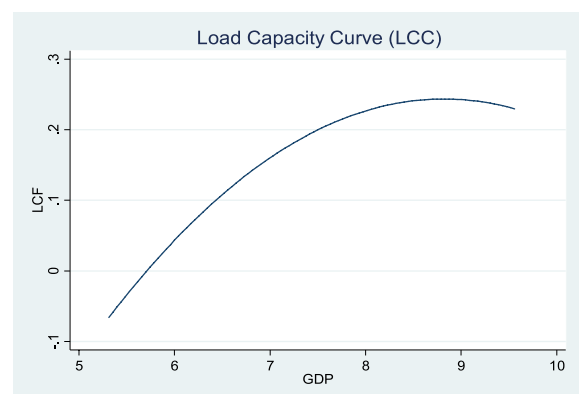


is a “higher-is-better” measure of ecological capacity, an inverted-U indicates that sustainability improves at low-income levels but worsens after the peak. This distinction explains why the same mathematical shape conveys opposite environmental interpretations. This finding reinforces the importance of an LCF-based approach to assessing the balance between ecological capacity and development pressures, and the need for early policy interventions to prevent economic growth from leading to long-term environmental degradation.

These results therefore diverge from the LCC hypothesis documented in studies such as Dai et al. [11] and Emre Caglar et al. [17], which found a U-shape for Turkey and ASEAN economies. Instead, our findings align more closely with the results of Okere et al. [37] research in North Africa show an inverse-U relationship between GDP per capita and ecological load capacity at the 25th and 50th quantiles, indicating that in the early and middle stages of economic growth, pressure on environmental capacity tends to increase, but after passing a certain point, the effect decreases. In this study, two-step system GMM estimates also show a similar non-linear pattern, with positive coefficients for GDP and negative coefficients for GDP² on LCF, confirming the inverted-U relationship across the sample of developing countries. The main difference lies in the consistency of the inverse-U effect; while Okere et al. [37] only identified this effect at certain quantiles, the results of this study show a consistent effect across the board. Sharif et al. [48] show that rising income at later stages can erode ecological capacity due to intensified consumption, resource exploitation, and energy-intensive production structures. For the developing countries included in this study, this inverted-U pattern likely reflects structural constraints such as limited technological readiness, weak environmental governance, and high dependence on natural resource extraction [23, 53].

Using the estimated coefficients of GDP and GDP² from the two-step System GMM model, the turning point of the LCF income relationship is calculated based on the standard quadratic form. Because the model uses the natural logarithm of GDP, the turning point in actual GDP is obtained by exponentiating the ratio $-\beta_{GDP} / (2\beta_{GDP^2})$. Based on the GMM estimates ($\beta_1 = 0.4447$ and $\beta_2 = -0.0252$), the turning point is 8.82 (ln GDP), which corresponds to approximately USD 6792. This value falls well within the observed lnGDP range (5.31–9.56) reported in the descriptive statistics, ensuring consistency between the model results and the data. This value represents the income level at which LCF reaches its maximum before starting to decline. This study found an inverted-U pattern as seen in Fig. 3, while emphasizing that economic development in developing countries is not yet supported by a sustainable production and consumption system. The magnitude of the turning point illustrates that many developing countries in the sample may already be positioned

Fig. 3 Load Capacity Curve in Developing Countries



near or above this threshold, implying that additional income growth could lead to further ecological capacity loss if not accompanied by structural, technological, and governance improvements.

4.2.2 Social, political and economic influences on LCF

By detailing the role of different systemic social and institutional variables on LCF, this study adds to the growing body of literature on the dynamics of sustainability in the Global South. Prior studies found the relationship between GDP and LCF to be in the form of an inverted U-shape, which is not in line with the theoretical expectations of the LCC curve. The analysis went on to show that it's not just the macroeconomic factors, but the quality of the institutions, social development, and the economic structure also significantly determine a country's ecological capacity.

The most notable finding from this output is the discovery of the negative and significant relationship of HDI and LCF. This finding runs counter to the widely held expectation that the advancements in HDI which denote improvements in health, education and overall living standards of the populace tend to promote a more ecologically cons and friendly consumption behavior. To the contrary, the data reveals that in most of the developing world, human development is not concomitant with rising ecological consciousness, nor the behavioral shift towards the consumption of sustainable goods and services. Eyuboglu and Uzar [19], and Nguyen et al. [35] observed that social development in the under gc countries is still highly based on a socio development model which is economically regressive and one that is vastly not ecologically oriented.

Increases in education and income often drive higher material consumption, particularly among the growing middle class, resulting in greater demand for energy-intensive goods, personal transportation, and resource-based products. Furthermore, in developing countries, increased educational attainment is not accompanied by a shift to environmentally friendly or high-skilled service sectors; instead, workers often remain concentrated in informal urban activities, increasing environmental pressures. Rising living standards often accelerate urban expansion without adequate environmentally friendly infrastructure, increasing pressure on land, water, and energy systems.

On the other hand, DPS has highly positive and statistically significant influence on LCF confirming the relevance of institutional dimensions to sustainable development. countries with a strong political stability tend to improve environmental sustainability more than those with weak political stability. This finding is consistent with the literature, for instance, Agheli and Taghvaei [1] and Cavalheiro et al. [10] which argue that a political stable country provides a strong base for the formulation and implementation of a range of environmental policies, regulation of resource depletion, and strengthening of the environmental governance system.

Concerning economy and environment, TNR positively affecting factors like LCF. Hence, it can be assumed. If good natural resource exploitation revenue governance is practiced, it can be utilized economically for environmental restoration and green programs. This is in line with [16] where it is highlighted that resource use is not negative depending on fiscal policy and where the rent revenue is allocated. On the contrary, IND is significantly adversely LCF is contrary. This means the industry in the developing world is still in the hands of highly energy consuming and inefficient, old, and unsustainable technologies. This holds true in Jin and Huang [25] and Nulambeli and Jaiyeoba [36] that with or without a shift to green industry, (increasing production capacity) reduced ecosystem space and decreased unsustainability. Environmentally unbalanced and urban industrial growth pressures on Ahmad et al. [3] and Lu et al. [29] highlighted the declining ecological carrying capacity, especially once the economy hits a particular income value.

These structural pressures combined with rapid industrialization and urbanization that lack green transitions help explain why income growth eventually drives LCF downward rather than supporting long-term ecological resilience.

Variables such as TO and URB negatively affect the loss of resource sustainability, while FD and RE positively affect the increase of environmental sustainability. Nonetheless, there is no significant impact on LCF. Such insignificance is understandable considering the structural realities of developing countries, which continue to encounter numerous obstacles. Regarding trade openness, there is an inclination of the effect to be ambiguous, depending on the export–import structure. If the export composition is primarily raw materials, sustainability is negatively impacted, as pointed out by Fang et al. [20] and also Dam and Sarkodie [12]. There is an increase of LCF as rapid Urbanization, if not combined with inclusive urban planning and robust governance. The environmental sustainability of financing of productive activities that support the empowerment of green infrastructure, renewable energy, and small community enterprises, is financed by developing the financial sector and renewable energy.

As a whole, these findings affirm the hypotheses stating that the quality of institutions, human development direction, economics composition, and environmental sustainability are interrelated in developing economies. Although LCC hypothesis was not confirmed in this study, the findings still imply that, in order to attain and develop sustainably, the

shift of institution(s) and structure(s) to be put as the highest priority in order to achieve transformational objectives targeting the enhancement of ecologically sustainable development within the economy.

4.3 Robustness test

To evaluate the robustness of the two-step GMM System estimation results in Table 6, this study conducted a series of robustness tests as presented in Table 8. Replacing the trade openness variable with the Globalization Index (Model 1) shows that all main variables maintain the direction of influence consistent with the basic model, including the positive relationship between GDP and the negative relationship between GDP² and LCF. The LCF lag coefficient also remained stable (0.9470), reflecting the strong dynamics of LCF as shown in the main results. The removal of the urbanization variable in Model 2 did not change the pattern of significance or the direction of the relationship for core variables such as GDP, GDP², TNR, RE, and IND, confirming that the model is not sensitive to possible over-specification.

The consistency of the results is even more apparent when using alternative estimators. In the one-step GMM system (Model 3), the main variables such as GDP, GDP², TNR, and HDI remain significant with coefficient signs consistent with the main model. Meanwhile, the PCSE estimation (Model 4), which is designed to handle heteroscedasticity and cross-sectional dependence, produces a coefficient pattern consistent with the GMM approach. GDP again shows a positive effect, while GDP² has a strong negative effect on LCF, confirming the existence of a non-linear relationship pattern as found in the main findings. Overall, the stability of the coefficients across various specifications and estimation methods indicates that the research conclusions are not sensitive to the use of alternative indicators, the removal of certain variables, or differences in econometric approaches. These findings reinforce the reliability of empirical results related to LCF determinants in developing countries.

For the analysis of all developing countries, a two-step System GMM model was used to capture the dynamics of dependent lags and the potential endogeneity of variables. However, for the analysis of heterogeneity based on income groups (Upper Middle Income (UMI) and Low Income (LI)/Lower Middle Income (LMI), PCSE was used. The PCSE model was chosen for the analysis of these groups because the smaller number of countries risks producing too many instruments

Table 8 Robustness test

Variable	Model 1 Replacement	Model 2 Remove	Model 4 GMM onestep	Model 5 PCSE
L1.LCF	0.9470***	0.9481***	0.9743***	
GDP	0.4159**	0.4356***	0.4040***	1.8202***
GDP2	−0.0236**	−0.0246**	−0.0238***	−0.0860***
TO		−0.0076	−0.0063	−0.2841***
GI	−0.0330			
FD	0.0148	0.0096	−0.0037	−0.2918***
HDI	−0.1331	−0.1709**	−0.0957**	−0.4910***
TNR	0.0196***	0.0187***	0.0124*	0.2692***
RE	0.0121	0.0109	0.0008	0.2101***
URB	−0.0007		0.0026	−0.0802***
IND	−0.0846***	−0.0817***	−0.0819**	0.0677
DPS	0.0312**	0.0390**	0.0217	0.4081***
Constant	−1.5064**	−1.7378***	−1.5270**	−8.6111***
Number of obs	1769	1769	1769	1,830
Number of instruments	32	31	32	
Number of groups	61	61	61	61
R ²				0.4145
AR(2)	0.303	0.301		
Hansen J-Test	0.578	0.544		
Wald Chi ²	38,987.54***	39,598.56***	35,081.73	6513.48***

*** Significant at 1%

** Significant at 5%

* Significant at 10%

when using GMM, which could reduce the validity of the estimates. With the PCSE approach, the effects of the variables can still be analyzed with better stability of coefficients and standard errors.

The heterogeneity analysis shows differences in the effects of LCF determinants between country groups. In the UMI group, GDP has a significant positive effect on LCF, while the HDI coefficient is significantly negative, indicating that improvements in human development do not fully support environmental sustainability. RE and URB have a significant effect as hypothesized. Conversely, in the LI & LMI groups, the relationship between GDP and LCF is reversed (negative GDP, positive GDP), indicating different EKC dynamics in low-income countries. HDI is not significant, while RE and TNR have a strong positive effect on LCF. The differences in direction and significance of the coefficients between groups confirm the heterogeneity of the influence of LCF determinants based on income level, so that the analysis per group provides a more accurate picture than the combined analysis of all developing countries (Table 9).

5 Conclusions & policy implications

5.1 Conclusion

This study analyzes the determinants of LCF in developing countries in the context of sustainable development. LCF is used as an indicator that combines natural conditions in supporting resource consumption, taking into account the supply and demand functions of resources. This study uses a two-step SYS-GMM with panel data from 61 developing countries during the period 1992–2021. To examine the relationship between economic growth and LCF, the LCC concept is applied, following the EKC framework. According to this concept, environmental quality tends to deteriorate during the early stages of economic growth but improves after reaching a certain level of development. However, in this study, the relationship between per capita income and LCF follows an inverted U pattern, suggesting that after passing a threshold, further economic growth reduces environmental sustainability and the conventional LCC curve may not fully apply to developing countries.

Empirical results increasingly highlight the role of squality and institutional governance. There is strong political stability and its significant positive impact on LCF. Hence the need of stable governance to foster LCF environmental sustainability. On the contrary, LCF is negatively impacted by HDI illustrating the integration of human development, even in the developing nation LCF sustainable consumption practice is not fully embraced. Total natural resource income (TNR) is positively impacting LCF depicting that responsible resource containing lcf that can only increase the ecological carrying capacity. LCF is drastically reduced by IND depicting the desperately required transformed industrial lcf to be more environmentally sustainable and inclusive of energy efficient structured in the transformation industrial lcf degraded to be more inclusive of energy sustainable eco efficient transformation. Other variables of lcf including TO, FD, RE and URB, LCF impact of variables is primarily determined by the structural, policy and institutional context of each country.

Table 9 Heterogeneity analysis of LCF by income group (PCSE estimates)

Variable	Upper (UMI)	Lower (LI & LMI)
GDP	1.374***	−2.661**
GDP2	−0.088**	0.149**
TO	−0.065***	−0.228***
GI	−0.030	−0.064
FD	−0.989***	0.073
HDI	0.022**	0.079***
TNR	0.092***	0.264***
RE	−0.059***	−0.168***
URB	−0.006	0.150
IND	1.541***	−0.505***
_cons	−5.549**	14.302**

*** Significant at 1%

** Significant at 5%

* Significant at 10%

Increasing an ecologically sustainable carrying capacity in impoverished nations takes much more than just economic growth. System transformations, effective state structures, integrated human development, and cohesive urban and resource management are equally necessary. Ideally, this is why the LCC framework must be realigned to developing countries, wherein the elements of economic growth, governance, and the environment are inextricably linked.

This study has several limitations. The availability of governance and institutional data is limited, which may affect the measurement of political stability's impact on LCF. Unobserved heterogeneity across countries, such as differences in policies, cultural practices, or resource endowments, may not be fully captured. Future research could expand this study by examining nonlinear effects and interactions, such as GDP³ or interactions between economic growth and institutional quality, to capture more complex dynamics. Incorporating more detailed governance and policy variables, sectoral analysis, and dynamic modeling approaches could provide deeper insights into the determinants of LCF. Furthermore, expanding environmental metrics to include indicators such as biodiversity, water stress, carbon footprint, or circular economy practices, and conducting cross-country or regional comparisons will help assess the generalizability of the Load Capacity Curve framework in evolving contexts.

5.2 Policy implications

Based on the research findings, several specific policy recommendations can be proposed, each linked to the relevant empirical variable. Since industrialization significantly reduces LCF, governments should promote energy-efficient industrial upgrading through green fiscal incentives, cleaner production standards, and the adoption of low-carbon technologies. Given that total natural resource rents positively affect LCF, natural resource exploitation should not only be used for short-term consumption but strategically allocated to finance green infrastructure and clean technologies that support environmental restoration. In addition, the integration of sustainable development principles into trade and finance strategies is crucial, for example through the implementation of green tax incentives, the development of green financing schemes, and the establishment of domestic carbon market mechanisms.

To develop long-term environmental policies that involve further rules and greater public participation, political and social stability are essential. With these policies in place, developing nations will be able to continue inclusive and sustainable economic growth, while alleviating ecological debt. Human development programs are essential and should promote awareness of sustainable consumption and environmental responsibility, to ensure development aligns with LCF. Lastly, trade openness, financial development, renewable energy, and urbanization were found to have no relevant effect, indicating that policy measures concerning these variables ought to be tailored to the specifics of a country, e.g. green financing, ecologically sustainable trade, and urban development that decreases ecological pressures. Developing countries can craft policies to be linked to each empirical finding, thus effectively sustaining inclusive environmental degradation and economically growth.

Author contributions H.R: methodology, formal analysis, writing—original draft. I.I, H.R, T.K: conceptualization, methodology, software, data curation, writing—original draft. L.I, T.K: investigation, resources. A.R.R: validation, writing—review and editing, visualization, supervision, project administration. I.I: conceptualization, validation, project administration.

Funding This research received no external funding. The study was self-funded by the authors.

Data availability All relevant data is available from the corresponding author upon reasonable request.

Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

AI declaration Generative AI tools were used solely for language refinement and did not contribute to the analysis, interpretation, or scientific content of this manuscript. All research findings and conclusions are the authors' own.

Competing interests The authors declare no competing interests.

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Appendix: List of countries included in the sample

1. Argentina	39. Ecuador
2. Guatemala	40. Mauritius
3. Niger	41. Togo
4. Guinea	42. Egypt
5. Pakistan	43. Mexico
6. Bangladesh	44. Tonga
7. Haiti	45. El Salvador
8. Paraguay	46. Mongolia
9. Benin	47. Tunisia
10. Honduras	48. Eswatini
11. Peru	49. Morocco
12. Bolivia	50. Turkey
13. India	51. Fiji
14. Philippines	52. Mozambique
15. Botswana	53. Uganda
16. Indonesia	54. Gabon
17. Republic of the Congo	55. Namibia
18. Brazil	56. Ukraine
19. Ivory Coast	57. Gambia
20. Senegal	58. Nepal
21. Burundi	59. Vietnam
22. Jordan	60. Ghana
23. Sierra Leone	61. Nicaragua
24. Cameroon	
25. Kenya	
26. South Africa	
27. China	
28. Lesotho	
29. Sudan	
30. Colombia	
31. Malaysia	
32. Syria	
33. Costa Rica	
34. Mali	
35. Tanzania	
36. Dominican Republic	
37. Mauritania	
38. Thailand	

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