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Assessing the Convergence in Load Capacity Factors among Major Polluting Countries: Evidence from Nahar-Inder and Unit Root Analyses

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Abstract

This study analyzes the LCF convergence of the world's ten largest polluters—Brazil, the United States, Germany, South Korea, India, China, Indonesia, Japan, Mexico, and France—using data for the period 1961–2024. The research goes beyond the static framework and the heterogeneous findings of the linear, structural-break, and nonlinear unit root tests. As an analytical contribution, it applies the Nahar–Inder (2002) methodology to the LCF literature for the first time. This approach models convergence towards the leading country (Brazil) as a dynamic polynomial function of time, thereby relaxing the restrictive assumption of stationarity. With the contribution of Bentzen and Tung (2021), changes in the speed of convergence (acceleration or deceleration) are also captured through second-derivative analysis. The findings stand in sharp contrast to those obtained from unit root tests: the Nahar–Inder methodology identifies strong convergence for seven countries (the United States, India, Japan, Indonesia, Germany, France, and South Korea), while China and Mexico exhibit divergence. This result indicates that economies appearing to be divergent under traditional tests (e.g., the U.S., Germany, France) are, in fact, dynamically converging. The results emphasise the necessity of differentiated policy trajectories for converging and diverging countries.

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One of the basic macroeconomic goals of all countries is to ensure sustainable economic growth. The basic indicator of economic growth is the increase in the level of real production over time. Countries resource endowments and technological levels shape their production activities. While the traditional inputs of the production process are labour and capital, Uri (1995), Stern (2011) and Ilesanmi and Tewari (2017) have put forward the idea that energy consumption should also be included as a basic input in production functions. Undoubtedly, the waste and intensive consumption activities that occur at the end of the production process also lead to environmental problems such as climate change, global warming, and air and water pollution.

The industrial revolution was the beginning of a period in which both the population and the production volume increased very rapidly in the world. Thus, the pressure created by the increasing population and production volume on the use of natural resources became an obstacle for countries to achieve a sustainable growth process by taking environmental quality into account (Baloch et al., 2019). The starting point of the energy-growth-environment relationship was the study titled "Limits to Growth" prepared by the Club of Rome in 1972. This study revealed that the intensive use of non-renewable resources in meeting energy needs was the most important threat to sustainable growth (Sinha and Schneider, 2024). To cope with this threat, many countries have understood the importance of turning to renewable energy sources so that the production process is not interrupted. In addition, the environmental problems caused by the use of non-renewable energy sources have attracted the attention of policy makers and scientists (Yilanci and Pata, 2020; Ni et al., 2022). In the late 1980s, the concept of "Sustainable Development" was defined in the meetings held within the United Nations, and the importance of environmental sustainability was emphasised. Because of these initiatives gaining an international dimension, the Kyoto Protocol was signed in 1997 and finally the Paris Climate Agreement was signed in 2015. All these developments can be considered a reflection of the desire of countries to act together to establish global environmental sustainability. In particular, controlling the emission of greenhouse gases such as carbon dioxide (CO_2), methane (CH_4), nitroxide (H_2O), hydrofluoridated carbons (HFCs), perfluoridated carbons (PFCs) and sulfur hexafluoride (SF_6) and keeping them below a certain level has gained great importance in terms of environmental sustainability (Ahmed et al., 2016). Because greenhouse gases, which cause global warming and climate change, have been seen to threaten food security, biodiversity and social life (Sinha and Schneider, 2024).

Wackernagel and Rees (1996) introduced the concept of ecological footprint, which is a comprehensive measure as an important indicator of the planet's capacity to renew itself. Simply put, every individual, production activity, region and various processes have an impact on the planet. These impacts manifest themselves in the form of pollution resulting from the use of resources provided by nature and require the use of biologically productive areas for renewal (Pereira and Ortega, 2012Two main reasons explain the ecological footprint's growing popularity in recent years. The first of these is that it defines a process that makes it possible to mathematically estimate the amount of resources that society will consume in a year, making it possible to compare this consumption with nature's capacity to renew itself. The second is that it defines the final results simply and intuitively as "land area" (Zhao et al., 2005). Although there are intense discussions on its calculation and evaluation (Zhao et al., 2005; Siche et al., 2010; Pereira and Ortega, 2012), the ecological footprint includes the impact of human activities on six basic productive areas and shows the land demand required for the continuation of current energy use. These areas are cropland, grazing

land, forest, fishing area, built-up and carbon uptake land (Wackernagel et al., 1999). Many researchers interested in environmental sustainability have conducted studies on ecological footprint, economic growth, and technology. In these studies, the ecological footprint was used as an environmental pollution indicator (instead of a single pollution indicator) since it is relatively broad when the components it contains are considered. However, since it only expresses the demand side of environmental sustainability, studies on sustainability have been lacking.

Biocapacity has been defined as a measure of biologically productive land and sea areas to provide ecological resources consumed by human beings and has become the main indicator of the supply side of environmental sustainability (Wackernagel et al., 2017; Borucke et al., 2013). The subcomponents of biological capacity are the regenerative capacity of built-up land, cropland, fishing grounds, forest land, and grazing land to meet livelihood demand (Gabbi et al., 2021). Biological capacity can also be considered as an indicator of the self-renewal process of resources existing in nature (Pererira and Ortega, 2012; Siche et al., 2010). Similar to the ecological footprint, biological capacity has recently become the focus of attention of researchers working on environmental sustainability-economic growth-energy issues (Gabbi et al., 2021; Bastianoni et al., 2019). It has also been argued that since biocapacity is the most important criterion representing the supply side of environmental sustainability, it also requires new technology and management practices for the use and continuity of renewable resources (Goldfinger et al., 2014).

Biological capacity is determined by two fundamental factors. These are the surface area of agricultural land, pasture, fishing ground and forest within the borders of a region, and the second is the productivity level of the land or water owned (Wackernagel and Rees, 1996). In environmental sustainability discussions, the relationship between the ecological footprint, which reflects the amount of resources used, and the biological capacity, which reflects the amount of usable resources, plays a central role. Because of the United Nations Sustainable Development Goals, especially goals 6, 7, 8, 12, 13 and 14 emphasise the importance of environmental sustainability. These goals aim to achieve sustainable and inclusive economic development, sustainable production and consumption, combat climate change, protect oceans, seas and marine resources for sustainable development and provide equally accessible and sustainable modern energy for everyone. Therefore, considering both the ecological footprint and biological capacity at the same time is of great importance in terms of environmental sustainability.

Siche et al. (2010), Pereira and Ortega (2012) and Sarkodie (2021) defined the load capacity factor (LCF) index and developed a criterion that allows the use of both ecological footprint and biological capacity at the same time. LCF has been considered as the main indicator of ecological deficit or ecological surplus and has been the focus of attention of both policy makers and researchers (Sinha and Schneider, 2024). LCF is an index calculated as the ratio of biological capacity to ecological footprint. If this index value is less than 1, there is no environmental sustainability and the ecological "deficit" situation is valid. If the LCF value is greater than 1, there is environmental sustainability (Pata and Yilanci, 2021). Therefore, there is an ecological "surplus" (Mancini et al., 2018). Ecological deficits lead to excessive use of domestic natural resources, thereby creating a decrease in natural capital (Siche et al., 2008). Therefore, in countries with ecological deficits, measures must be taken against increasing environmental pressures. These measures can be summarised as carbon tax, applications that encourage renewable energy consumption, and technological developments for energy saving. Therefore, determining the stochastic properties of the LCF is a critical issue in terms of designing environmentally friendly policies. Because LCF can be evaluated as an indicator of the environmental sustainability balance.

The sustainability of LCF requires that it follows a stationary process from an econometric perspective. This means that the statistical properties (mean and variance) of the LCF series are not affected by the shocks

over time. The fact that the LCF series follows a stationary process means that shocks that occur in the short term do not have permanent effects on the series (Sinha and Schneider, 2024; Gomez and Rodriquez, 2024; Pata and Yilanci, 2021). The fact that the series does not follow a stationary process requires that the shocks that occur have permanent effects on the series and that the series does not return to its mean and/or trend in the long term. Şimşek et al. (2025), Pata and Yilanci (2021), Sinha and Schneider (2024), and Gomez and Rodriquez (2024) examined the stochastic convergence process for ecological balance and LCF series in their studies. These studies have been pioneers in the literature on environmental sustainability convergence. However, the presence of studies based only on the unit root technique in environmental sustainability convergence analyses can be considered a significant deficiency.

The main objective of this study is to analyse the convergence process, which is the main inference of the Solow-Swan (1956) model, for 10 countries in the period 1961-2022 using the Nahar-Inder (2002) convergence methodology. The importance of convergence analyses in terms of environmental indicators has been emphasised by Stern (2017) and has been highlighted in the design of common policies among countries. In fact, Stern (2017) stated that convergence studies on pollution-causing factors would yield more consistent results instead of Environmental Kuznets Curve Hypothesis (EKC) analyses and that time-sensitive environmental indicators would be better analysed in this way. Nahar-Inder (2002) and Bentzen and Tung (2021) proposed polynomial-type convergence in the models they developed as an alternative to the unit root technique. This technique is important because it allows convergence inference even if there is a unit root in the considered series. The findings regarding the existence of convergence behaviour in the series of interest provide inferences regarding the formation of environmental policies coordinatedly. The countries subject to the analysis are Brazil, the US, Germany, South Korea, India, China, Indonesia, Japan, Mexico, and France. The reason for choosing this sample is that they are the 10 countries with the highest levels of pollutants in the world according to their ecological footprint. On the other hand, the share of the 10 countries included in the analysis in the global gross domestic product is approximately 65%. This situation indicates that these highly polluting countries continue their economic performance without considering the effects of environmental degradation. these countries are in common agreement in achieving sustainable development goals. The fact that the analysed countries have a high share in the global economy and are highly polluting is of great importance in terms of environmental sustainability goals.

It is considered that this study will make two main contributions to the relevant literature. The first of these is that the selected 10 countries are particularly the top 10 polluters and the common characteristic features of the LCF series of this group of countries are determined. Based on this, it is thought that it will shed light on the implementation of common environmental policies in the relevant countries. The second is that it is the first application of the Nahar-Inder (2002) methodology on environmental convergence. In this way, we aimed to reveal the polynomial type convergence behaviours, to relax the constraint based on the stationarity condition in the series and to separate the country/countries that exhibit different behaviours in the sample.

Besides the introduction section, the rest of the study is organised as follows. The next section describes the related literature about LCF's convergence. Section 3 introduces the data collection, econometric methodology and findings. In section 4, concluding remarks are presented, along with policy implications and prospects for future research.

Literature Review

A review of the LCF literature reveals that there are only three studies focusing on convergence. The first is by Sinha and Schneider (2024), who examined the LCF series for the U.S. economy. The second is Pata

and Yilanci (2021), who analysed the sustainability of the ecological balance in G10 and N11 countries. The common feature of these two studies is that both employ unit root-based convergence analyses. The third study, by Gómez and Rodríguez (2024), focuses on seven countries in the Americas, examining environmental factors such as LCF, ecological footprint, and energy intensity, using unit root tests and convergence club methodologies. However, there are no existing studies in the literature that apply the Nahar-Inder (2002) polynomial-type convergence methodology to environmental indicators. Therefore, this study aims to fill this methodological gap within the LCF literature.

Despite the limited number of convergence studies, the LCF literature includes numerous contributions examining the determinants of LCF across various countries or country groups (Omri et al., 2021; Pata and Isik, 2021; Pata, 2021; Akadiri et al., 2022; Akhayere et al., 2023; Huilan et al., 2024; Alola et al., 2021; Ni et al., 2022; Ren et al., 2022; Guloglu et al., 2023; Kartal et al., 2023; Ullah et al., 2024; Xu et al., 2022; Pata et al., 2023; Pata and Kartal, 2023; Sun et al., 2024; Fang et al., 2024). Other studies have investigated LCF as an independent variable in models focusing on broader environmental indicators.

Although a large body of research examines the ecological footprint (EF) and its subcomponents, the literature on biocapacity convergence—the supply-side dimension of environmental quality—remains relatively scarce. A notable contribution is Sarkodie (2021), who analysed the environmental performance of Australia, Brazil, the U.S., Germany, Japan, India, Russia, and China using time-series techniques. Sarkodie found substantial crosscountry differences in biocapacity behaviour, identifying Brazil as the country with the most favourable ecological reserve. Similarly, Alvarado et al. (2022) and Gómez and Rodríguez (2024) contributed to this limited body of work. In general, the convergence literature on environmental sustainability has focused more heavily on the demand side (e.g., EF), while the supply side (e.g., BIO) has been relatively underexplored.

Despite the holistic structure of the LCF indicator, convergence research in this area remains relatively limited. Existing studies tend to focus on its components—ecological footprint (EF) and biocapacity (BIO) —and display methodological heterogeneity by relying primarily on unit root tests and club convergence approaches. The dominant approach in the environmental convergence literature is to assess the stationarity of the series, thereby determining whether the effects of shocks are permanent or transitory. Consequently, the literature distinguishes between traditional (linear) unit root tests and newer-generation tests that incorporate structural breaks and nonlinear dynamics.

For example, Pata and Yilanci (2021) applied traditional and Fourier quantile unit root tests to G10 and N11 countries and found sustainable (convergent) behaviour in 16 countries, while detecting unsustainability (divergence) in others, including the U.S., the U.K., and Japan. Similarly, Sinha and Schneider (2024) found that the LCF series for the U.S. is stationary and tends to revert to its long-term trend, indicating that although it is sensitive to energy-related shocks, it remains stable despite structural changes. On the other hand, Yilanci and Pata (2020), using a nonlinear panel unit root technique for the ASEAN-5 countries, found that the convergence dynamics of the ecological footprint were more evident in the second regime of the sample period.

Unit root tests have also been widely employed in EF convergence analyses. For instance, Ursavas and Yilanci (2022) applied Fourier ADF tests to MERCOSUR countries across different time frequencies, finding that convergence patterns varied between short and long horizons. Wu (2022) examined the stochastic convergence behaviour of ecological indicators in BRICS countries, reporting that the EF series followed a stochastic convergence process, meaning they tended to revert to a trend over time. These findings demonstrate that both methodology Ical choices and sample periods can fundamentally alter the convergence results.

In contrast to unit root-based approaches, the Phillips-Sul club convergence methodology examines whether groups of countries with similar characteristics converge into sub-clubs when full-sample convergence does not hold. This approach is widely used in the EF convergence literature. For example, Bilgili and Ulucak (2018) identified a single convergence club among the G20 countries, attributing it to similar initial environmental characteristics. In contrast, Haider and Akram (2019) identified two distinct clubs among 77 countries and demonstrated that countries with lower EF values experienced faster convergence. Ulucak and Apergis (2018) (EU countries), Bigerna et al. (2022) (108 countries), and Arogundade et al. (2024) (189 countries) each identified multiple convergence clubs, highlighting the presence of heterogeneity that hinders the implementation of common environmental policies and underscores the necessity of club-specific policy frameworks.

The club approach has also been applied in biocapacity (BIO) convergence studies. Alvarado et al. (2022) identified five convergence clubs among Latin American countries, revealing heterogeneous transition dynamics. Similarly, Gómez and Rodríguez (2024) found no single convergence club among the seven American countries when analysing environmental factors.

Much of the literature has focused on identifying the determinants of LCF to understand the reasons behind convergence dynamics. Renewable and non-renewable energy consumption, trade openness, urban population, human capital, institutional quality and technological progress are major influencing factors. Theoretical framework for how changes in the economy affect environmental indicators For instance, Omri et al. (2021) found a positive relationship between governance quality and LCF; Huilan et al. (2024) showed that trade openness enhances LCF; and Akadiri et al. (2022) experimented on financial globalisation effects on LCF. The effect of digitalisation on environmental management was studied by Ren et al. (2022), while the effect of tourism, real income and urbanisation on pollution was studied by Alola et al. (2021). Many studies, including those by Pata and Isik (2021), Pata (2021), and Pata et al. (2023), have studied the human capital, energy intensity and renewable energy for China, the US, Japan and Latin American countries from several angles. Akhayere et al. (2023), Ni et al. (2022), Güloglu et al. (2023), Kartal et al. (2023), Ullah et al. (2024), Xu et al. (2022), Pata & Kartal (2023), Sun et al. (2024) and Fang et al. (2024) examined the complex interplay between the consumption of renewables/fossil fuels and LCF using different econometric techniques. In addition to these factors, recent research highlights new variables. For instance, Adebayo et al. (2025) decoded the environmental role of nuclear energy in reducing GHGS emissions (thus indirectly improving LCF), while studies such as Adebayo (2025a), Olanrewaju et al. (2025), and Adebayo (2025b) emphasise the critical impact of climate policy uncertainty, economic policy uncertainty, and ESG sustainability uncertainty on sectoral emissions and energy markets.

These studies collectively demonstrate how EF (resource demand) and BIO (resource supply) interact with structural economic changes such as technological progress and deindustrialisation. Research on technological innovation and R&D demonstrates that improvements in energy efficiency and deindustrialisation reduce EF, thereby mitigating the ecological impact of economic growth and promoting convergence. Conversely, studies emphasising governance quality and land-use policies provide theoretical support for enhancing biocapacity (BIO) and strengthening the environmental resource base. This dual perspective provides an important foundation for understanding the policy mechanisms underlying the convergence and divergence processes.

The literature review thus reveals that LCF convergence studies remain limited, and existing approaches largely depend on the stationarity assumption. Traditional unit root tests offer only a binary (yes/no) and static answer to the convergence question, neglecting the dynamic aspects (acceleration or deceleration) of the convergence process.

The originality of this study lies in being the first to apply the Nahar-Inder (2002) polynomial-type convergence methodology to the LCF series, thereby overcoming the limitations of stationarity-based approaches. This method provides a more flexible analytical framework that does not impose the stationarity constraint for convergence inference. Furthermore, with the contribution of Bentzen and Tung (2021), the methodology incorporates second-derivative analysis to capture the evolving speed of convergence or divergence over time, offering a much richer empirical basis for policy interpretation. This framework allows for modelling the complex convergence dynamics that traditional unit root tests tend to overlook.

Data Set and Methodology

Data Set

For the purpose of this research, a convergence analysis will be performed utilising LCF data for the ten largest polluters in the world: Brazil, China, France, Germany, India, Indonesia, Japan, Mexico, South Korea and the United States. The choice of sampling in this study was based on the Global Footprint Network (GFN) data. The selected countries are those that have the highest Ecological Footprints (EF) in 2024. This variable was chosen because it is among the most used in the literature and is a good overall reflection of environmental degradation. According to a 2025 report by World Economics, the 10 most polluted countries share roughly 60% of global income. Similarly, the 2024 World Bank report also justifies that the top ten polluted nations, 2025, shared actually close to 60% of global income. The LCF series used in the analysis were constructed as the ratio of biocapacity to ecological footprint and were extracted from the Global Footprint Network (GFN). The dataset contains 64 yearly observations for each country between 1961 and 2024. The duration will allow for long-term convergence dynamics and possible structural changes. Table 1 includes the descriptive statistics for the relevant series.

Table 1
Descriptive Statistics

	Brazil	China	France	Germany	India
Mean	5.2593	0.5100	0.4809	0.2876	0.5019
Median	4.5456	0.4803	0.4865	0.2983	0.5000
Maximum	10.682	1.0909	0.5509	0.3899	0.7547
Minimum	3.0448	0.1961	0.3849	0.2034	0.2882
Std. Dev.	2.2453	0.2673	0.0395	0.0490	0.1441
Skewness	1.1396	0.6503	-0.6262	-0.1122	0.1182
Kurtosis	3.0686	2.4197	2.6898	2.0909	1.6931
Jarque-Bera	13.86672	5.40996	4.44028	2.33829	4.70343
Sum	336.6005	32.6460	30.7790	18.4086	32.1226
Sum Sq. Dev.	317.6116	4.50253	0.09870	0.15142	1.30927
Observations	64	64	64	64	64
	Indonesia	**Japan**	**Mexico**	**S. Korea**	**USA**
Mean	1.2850	0.1494	0.8023	0.3483	0.4713
Median	1.2402	0.1373	0.6770	0.1832	0.4631
Maximum	1.9504	0.2977	1.8341	1.3614	0.6486
Minimum	0.6451	0.1134	0.4046	0.1057	0.3723
Std. Dev.	0.4372	0.0440	0.4231	0.3395	0.0660
Skewness	0.2368	2.2306	1.1887	1.7041	1.1610

	Brazil	China	France	Germany	India
Kurtosis	1.6069	7.1760	3.1980	4.9021	4.2884
Jarque-Bera	5.77279	99.5799	15.1783	40.6249	18.8058
Sum	82.2444	9.56680	51.3513	22.2946	30.1682
Sum Sq. Dev.	12.0461	0.12198	11.2797	7.26559	0.27524
Observations	64	64	64	64	64

Descriptive statistics for the 64 annual observations for the 10 countries in question show significant variation throughout the series. According to the mean values, Germany has the lowest level (0.2876) and Brazil has the highest level (5.2593). Standard deviation values, which represent the volatility of the series, further highlight this divergence. The most volatile series in the sample is Brazil (2.2453), while the most stable ones are France (0.0395), Japan (0.0440), and Germany (0.0490).

After explaining the descriptive statistics of the series used in the analysis and the structure of the data set, examining the course of these series over time is crucial to better understand the convergence dynamics. For this purpose, the time series graph created using the logarithmic values of the series is presented in Figure 1.
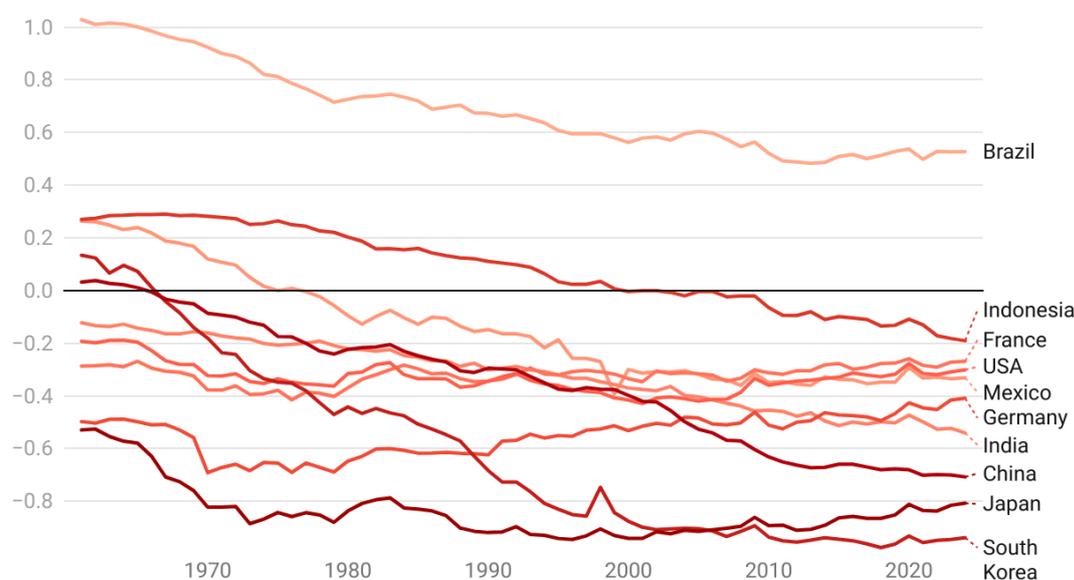
Figure 1

LCF Paths of Countries (1961-2022)

Figure 1 shows how the logarithmic LCF series for the ten countries being studied changed from 1961 to 2024. The most important thing to note about the figure is that Brazil has always had the highest level throughout the sample period. Another interesting trend is that the US, Germany, France, and Mexico have slowly come together to form a band that is easy to see, especially after the 1990s. In general, most countries show a downward trend over time, but at different speeds. This pattern also helps us understand how Biocapacity and Ecological Footprint, the two variables that make up the LCF, work together. The rapid rise in the Ecological Footprint values during the period in question is most likely what caused the downward trend.

Econometric Methodology

The convergence hypothesis, which is based on the growth theories of Solow (1956), Swan (1956), Cass (1965) and Koopmans (1965) and is the basic inference of the neoclassical growth theory, is defined as the

inverse proportion of the per capita growth rate of a country to the initial per capita income growth rate. The convergence hypothesis states that low-income countries, especially those with similar preferences and technology, tend to grow faster than high-income countries, and that low-income countries will converge to the income level of high-income countries. The main intuition here can be explained by the fact that capital in poor countries is relatively scarce and therefore its marginal product is high, while capital in rich countries is abundant and therefore its marginal product is low. With the increase in access to long-term macroeconomic series and the development of econometric techniques since the 1980s, the convergence hypothesis has found widespread use in the literature.

Bernard and Durlauf (1996), define the convergence hypothesis in the context of time series analysis, as shown in equation (1).

$$\lim_{k \to \infty} E\left(y_{i,t+k} - y_{j,t+k} \mid\right) I_t) = 0 \tag{1}$$

In equation (1), $y_{i,t}$ and $y_{j,t}$ represent the per capita income of countries i and j, and the term I_t represents the entire information set accessible at time t. According to equation (1), as the estimation horizon approaches infinity, the per capita income differences between countries approach zero over time. This situation shows the validity of the convergence hypothesis. However, when the number of countries subject to analysis is more than two, equation (1) cannot be used. In this case, convergence analyses are based on deviations from the leading country or the sample mean subject to the sample. The convergence behaviour of a country towards the sample mean or leader is shown in equation (2).

$$Lim_{k \to \infty} E\left(y_{i,t+k} - \overline{y_t}\right) = 0 \tag{2}$$

The term $\overline{y_t}$ in equation (2) represents the sample mean or the leading country. According to Bernard and Durlauf (1996), the convergence hypothesis is tested by applying the unit root test to the series obtained by deriving equation (2).

The main purpose of this study is to analyse the convergence hypothesis using unit root tests and the Nahar-Inder test. In this direction, to determine the structure of the series in the most accurate way and to increase the reliability of the analysis results, traditional unit root tests (ADF, PP), structural break unit root test (Zivot-Andrews), nonlinear unit root tests (KSS, Sollis, Kruse, Cuestas-Ordoñez) and Nahar-Inder test are used. The methodological basis and test procedures of these tests are explained below.

The ADF unit root test, developed by Dickey and Fuller (1979, 1981), analyzes the presence of a unit root in an autoregressive process. The test performs the unit root test by including the lagged difference values of the variable into the equation to eliminate the presence of autocorrelation in the error terms. The estimated equation of the ADF test is as follows:

$$\Delta y_t = a_0 + a_1 t + \delta y_{t-1} + \sum_{i=1}^{p} \beta_i \Delta y_{t-i} + \varepsilon_t \tag{3}$$

In equation (3), Δ represents the difference operator, y_t represents the LCF series of the relevant country, which is taken from the leader, t represents the trend and p represents the appropriate lag length. In this direction, the null hypothesis of the test is tested as $H_0 : \delta = 0$ (unit root exists, the series is not stationary) and the alternative hypothesis is tested as $H_1 : \delta < 0$ (the series is stationary).

The PP test, developed by Phillips and Perron (1988) as an alternative to the ADF test, corrects the heteroscedasticity and autocorrelation problems in the error terms with a nonparametric method. Instead of the lag length addition application in the ADF, the PP test recalculates the t-statistic obtained from the Dickey-Fuller regression with the Newey-West correction. In this case, where the hypotheses have the same $H_0 : \delta = 0$) with the ADF test, the basic regression equation is stated in (4).

$$\Delta y_t = a_0 + a_1 t + \delta y_{t-1} + \varepsilon_t \tag{4}$$

The PP test tests the existence of a unit root in a way that is less sensitive to the choice of lag length by correcting the t-statistics of the δ coefficient in equation (4).

Since traditional unit root tests such as ADF and PP may be misleading under the presence of structural breaks that may occur due to internal and external structural shocks in the economy, Zivot and Andrews (1992) developed a test procedure that allows the existence of a single structural break in the series, the time of which is not known in advance, to control this possibility. Accordingly, the Z-A structural break unit root test tests the existence of a unit root by estimating the following equation:

$$\Delta y_t = \mu + \beta t + \theta DU_t(\lambda) + \gamma DT_t(\lambda) + a y_{t-1} + \sum_{i=1}^{k} c_i \Delta y_{t-i} + \varepsilon_t \tag{5}$$

DU in Equation (5) is a dummy variable representing the break in the level and DT in the slope, and they are defined as stated in (6).

$$DU_t(\lambda) = \begin{cases} 1 & t > T_B \\ 0 & t \le T_B \end{cases} \quad and \quad DT_t(\lambda) \begin{cases} t - T\lambda & t > T_B \\ 0 & t \le T_B \end{cases} \tag{6}$$

Here T_B represents the break time and $\lambda = T_B/T$ represents the break rate. $DU_t(\lambda)$ represents the dummy variable for the level break and takes the value of 1 if $t > T_B$ and 0 if $t \le T_B$. $DT_t(\lambda)$ is the dummy variable for the trend break and takes the value of $t - T\lambda$ if $t > T_B$i otherwise 0. Accordingly, the Z-A test selects the λ value showing the smallest t-statistic as the break point and tests the unit root status.

Macroeconomic time series may be asymmetric or nonlinear in nature due to changes in the economy or their structure. In this case, modern tests have been developed to test such dynamics. One of the important tests that is frequently used in the literature and tests stationarity in nonlinear series is the KSS (2003) unit root test. The test developed by Kapetanios et al. (2003) tests stationarity in nonlinear structures based on the exponential smooth transition autoregressive (ESTAR) model. The basic model of the KSS unit root test is specified in (7).

$$\Delta y_t = \gamma y_{t-1} \left[1 - \exp(-\theta y_{t-d}^2) \right] + \varepsilon_t \tag{7}$$

However, because the parameter θ cannot be tested directly in equation (7), the following auxiliary regression is created with the first-order Taylor approximation.

$$\Delta y_t = \delta y_{t-1}^3 + \Sigma_{j=1}^{p} p_j \Delta y_{t-j} + \eta_t (8) \tag{8}$$

KSS (2003) tests the null hypothesis $H_0 : \delta = 0$ and the alternative hypothesis $H_1 : \delta < 0$ through equation (8). If the calculated test statistic is smaller than the critical value, the null hypothesis is rejected and it is concluded that the series has a nonlinear structure. Another approach among nonlinear unit root tests is the method developed by Sollis (2009), which tests stationarity against asymmetric exponential smooth transition autoregressive (AESTAR) processes. The Sollis (2009) test considers asymmetric adjustment mechanisms by improving the KSS (2003) test. In this direction, Sollis (2009) proposed the auxiliary regression model specified in (9).

$$\Delta y_t = \delta_1 y_{t-1}^3 + \delta_2 y_{t-1}^4 + \Sigma_{j=1}^{\rho} c_j \Delta y_{t-j} + \varepsilon_t \tag{9}$$

The term y_{t-1}^3 in equation (9) is used to capture symmetric nonlinear effects, while the term y_{t-1}^4 is used to capture asymmetric effects, while the term $\sum_{j=1}^{\rho} c_j \Delta y_{t-j}$ is included in the model to control autocorrelation. In this context, the null hypothesis of the Sollis (2009) test, $H_0 : \delta_1 = \delta_2 = 0$, indicates that the series is nonlinear and nonstationary, while the alternative hypothesis $H_A : \delta_1 \ne \delta_2 \ne 0$ indicates that the series is nonlinear and stationary in an asymmetric structure. Another test frequently used in the literature among

nonlinear unit root tests is the Kruse (2011) test. The Kruse (2011) test was developed by taking into account the cases where the location parameter may be different from zero in the KSS (2003) test, and the suggested regression equation is (10).

$$\Delta y_t = \delta_1 y_{t-1}^3 + \delta_2 y_{t-1}^2 + \sum_{j=1}^{\rho} \phi_j \Delta y_{t-j} + \varepsilon_t \tag{10}$$

In equation (10), unlike KSS (2003), the addition of the term y_{t-1}^2 to the model includes the non-zero case of the location parameter in the model. Thus, the Kruse (2011) test tests the null hypothesis of a unit root ($H_0 : \delta_1 = \delta_2 = 0$) against the stationary ESTAR process alternative ($H_A : \delta_1 < 0, \delta_2 \neq 0$). The nonlinear unit root test developed by Cuestas and Ordóñez (2014) considers deterministic trends and asymmetric adjustments. The test performs the stationarity test by focusing on different speeds of return to the mean or trend and structural changes. The model specification of the test is given in (11).

$$y_t = g(t) + \varepsilon_t \tag{11}$$

The term $g(t)$ in Equation (11) is a non-constant function of time and $g(t)$ is modelled as $g(t) = g_1 + g_2 t + g_3 L_t(\gamma) + g_4 t L_t(\gamma)$. Here $L_t(\gamma)$ is the logistic exponential smooth transition function and is defined as $L_t(\gamma) = \frac{1}{(1+e^{-\gamma t})\gamma}$ and $\gamma > 0$. In this case, the Cuestas and Ordóñez (2014) test is the null hypothesis $H_0 : \delta = 0$ alternative hypothesis $H_A : \delta < 0$. The null hypothesis (H_0) is expressed as the series having a unit root, while the alternative hypothesis (H_A) means that the series is stationary under smooth transition breaks with a non-linear process around a deterministic component. The unit root tests with the given methodology have constructed the convergence hypothesis on the stationarity condition in the series whose difference is taken from the mean or the leading country. From here, the convergence hypothesis is examined under the constraint of the statistical properties of the obtained series. This situation provides a narrow field of action in terms of revealing the convergence dynamics in the examined sample.

The convergence test proposed by Nahar and Inder (2002) is a method used to analyse economic convergence processes by considering time series data. This method stands out especially for allowing the examination of processes that are not stationary but still show convergence behaviour. In addition, the Nahar-Inder (2002) test is based on less restrictive assumptions compared to traditional unit root tests because it was developed only for the examination of convergence processes. The basic logic of the Nahar-Inder (2002) test is to measure whether a country with a lower LCF value approaches the level of the country with a higher LCF value, which is determined as the "leader." In this context, the leading country in the study was Brazil, which had the highest LCF value throughout the study period. The Nahar-Inder (2002) test starts by first considering the logarithmic difference $(w_{i,t})$ of the LCF series between a country i and the leading country La.

$$w_{i,t} = logLCF_{i,t} - logLCF_{L,t} \tag{12}$$

According to Equation (12), if country i converges to the leader country L over time, this difference $(w_{i,t})$, which is initially negative, will approach zero over time. This means that $(w_{i,t})$ is an increasing function over time. The Nahar-Inder (2002) test indicates that this LCF difference series $(w_{i,t})$ can be modelled as a time-dependent polynomial function.

$$w_{it} = \theta_0 + \theta_1 t + \theta_2 t^2 + ... + \theta_{k-1} t^{k-1} + \theta_k t^k + \varepsilon_{i,t} \tag{13}$$

In equation (13), t represents time, k represents the degree of the polynomial and θ represents the coefficients. The realisation of a convergence process depends on the slope of this function being positive and statistically significant. In this direction, the average slope function of $(w_{i,t})$ can be calculated using equation (14) after estimating the parameters in equation (12).

$$\frac{1}{T}\Sigma_{t=1}^{T}\frac{\partial}{\partial t}w_{i,t} = \theta_1 + \theta_2 r_2 + ... + \theta_k r_k r_k = \frac{k}{T}\Sigma_{t=1}^{T}t^{k-1} \tag{14}$$

The last step of the testing procedure is to test the null hypothesis $(H_0 : \theta r' \le 0)$ which states that there is no convergence behaviour. The test is generally applied by following these steps. First, equation (13) is used to estimate the θ parameters, and the AIC information criterion determines the appropriate polynomial degree k. Then, the r vector is calculated for the determined k value as specified in equation (14). Finally, a t-test was performed regarding the θ restrictions specified in the null hypothesis. The rejection of the null hypothesis is interpreted in favour of convergence because the slope function takes a statistically significant positive value and shows that the LCF difference between country i and the leader country L has decreased.

Bentzen and Tung (2021) contributed to the Nahar-Inder (2002) test by stating that if the second-order derivative of equation (13) is taken and this value is positive, the convergence process is strong in the second part of the time interval, and if the slope is negative, the convergence is more pronounced at the beginning of the period. In this direction, Bentzen and Tung (2021) calculated the test statistic as (15) to include the second-order derivative in the Nahar-Inder (2002) methodology.

$$\frac{1}{T}\Sigma_{t=1}^{T}\frac{\partial^2}{\partial t^2}w_{it} = \theta_2 s_2 + \theta_3 s_3 + ... + \theta_k s_k s_k = \frac{k(k-1)}{T}\Sigma_{t=1}^{T}t^{k-2} \tag{15}$$

Accordingly, the hypotheses of the test are $H_1 : \theta s' \le 0$ and $H_2 : \theta s' \ge 0$a. Rejecting the H_1 hypothesis indicates that the test statistic has a positive value and the convergence accelerates in the last part of the period with the increasing value of the slope function. Similarly, rejecting the H_2 hypothesis indicates that the convergence occurs at the beginning of the period with the decreasing value of the slope function. Thanks to this analysis, it is possible to see how the convergence dynamics of the countries in the selected sample behave throughout the sample period. Thus, it becomes possible to analyse the effects of the shocks that occur during the sample period on the convergence process.

Findings and Discussion

In this section, the empirical results of the econometric techniques explained in the methodology section of the study are presented. In the first stage of the analysis, the stationarity properties of the LCF series of the world's most polluting countries, China, USA, India, Japan, Indonesia, Germany, Mexico, France and South Korea, were examined by taking the difference from the leader (Brazil). In this context, in addition to the traditional unit root tests ADF and PP, the Zivot-Andrews (Z-A) tests, which are sensitive to structural breaks, and the KSS (2003), Sollis (2009), Kruse (2011) and Cuestas-Ordóñez (2014) tests, which are frequently used in the literature in nonlinear structures and take into account the soft structural breaks in the series, were used to analyse whether the series exhibited convergence behaviour. Following the unit root tests, the Nahar-Inder (2002) test, which stands out both for showing intra-sample mobility and allowing the examination of processes that are non-stationary but still show convergence behaviour, was applied to test the convergence hypothesis between countries. Later, the method examining the time periods of convergence proposed by Bentzen and Tung (2021) was applied. Brazil was selected as the leading country because it had the highest LCF value while creating the series used in the convergence analysis. The obtained test results are summarised in Table 2.

Table 2

Unit Root Test Results

	ADF	PP	Z-A	KSS	Sollis	Kruse	Cuestas-Ordóñez
China	−1.4908	−1.4703	−4.9134* [2004]	−1.6033	1.4204	3.6319	−2.3740
USA	−3.2189*	−2.4534	−4.1598 [1992]	−2.0256	0.8170	4.5755	−2.0259
India	−1.2061	−1.0241	3.6912 [1976]	−1.1428	3.9071	1.8128	−3.9805***
Japan	−2.7811	−2.8660	−4.8979* [1988]	−3.4929***	4.5084	12.2954*	−2.7961
Indonesia	−1.5333	−1.4722	−3.2134 [1974]	−1.1428	4.9266	2.7663	−1.8652
Germany	−2.4555	−2.5150	−3.5214 [1991]	−2.4428	8.3270**	5.8719	−2.4364
Mexico	−3.7650**	−3.7873**	−5.1505** [1999]	−4.7072***	4.6475	24.5696***	−4.8477***
France	−1.2594	−1.4718	−4.0033 [1993]	−1.8155	8.7290***	3.3639	−2.5547
South Korea	−1.3832	−1.2622	−3.8469 [1990]	−1.8926	6.8402**	3.7999	−2.6398

Note: In the unit root tests, the optimal lag lengths were determined based on the Akaike Information Criterion (AIC). In the Zivot–Andrews (Z-A) test, the break dates shown in parentheses (e.g., [2004]) are automatically selected from the series in accordance with the test's methodological procedure.

Within the framework of the unit root test results summarised in Table 2, it is possible to obtain insights into whether the LCF series of the most polluting countries analysed exhibit convergence behaviour over time relative to the values of the leading country. When the differential series between each country and the leader is stationary, convergence is considered valid; however, the presence of a unit root in the differential series indicates divergence. The findings obtained in this context point to a heterogeneous convergence pattern within the analysed group of countries.

Mexico exhibits the most consistent evidence of convergence, as nearly all traditional (ADF, PP), structural break (Z-A), and nonlinear (KSS, Kruse, Cuestas-Ordóñez) tests, except for the Sollis test, support the convergence hypothesis. In contrast, the results for other countries are more mixed. For instance, in Japan, the traditional unit root tests and the Sollis test indicate divergence, whereas the Z-A test (with a 1988 break) and the nonlinear KSS and Kruse tests provide evidence in favour of convergence. The results indicate that the convergence process in Japan follows a nonlinear pattern or is subject to a structural break.

The convergence evidence for the remaining countries is weaker and more sensitive to the testing methodology. Specifically, the ADF test alone supports convergence for the United States; the Z-A test (with a 2004 break) does so for China; the Cuestas-Ordóñez test, which allows for smooth structural shifts, supports convergence for India; and the Sollis test alone indicates convergence for Germany, France, and South Korea, while all other tests point to divergence for these countries. For Indonesia, all tests consistently indicate divergence.

The consistent convergence behaviour observed in Mexico and the conditional convergence detected in Japan, particularly in the nonlinear tests, suggest that technological advancements and investment incentive mechanisms that promote low-carbon emissions have been relatively internalised in these countries. Conversely, the widespread divergence (or weak, test-specific convergence) observed in other countries indicates that environmental quality has not progressed at the same pace as in the leading country. In this context, it appears that imbalances have emerged between economic growth dynamics and carbon reduction policies, and that structural challenges related to environmental sustainability have yet to be fully addressed. Consequently, in countries demonstrating strong and consistent convergence with the leader

(such as Mexico), it can be argued that environmental quality strategies are more resilient to shocks and that sustainable environmental transformation has begun to institutionalise.

These results also show that traditional unit root tests can give wrong results in convergence analyses and that outcomes can change significantly when structural breaks and nonlinear dynamics are considered. The diverse structure seen in the results underscores the necessity for more adaptable methodologies, such as the Nahar–Inder test, that do not enforce rigid stationarity assumptions.

As mentioned before, unlike the studies summarised above, the main contribution of the study is the results obtained from the Nahar-Inder (2002) technique applied to relax the stationarity constraint of the convergence dynamics and to determine in which period of the sample period the convergence process is strong.

In summary, the unit root test results yielded different results for the countries examined due to their different structures, which prevented a definitive judgement. This result highlights the complexity of convergence dynamics and reveals the importance of using more flexible methodologies such as Nahar-Inder, which are used only in convergence analyses and which state that the convergence hypothesis may be valid even in non-stationary structures. For this reason, to deepen the findings provided by the unit root tests and to analyse the dynamics of the convergence processes in a more flexible framework, a polynomial-type convergence test based on the time series methodology developed by Nahar and Inder (2002) was applied. The test measures the convergence or divergence path of countries with the "average slope" coefficient. A positive and significant slope coefficient indicates convergence, while a negative and significant coefficient indicates divergence. The results obtained are summarised in Table 3.

Table 3

Nahar-Inder Test Results

Leader: Brazil	Average slope *(k; t-stat)*;	Second order, mean *(t-stat)*;
China	−0,008299*** (k=4, *-5.4002*)	0,000461** (*1.9758*)
USA	0,001657*** (k = 3; *69.7967*)	−0,00006*** (*-3.1369*)
India	0,00463** (k = 3; *2.5078*)	−0,0007*** (*-12.4336*)
Japan	0,0107*** (k = 4; *5.7774*)	0,000129*** (*6.6708*)
Indonesia	0,007926*** (k = 6; *4.6285*)	−0,00012*** (*-3.9250*)
Germany	0,002029*** (k = 4; *11.7676*)	0,0007014*** (*2.8413*)
Mexico	−0,002220*** (k=3; *-2.8090*)	0,000269*** (*4.1521*)
France	0,001929*** (k = 3; *16.5266*)	−0,00047*** (*-8.5422*)
South Korea	0,06087*** (k = 3; *27.6743*)	0,000929*** (*15.7384*)

The analysis was further expanded using the Nahar-Inder (2002) methodology in response to the unit root tests' heterogeneous and methodologically sensitive results. This test offers a more adaptable analytical framework by removing the convergence analysis from the rigidity of the stationarity constraint. Comparing the results of the unit root tests to the findings compiled in Table 3, which covers the years 1961–2024, provides a significantly different and more lucid viewpoint.

For the United States, India, Japan, Indonesia, Germany, France, and South Korea, the average slope coefficients were found to be positive and statistically significant. This finding indicates that these seven countries are on a strong convergence path towards the leading country, Brazil.

The significance of these results becomes even more evident when compared with the findings in Table 2. For instance, several large economies, including the United States, Indonesia, Germany, and France, which

exhibited divergence (unit root behaviour) in nearly all traditional unit root tests, actually display convergence towards the leader country according to the Nahar-Inder test.

The most striking contrast emerges in the case of Mexico. While Mexico displayed the strongest and most consistent convergence pattern across nearly all traditional, structural-break, and nonlinear tests in Table 2, the Nahar-Inder test revealed that the country diverged from Brazil, with a negative and statistically significant coefficient. Similarly, China, which exhibited divergence in all tests except the Z-A test, continues to show divergence under this methodology. These sharp discrepancies clearly illustrate the limitations of stationarity-based tests and underscore the distinctive contribution of the polynomial-type convergence methodology employed in this study.

Additionally, the second-derivative analysis put forth by Bentzen and Tung (2021) elucidates the dynamics of these convergence and divergence processes. The positive and statistically significant second-order coefficients for Japan, Germany, and South Korea indicate that these countries are converging at a faster rate than they were at the beginning of the sample period. Conversely, the negative coefficients for the United States, India, Indonesia, and France indicate that convergence was faster in the past but has slowed down over time. For China and Mexico, which are diverging countries, the positive second-order coefficients mean that their negative divergence slopes have become less steep over time. This means that the speed of divergence has slowly slowed down.

In conclusion, the Nahar–Inder (2002) test transcends the static yes/no framework of conventional unit root testing by modelling convergence as a dynamic process. When complemented by the contribution of Bentzen and Tung (2021), it not only identifies the direction of convergence but also captures its changing speed over time, thereby providing a richer foundation for policy interpretation and empirical inference.

Conclusion and recommendations

The main purpose of this study is to examine whether the LCF values in the 10 most polluting countries show convergence behaviour towards the sample leader Bazil. For this purpose, the study used LCF data for the period 1961-2024, using both traditional (linear and structural break) and innovative (non-linear) unit root tests and the Nahar-Inder methodology based on the time series technique that allows convergence inference even in the presence of unit roots in the series. Because of the unit root examination, convergence inference was made for a limited number of countries in the sample. According to various unit root test results, convergence has generally been found to be valid in Japan and Mexico. The study identified Brazil as the leading country in the LCF. In addition to Brazil's leadership in the LCF, its integration of low-carbon electricity, such as biofuels, and biofuel in transportation is considered significant. An examination of the countries where convergence has been achieved reveals that Japan's implementation of sectoral energy efficiency standards has been effective. Japan's significant R&D activities in both battery and hybrid vehicle technologies, along with its long-term plans for climate policy, have led to a trend towards a steady reduction in carbon intensity. Therefore, the trend towards convergence with a leading country supports these developments. Mexico was the first developing country to legally adopt a carbon reduction policy document. Mexico has recently been significantly increasing its renewable energy investments to reduce its dependence on non-renewable energy. Mexico, a country that stands out as a country that utilises low-carbon mechanisms in international trade, tends to converge towards the leader country according to unit root tests with various strength characteristics. In countries where unit root tests generally reveal divergence, policy heterogeneity is noteworthy. In this context, despite periodic declines in carbon emissions in the US, increasing policy instability and uncertainty at the federal level are known. In the US, fossil fuel subsidies and presidential changes, coupled with diverging policies, contribute to this conclusion. Meanwhile, the economies of China, India, and Indonesia are characterised by high economic growth rates

and increasing energy demand in response to increased production. As a result, environmental pollution is increasing due to the continued high levels of non-renewable energy consumption in these countries. The decline in convergence with the leading country accounts for this outcome. Developed countries such as Germany and France have energy transition policies aimed at reducing carbon emissions. However, high industrial density, concerns about energy supply security, and uncertainties in energy policies (especially nuclear energy) prevent environmental pollution from reaching the desired levels. These developments could lead to divergence from the leading country. Studies supporting and contradicting these findings are limited. For example, Sinha and Schneider (2024) reached a conclusion in favour of convergence in their study examining the stationarity properties of the LCF series for the US and stated that the LCF series for the US has a negative slope and exhibits a trend-returning behaviour in the long run. On the other hand, Pata and Yilanci (2021) applied new generation unit root tests in their study investigating the sustainability of the ecological balance in G10 and N11 countries and concluded that the persistence effect of shocks in G10 countries is stronger than in N11 countries. Şimşek et al. (2025), who investigated the convergence hypothesis of ecological balance through similar panel data techniques, concluded that convergence has occurred. Finally, Yilanci and Pata (2020), in their study, examined the ecological footprint convergence using the non-linear panel unit root technique for the ASEAN-5 countries and found that the ecological footprint convergence dynamics in the ASEAN-5 countries were more pronounced in the second regime of the sample period. They also emphasised that the transition process dynamics continued for Vietnam. The findings obtained from the unit root tests applied to the sample considered in this study are similar to the sample studies presented above.

According to the unit root test results obtained in the study, some countries (especially the US, France, and Germany) are significantly investing in renewable energy and working towards sustainable development goals. The fact that these countries are among the most developed and have taken significant steps towards a sustainable environment can call into question the unit root results. The lack of a consensus in the literature has led to the need for a different testing methodology. In this context, this study utilises the Nahar-Inder technique, which allows for the examination of non-stationary yet converging processes. Examining the results obtained using the Nahar-Inder technique, also known as polynomial-type convergence analysis, reveals divergence for China and Mexico, while convergence is found for the US, France, Indonesia, India, South Korea, Japan, and Germany. The convergence of environmental quality indicators among countries is important in terms of achieving climate change, global warming and sustainable development goals. In addition, convergence inference in terms of environmental quality indicators is necessary for the adoption of common environmental policies among countries and the implementation of these policies. Since LCF is defined as the ratio of the biological capacity to the ecological footprint, it is the basic indicator of environmental sustainability. As an indicator that simultaneously expresses the supply and demand sides of environmental quality, LCF has recently been the focus of researchers. While an LCF value greater than 1 in countries indicates the existence of environmental sustainability (excess), a value less than 1 means that there is no environmental sustainability (deficit). Studies in the literature show that factors such as renewable energy consumption, non-renewable energy consumption, trade openness, urbanisation, human capital, public governance and technological developments are among the determinants of LCF. Therefore, the findings of the analyses in favour of convergence mean that common policies regarding the above-mentioned factors can be adopted in the relevant countries. Most of these policies may be of a nature that reduces the ecological footprint and increases the biological capacity. In countries where convergence is observed, the LCF dynamics align toward a common steady-state equilibrium. This inference shows that common environmental policies can be implemented in countries where the convergence hypothesis is valid in terms of LCF. However, while implementing these policies, it should not be forgotten that the natural

resource reserves, human capital stock, technological characteristics and geographical conditions of the countries may be different.

As a result, this study uses the Nahar-Inder technique for the first time in the environmental sustainability literature and shows how the convergence process follows a path over time with a second derivative analysis. Thus, it provides an opportunity to understand the effects of developments experienced during the sample period, such as wars, crises or technological developments, on convergence dynamics. Therefore, it contributes to the environmental sustainability literature. In addition, it contributes to the increase in environmental awareness at the international level by simultaneously considering the demand and supply sides of environmental sustainability. The basic policy recommendations of the study are that countries should implement carbon taxes to reduce their ecological footprints, governments should apply regulations that increase environmental quality, encourage the provision of energy required for economic activities from environmentally friendly sources and support R&D activities to be carried out in this regard.

It is recommended that future studies should be conducted to reveal the convergence pattern of LCF dynamics for different country samples and even expand the environmental sustainability literature by delving into the sub-components of ecological footprint and biocapacity.

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References

Ahmed, A., Uddin, G. S. and Sohag, K. (2016). Biomass energy, technological progress and the environmental Kuznets curve: Evidence from selected European countries. *Biomass and Bioenergy, 90*, 202-208. https://doi.org/10.1016/j.biombioe.2016.04.004.

Adebayo, T. S. (2025a). Response of sectoral CO_2 emissions to climate and economic policy uncertainties: a multi-frequency quantile analysis. *Applied Economics*, 1–20. https://doi.org/10.1080/00036846.2025.2490857.

Adebayo, T. S. (2025b). How do the energy and precious metals markets respond to climate policy uncertainty? A multi-frequency quantile framework. *Applied Economics Letters*, 1–7. doi:10.1080/13504851.2025.2548962.

Adebayo, T. S., Ozsahin, D. U., Olanrewaju, V. O., & Uzun, B. (2025). Decoding the environmental role of nuclear and renewable energy consumption: A time-frequency perspective. *Annals of Nuclear Energy*, 111660. https://doi.org/10.1016/j.anucene.2025.111660.

Akadiri, S. S., Adebayo, T. S., Riti, J. S., Awosusi, A. A., & Inusa, E. M. (2022). The effect of financial globalisation and natural resource rent on load capacity factor in India: an analysis using the dual adjustment approach. *Environ Sci Pollut Res*, 29(59), 89045-89062. https://doi.org/10.1007/s11356-022-22012-0.

Akhayere, E., Kartal, M. T., Adebayo, T. S., & Kavaz, D. (2023). Role of energy consumption and trade openness towards environmental sustainability in Turkey. *Environmental Science and Pollution Research*, 30(8), 21156-21168. https://doi.org/10.1007/s11356-022-23639-9.

Alola, A. A., Lasisi, T. T., Eluwole, K. K., & Alola, U. V. (2021). Pollutant emission effect of tourism, real income, energy utilisation, and urbanisation in OECD countries: a panel quantile approach. *Environ Sci Pollut Res*, 28, 1752-1761. https://doi.org/10.1007/s11356-020-10556-y.

Alvarado, R., Tillaguango, B., Cuesta, L. *et al.* Biocapacity convergence clubs in Latin America: an analysis of their determining factors using quantile regressions. *Environ Sci Pollut Res, 29*, 66605–66621 (2022). https://doi.org/10.1007/s11356-022-20567-6.

Arogundade, S., Hassan, A., Akpa, E. (2024). Closer together or farther apart: Are there club convergences in the ecological footprint? *Environmental Science and Pollution Research*, 30, 15293–15310. DOI: 10.1007/s11356-022-23203-5.

Baloch, M. A., Mahmood, N., & Zhang, J. W. (2019). Effect of natural resources, renewable energy and economic development on CO2 emissions in BRICS countries. *Science of the total environment*, 678, 632-638. https://doi.org/10.1016/j.scitotenv.2019.05.028.

Bastianoni, S., Coscieme, L., Caro, D., Marchettini, N., & Pulselli, F. M. (2019). The needs of sustainability: The overarching contribution of systems approach. *Ecological Indicators*, 100, 69-73. https://doi.org/10.1016/j.ecolind.2018.08.024.

Bentzen, J., & Tung, L. T. (2021). Regional income convergence in an emerging Asian economy: empirical evidence from Vietnam. *Post-Communist Economies*, 33(1), 64-78. doi:10.1080/14631377.2020.1722587.

Bernard, A. B. and Durlauf, S. N. (1996). Interpreting the tests of the convergence hypothesis. *Journal of econometrics, 71*(1-2), 161-173. doi:10.1016/03044076(94)01699-2.

Bigerna, S., Bollino, C. A., & Polinori, P. (2022). Convergence of ecological footprint and sustainable policy options. *Journal of Policy Modelling*, 44(3), 564-577. https://doi.org/10.1016/j.jpolmod.2022.07.001.

Bilgili, F. and Ulucak, R. (2018). Is there deterministic, stochastic, and/or club convergence in ecological footprint indicator among G20 countries? Environmental *Science and Pollution Research*, 25(35), 35404-35419. https://doi.org/10.1007/s11356-018-3457-1.

Borucke, M., Moore, D., Cranston, G., Gracey, K., Iha, K., Larson, J. Galli, A. (2013). Accounting for demand and supply of the biosphere's regenerative capacity: The National Footprint Accounts' underlying methodology and framework. *Ecological indicators*, 24, 518-533. https://doi.org/10.1016/j.ecolind.2012.08.005.

Cass, D. (1965). Optimum growth in an aggregative model of capital accumulation. *The Review of Economic Studies*, 32(3), 233-240. https://doi.org/10.2307/2295827.

Cuestas, J. C., & Ordóñez, J. (2014). Smooth transitions, asymmetric adjustment and unit roots. *Applied Economics Letters*, 21(14), 969-972. https://doi.org/10.1080/13504851.2014.902016.

Dickey, D. A., & Fuller, W. A. (1979). Distribution of the estimators for autoregressive time series with a unit root. *Journal of the American statistical association*, 74(366a), 427-431. doi:10.1080/01621459.1979.10482531.

Dickey, D. A., & Fuller, W. A. (1981). Likelihood ratio statistics for autoregressive time series with a unit root. *Econometrica: Journal of the Econometric Society*, 1057-1072. https://doi.org/10.2307/1912517.

Fang, Z., Wang, T., & Yang, C. (2024). Nexus among natural resources, environmental sustainability, and political risk: Testing the load capacity factor curve hypothesis. *Resour Policy*, 90, 104791. https://doi.org/10.1016/j.resourpol.2024.104791.

Gabbi, G., Matthias, M., Patrizi, N., Pulselli, F. M., & Bastianoni, S. (2021). The biocapacity adjusted economic growth. Developing a new indicator. *Ecological Indicators*, 122, 107318. doi:10.1016/j.ecolind.2020.107318.

Goldfinger S, Wackernagel M, Galli A, Lazarus E, Lin D (2014) Footprint facts and fallacies: A response to Giampietro and Saltelli (2014) "Footprints to Nowhere." *Ecological Indicators, 46*, 622–632. doi:10.1016/j.ecolind.2014.04.025.

Gómez, M., & Rodríguez, J. C. (2024). Analysis of the convergence of environmental sustainability and its main determinants: The case of the Americas (1990–2022). *Sustainability*, 16(16), 6819. https://doi.org/10.3390/su16166819.

Guloglu, B., Caglar, A. E., & Pata, U. K. (2023). Analysing the determinants of the load capacity factor in OECD countries: evidence from advanced quantile panel data methods. *Gondwana Research*, 118, 92-104. doi:10.1016/j.gr.2023.02.013.

Haider, S., & Akram, V. (2019). Club convergence analysis of ecological and carbon footprint: evidence from a cross-country analysis. *Carbon Management*, 10(5), 451-463. https://doi.org/10.1080/17583004.2019.1640135.

Huilan, W., Akadiri, S. S., Haouas, I., Awosusi, A. A., & Odu, A. T. (2024). Impact of trade liberalisation and renewable energy on load capacity factor: Evidence from novel dual adjustment approach. *Energy & Environment*, 35(2), 795-814. https://doi.org/10.1177/0958305X221137559.

Ilesanmi, K. D. and Tewari, D. D. (2017). Energy consumption, human capital investment and economic growth in South Africa: a vector error correction model analysis. *OPEC Energy Review*, *41*(1), 55-70. https://doi.org/10.1111/opec.12094.

Kapetanios, G., Shin, Y. and Snell, A. (2003). Testing for a unit root in the nonlinear STAR framework. *Journal of econometrics*, *112*(2), 359-379. doi:10.1016/S0304-4076(02)00202-6.

Kartal, M. T., Samour, A., Adebayo, T. S., & Depren, S. K. (2023). Do nuclear energy and renewable energy surge environmental quality in the United States? New insights from novel bootstrap Fourier Granger causality in quantiles approach. *Prog Nucl Energy*, *155*, 104509. https://doi.org/10.1016/j.pnucene.2022.104509.

Koopmans, T. C. (1965) On the concept of optimal economic growth. In: Study week on the econometric approach to development planning. North-Holland, Amsterdam, pp 225–300.

Kruse, R. (2011). A new unit root test against ESTAR based on a class of modified statistics. *Statistical Papers*, *52*, 71-85. doi:10.1007/s00362-009-0204-1.

Mancini, M. S., Galli, A., Coscieme, L., Niccolucci, V., Lin, D., Pulselli, F. M., ... Marchettini, N. (2018). Exploring ecosystem services assessment through Ecological Footprint accounting. *Ecosystem Services*, *30*, 228-235. https://doi.org/10.1016/j.ecoser.2018.01.010.

Nahar, S. and Inder, B. (2002). Testing convergence in economic growth for OECD countries. *Applied Economics*, *34*(16), 2011-2022. doi:10.1080/00036840110117837.

Ni, Z., Yang, J., & Razzaq, A. (2022). How do natural resources, digitalisation, and institutional governance contribute to ecological sustainability through load capacity factors in highly resource-consuming economies?. *Resour Policy*, *79*, 103068. https://doi.org/10.1016/j.resourpol.2022.103068.

Olanrewaju, V. O., Adebayo, T. S., & Uzun, B. (2025). Navigating the impact of ESG sustainability uncertainty on fossil fuel prices: evidence from wavelet cross-quantile regression. *Applied Economics*, 1–17. https://doi.org/10.1080/00036846.2025.2535552.

Omri, A., Kahia, M., & Kahouli, B. (2021). Does good governance moderate the financial development-CO 2 emissions relationship?. *Environmental Science and Pollution Research*, *28*, 47503-47516. https://doi.org/10.1007/s11356-021-14014-1.

Pata, U. K. (2021). Do renewable energy and health expenditures improve the load capacity factor in the USA and Japan? A new approach to environmental issues. *The European Journal of Health Economics*, *22*(9), https://doi.org/10.1007/s10198-021-01321-0.

Pata, U. K., & Isik, C. (2021). Determinants of the load capacity factor in China: a novel dynamic ARDL approach for ecological footprint accounting. *Resour Policy*, *74*, 102313. https://doi.org/10.1016/j.resourpol.2021.102313.

Pata, U. K., & Kartal, M. T. (2023). Impact of nuclear and renewable energy sources on environment quality: Testing the EKC and LCC hypotheses for South Korea. *Nuclear Engineering and Technology*, *55*(2), 587-594. doi:10.1016/j.net.2022.10.027.

Pata, U. K., & Yilanci, V. (2021). Investigating the persistence of shocks on the ecological balance: evidence from G10 and N11 countries. *Sustainable Production and Consumption*, *28*, 624-636. https://doi.org/10.1016/j.spc.2021.06.027.

Pata, U. K., Kartal, M. T., Dam, M. M., & Kaya, F. (2023). Navigating the impact of renewable energy, trade openness, income, and globalisation on load capacity factor: the case of Latin American and Caribbean (LAC) countries. *Int J Energy Res*, *2023*(1), 6828781. https://doi.org/10.1155/2023/6828781.

Pereira, L. and Ortega, E. (2012). A modified footprint method: The case study of Brazil. *Ecological Indicators*, *16*, 113-127. doi:10.1016/j.ecolind.2011.06.016.

Phillips, P. C., & Perron, P. (1988). Testing for a unit root in time series regression. *Biometrika*, *75*(2), 335-346. doi: 10.1093/biomet/75.2.335.

Ren, S., Hao, Y., Wu, H., 2022. Digitalisation and environmental governance: does internet development reduce environmental pollution? J. Environ. Plann. Manag. doi:10.1080/09640568.2022.2033959.

Sarkodie, S. A. (2021). Environmental performance, biocapacity, carbon & ecological footprint of nations: Drivers, trends and mitigation options. *Science of the Total Environment*, *751*, 141912. doi:10.1016/j.scitotenv.2020.141912.

Siche, J. R., Agostinho, F., Ortega, E. and Romeiro, A. (2008). Sustainability of nations by indices: Comparative study between environmental sustainability index, ecological footprint and the energy performance indices. *Ecol Econ*, *66*(4), 628-637. https://doi.org/10.1016/j.ecolecon.2007.10.023.

Siche, R., Pereira, L., Agostinho, F. and Ortega, E. (2010). Convergence of ecological footprint and energy analysis as a sustainability indicator of countries: Peru as case study. *Commun Nonlinear Sci Numerical Simul*, *15*(10), 3182-3192. https://doi.org/10.1016/j.cnsns.2009.10.027.

Sinha, A., & Schneider, N. (2024). Stationarity and convergence of LCF series. *Gondwana Research*, *129*, 425-440. https://doi.org/10.1016/j.gr.2023.08.009.

Sollis, R. (2009). A simple unit root test against asymmetric STAR nonlinearity with an application to real exchange rates in Nordic countries. *Economic modelling*, *26*(1), 118-125. https://doi.org/10.1016/j.econmod.2008.06.002.

Solow, R. M. (1956). A contribution to the theory of economic growth. *The Quarterly Journal of Economics*, *70*(1), 65-94. https://doi.org/10.2307/1884513.

Stern, D. I. (2011). The role of energy in economic growth. *Annals of the New York Academy of Sciences*, *1219*(1), 26-51. doi: 10.1111/j.1749-6632.2010.05921.x.

Stern, D. I. (2017). The environmental Kuznets curve after 25 years. *Journal of Bioeconomics*, *19*, 7-28. DOI 10.1007/s10818-017-9243-1.

Sun, Y., Usman, M., Radulescu, M., Pata, U. K., & Balsalobre-Lorente, D. (2024). New insights from the STIPART model on how environmental-related technologies, natural resources and the use of the renewable energy influence load capacity factor. *Gondwana Research*, *129*, 398-411. doi:10.1016/j.gr.2023.05.018.

Swan, T. W. (1956). Economic growth and capital accumulation. *Economic record*, *32*(2), 334-361. https://doi.org/10.1111/j.1475-4932.1956.tb00434.x.

Şimşek, O., Güler, İ., Özbek, S., Naimoğlu, M., & Adalı, Z. (2025). Assessing the convergence of cropland ecological balance: a panel data analysis of 13 major agricultural countries. *Journal of Environmental & Earth Sciences*, *7*(7), 16–34. https://doi.org/10.30564/jees.v7i7.7676

Ullah, S., Luo, R., Adebayo, T. S., & Kartal, M. T. (2024). Paving the ways towards sustainable development: the asymmetric effect of economic complexity, renewable electricity, and foreign direct investment on the environmental sustainability in BRICS-T. *Environment, Development and Sustainability*, *26*(4), 9115-9139. https://doi.org/10.1007/s10668-023-03085-4.

Ulucak, R. Apergis, N. (2018). Does convergence really matter for the environment? An application based on club convergence and the ecological footprint concept for the EU countries. *Environmental Science & Policy, 80*, 21–27. https://doi.org/10.1016/j.envsci.2017.11.002.

Uri, N. D. (1995). A reconsideration of effect of energy scarcity on economic growth. *Energy*, *20*(1), 1-12. doi:10.1016/0360-5442(94)00053-6.

Ursavas, U., & Yilanci, V. (2022). Convergence analysis of ecological footprint at different time scales: Evidence from Southern Common Market countries. Energy & *Environment*. doi: 10.1177/0958305X221120930.

Wackernagel, M., & Rees, W. (1996). *"Our ecological footprint: reducing human impact on the earth".* (Vol. 9). New society publishers.

Wackernagel, M., Hanscom, L. and Lin, D. (2017). Making the sustainable development goals consistent with sustainability. *Frontiers in Energy Research*, *5*, 18. doi:10.3389/fenrg.2017.00018.

Wackernagel, M., Onisto, L., Bello, P., Linares, A. C., Falfán, I. S. L., García, J. M., & Guerrero, M. G. S. (1999). National natural capital accounting with the ecological footprint concept. *Ecological Economics*, *29*(3), 375-390.

World Bank (2025). Data, available at: https://databank.worldbank.org/ (15.10.2025).

World Economics (2025). Data, available at: https://www.worldeconomics.com (11.10.2025).

Wu, J. (2022). Testing the stochastic convergence of ecological indicators in BRICS from the perspective of public health. *Frontiers in Public Health*. doi:10.3389/fpubh.2022.897459.

Xu, D., Salem, S., Awosusi, A. A., Abdurakhmanova, G., Altuntaş, M., Oluwajana, D., & Ojekemi, O. (2022). Load capacity factor and financial globalisation in Brazil: the role of renewable energy and urbanisation. *Frontiers in Environmental Science*, *9*, 823185. https://doi.org/10.3389/fenvs.2021.823185.

Yilanci, V., & Pata, U. K. (2020). Are shocks to the ecological balance permanent or temporary? Evidence from LM unit root tests. *Journal of Cleaner Production*, *276*, 124294. https://doi.org/10.1016/j.jclepro.2020.124294.

Zhao, S., Li, Z. and Li, W. (2005). A modified method of ecological footprint calculation and its application. *Ecological Modelling*, *185*(1), 65-75. doi:10.1016/j.ecolmodel.2004.11.016.

Zivot, E. and Andrews, D. W. K. (2002). Further evidence on the great crash, the oil-price shock, and the unit-root hypothesis. *Journal of business & economic statistics*, *20*(1), 25-44. https://doi.org/10.1198/073500102753410372.