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Research article

Assessing the environmental sustainability gap in G20 economies: The roles of economic growth, energy mix, foreign direct investment, and population

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ABSTRACT

There is serious debate among researchers regarding the sustainability implications of economic prosperity and energy dependence. Energy consumption has a critical linkage with economic growth, but it also degrades environmental quality. Therefore, it is important to investigate the relationship between economic growth, the energy mix, and environmental sustainability. However, empirical literature utilizes narrow variables to capture environmental sustainability. Because of this, this research introduces a new environmental sustainability variable using entropy weighting and combining deforestation, household carbon emissions, and life expectancy. This study examines the relationship between environmental sustainability, economic growth, and other selected variables using data from 2002 to 2019 for the G20 and its high-, upper-, and low-middle-income member countries. Since shocks in one G20 country can affect another, this study uses the Augmented Mean Group (AMG) technique for empirical analysis. The results of this study indicate that Gross Domestic Product (EG) and its square term did not support the Environmental Kuznets Curve (EKC) theory. The energy mix has a positive impact on the environmental sustainability gap across all the samples except for the upper-middle-income group. Foreign direct investment positively affects this gap, while population growth has no significant impact. These findings demonstrate that policymakers should support environmentally friendly and clean energy sources to foster long-term economic growth and sustainability.

1. Introduction

Since Robert Solow developed the production function theory in 1957, labor and capital have been regarded as significant categories of inputs necessary for economic growth [1]. In addition, many economists have considered human capital as another important source of economic growth. However, recent research has suggested that energy, traditionally considered a land input, can play a

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crucial role in development comparable to labor and capital [2]. However, despite the economic benefits of energy, the expansion of alternative energy sources, especially nuclear energy, continues to be debated, as it may also contribute to climate change positively [3]. Energy can be renewable, non-renewable, or fossil fuel-based. The primary source of non-renewable energy is the earth, as natural resources are not consistently available. In contrast, renewable energy, on the other hand, has a replenishment rate suitable for current demand. Furthermore, recognizing the fundamental value of creating new, renewable energy sources and using existing, non-renewable energy-producing sources is very critical for a sustainable environment. The observation sparked the debate over switching to renewable energy. While using conventional energy has advantages such as rapid, short-term economic growth, it also has drawbacks such as creating environmental pollution, noise from transportation, and infrastructure impacts like the building of roads [4]. Thus, non-renewable sources are considered a major challenge in building a sustainable environment [5].

According to Ref. [6], natural resources are very vital for economic development. While the study [7] revealed that fossil fuels are extensively used for energy supply today, these sources will eventually run out, causing environmental issues throughout the world. However, the exploitation of these resources has significant consequences for environmental sustainability. Fossil fuels are extensively used for economic activity, and this pattern of fossil fuel sources will eventually run out. Notably, this extensive use of fossil resources also causes environmental problems throughout the world. Over-reliance on non-renewable energy produces carbon dioxide, which increases climate risk [2]. The utilization of renewable energy sources for energy generation has become more significant with time due to these detrimental impacts and the finite supply of fossil fuels in nature. Globally, it is believed that the past ten years of energy usage have directly contributed to climate change [8]. Furthermore, high energy costs and a lack of supply negatively influenced economic growth in several nations. In particular, the quadrupling of world oil prices between 1973 and 1974 highlighted OPEC's threat to oil-importing economies [9]. This energy crisis resulted from a gap between energy demand and supply. Oil was the main component of economic growth; however, the energy crisis of the 1970s hindered the development of many industrialized countries due to the oil crisis. Recent COVID-19 has also caused oil and energy crises by slowing the growth of the economy all over the world [10]. These oil crises became a turning point for energy alternatives to avoid such an economic depression.

Energy derived from fossil fuels is thought to be a significant factor in environmental deterioration. All parts of the world have recognized climate change as a significant challenge. The United Nations Climate Change Conference 2015 has emphasized that a concrete strategy is needed to control the temperature below 2 °C in most economies. In this regard [11], asserts that the digital transformation of high-carbon sectors is more significantly impacted by China's low-carbon city pilot program. In addition, it seeks to promote a sustainable approach for countries to enhance economic growth and manage the effects of climate change. As a result, nearly 200 countries reached an agreement in Glasgow in 2021 [12]. The conference ratified the remaining provisions of the Paris Agreement and maintained the previous COP-21 target of 1.5 °C warming. Therefore, policies for sustainable infrastructure are needed to develop and promote alternative green energy sources. For example, high-income countries in the G20 panel have set a target of using energy from clean sources for at least 30% of their energy needs by 2025. Similarly, sustainable renewable technologies currently provide about 19 percent of the world's total energy consumption, but the goal is to double that number by 2050.

Previous studies have identified several barriers that prevent the adoption of renewable energy technologies, including social, environmental, technological, and cost barriers. In particular, market constraints are linked to cost structures, and political constraints as well as institutional structures are important, while others are related to technology. More importantly, financing is considered to be at the top of all barriers to the evolution of these green energy technologies. Ongoing efforts to shift energy patterns to a more environmentally friendly and sustainable domain have been more costly for lower-middle-income countries. These expensive energy technologies greatly affect the efforts of developing countries towards building a sustainable environment. Therefore, this study intends to focus on how the current economic development and energy level of G20 countries affect the level of sustainability in the environment.

Figs. 1–4 present some important statistics for G20 economies. Specifically, Fig. 1 shows the United States of America (USA), Australia, and the United Kingdom are the top three countries in GDP output. However, India has the lowest per capita GDP of the G-20 economies. Furthermore, fossil energy resources still have a dominant share in the world economy, and they have significant impacts on CO2 emissions. Therefore, economic growth hurts environmental quality. As a result, a substantial ratio of CO2 emissions originates

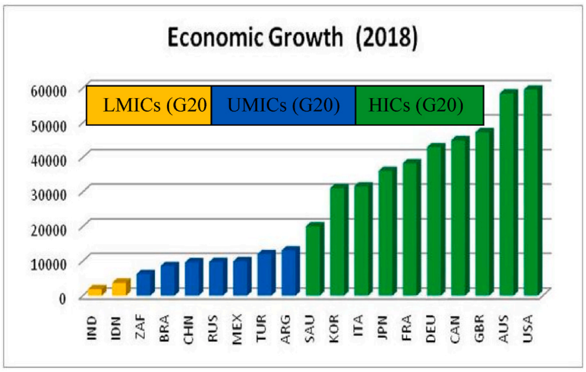

Fig. 1. GDP per capita (constant US $) in 2018 of G-20 Economies (Source: World Development Indicators).

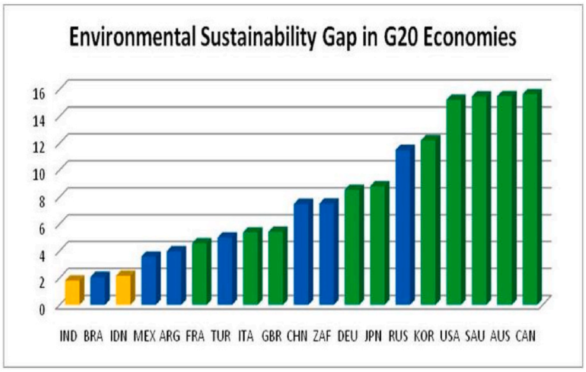

Fig. 2. CO2 emissions per capita in 2018 of G-20 Economies (Source: World Development Indicators).

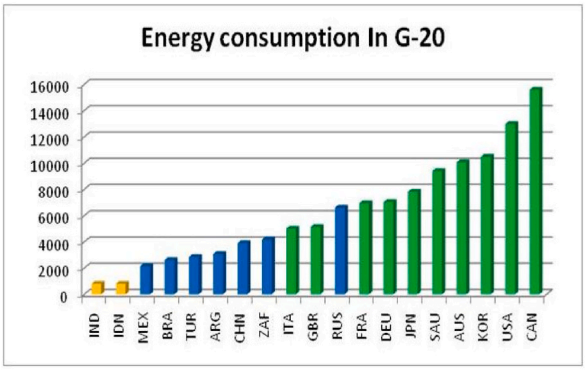

Fig. 3. Energy consumption ((kWh per capita)) status of G-20 (Source: World Development Indicators).

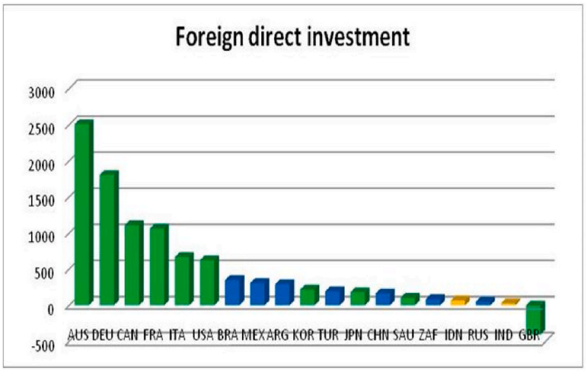

Fig. 4. FDI (net inflows (per capita)) status of G-20 based on 2018 (Source: World Development Indicators).

from energy consumption and economic development [13]. As mentioned in Fig. 1, India has the lowest per capita share of G-20 economies; their share of CO2 emissions is also the weakest in this group. In addition, Fig. 2 demonstrates that Canada is the leading exporter of CO2, trailed by Australia and Saudi Arabia, respectively. The USA has the highest GDP per capita, whereas Canada is on top in CO2 emissions. This conjecture is true because the USA has shifted its industry to neighboring countries, and Canada is the largest receiver of that industry [8].

Fig. 3 demonstrates the energy mix in G-20 economies. It is evident that when it comes to electricity consumption, Canada leads the way, followed by the United States in second place and the Korean Republic in third. In this view, CO2 emissions are directly associated with electricity production, as its production primarily depends on fossil inputs. Therefore, Canada, for example, is at the top in electric power consumption and, hence, also has the highest CO2 emissions due to increased fossil input. On the other hand, India has the lowest share of CO2 emissions because it has the weakest energy consumption trend among G-20 economies. According to the International Energy Agency, the energy pattern in G-20 countries changed significantly, notably in high-income countries. Numerous economies have managed their energy-changing plans based on international obligations, showing typical but discriminatory duties and abilities. Foreign direct investment (FDI) in G-20 economies is shown in Fig. 4. Australia, Germany, and Canada are the countries with the highest receivers of FDI. In addition, FDI is negative for the United Kingdom (UK), primarily due to the Brexit issue.

Notably, low-middle-income countries' energy consumption has significantly expanded due to rapid population and economic growth. Still, their fossil energy consumption is much smaller than that of upper-middle and high-income economies in the G20 panel. It is noted that these countries mainly rely on fossil fuels to meet their expanding energy needs. However, there is a significant gap between the potential supply of fossil fuel energy and the amount needed to achieve the set socio-economic targets by 2025. As a result, these countries must transition to renewable energy sources to ensure a secure energy supply and reduce environmental risks.

Owing to the above discussion, this study intends to provide an analysis of environmental sustainability using economic growth, energy mix, FDI, and population growth in G20 countries. As such, this study contributes to the empirical analysis in significant ways. First, previous studies have mostly used single variables to measure environmental sustainability. In contrast to these studies, this study introduces a new indicator of the environmental sustainability gap in the empirical literature. Specifically, this study uses entropy weightage to calculate this environmental sustainability gap using forestry, life expectancy, and household carbon emissions. To the best of these authors' knowledge, no studies have yet combined these variables to come up with the environmental sustainability gap. As such, this study is unique. Second, while previous studies have been conducted to assess environmental sustainability analysis in G20 economies, they have not categorized these economies into high, upper, and lower-middle-income economies. Yet, it is important to analyze the sub-sample of G20 economies to see if the whole panel results hold when it comes to different income classifications. Third, since shocks in one G20 country can affect another G20 country, there is a need to account for these shocks. Therefore, this study uses second-generation econometric techniques that can control cross-sectional shocks or cross-sectional dependence (CSD) between the units. Specifically, the study uses the Augmented Mean Group (AMG) technique as a long-run technique that can provide robust and valid analysis in the presence of CSD.

The rest of the study's structure consists of a literature review, an empirical framework, estimations, and a discussion, with the conclusion and potential policy repercussions presented in the final section.

2. Literature review

2.1. Empirical literature review

Global warming is the world's most significant and pressing issue of our day. Carbon dioxide (CO2) is the primary cause of this worldwide issue. In 1961, there were 9.4344 billion tons of CO2 emissions worldwide; by 2011, that number had risen to 34.649 billion tons [13]. If current trends continue, CO2 emissions could reach concerning levels by the middle of this century. However, environmental innovation can significantly improve the environment. Global warming occurred in the same year as the Industrial Revolution. In this regard [14], agree that these processes are connected. People have used non-human energy sources to promote industrialization and overall development. Therefore, reducing CO2 emissions has been the main objective of the past few decades to save the climate [5]. Additionally, effectively transitioning energy to reduce CO2 emissions should be a key goal for all nations worldwide. The current structure of economic development is fossil-based. This economic infrastructure has a significant negative impact on the environment. On the other hand, as the economic level of developed countries increased, people invested more in a better environment. This investment had a positive impact on their sustainable environment, which also positively affected their GDP per capita [15].

In this regard, several studies have linked environmental degradation to factors such as economic growth, energy consumption, population, and foreign direct investment. Specifically, the study by Ref. [16] showed that academics still disagree about how to maintain environmental sustainability while promoting economic expansion and energy use. For electricity generation, many industrialized economies continue to rely on fossil fuels. Their analysis used fully modified ordinary least squares, and they used a data set that covered the G20 countries from 1995 to 2018. Notably, the findings showed that there were differences in the impact of energy use on CO2. This implies that sources that contribute to the increase in greenhouse gas emissions are still used in the production of power. Furthermore, for these economies, the GDP and its square-term results validate the idea of the Environmental Kuznets Curve. Based on these findings, authorities should support clean and green power sources to support long-term economic growth. A study by Ref. [17] pointed out that as the proportion of renewable energy sources in electricity production increases, end users are critical to ensuring that supply and demand are balanced, overall system costs are reduced, and carbon dioxide emissions are reduced. Another study showed that the speed of CO2 emissions is directly related to population and that population growth has increased CO2 emissions [18].

Given the current wave of CO2 emissions and the negative impact of fossil energy on global warming, a sustainable energy transition is currently more important to mitigate this problem. In this regard, the study of [19] revealed that the energy transition from conventional to sustainable energy is not possible without easy access to clean energy. Their study showed that different economies have made smooth transitions, but there is still a wide gap in developing countries. The result of their study showed that while developed countries are doing more on energy transition, there are still high deviation trends in lower-middle-income countries. Their results showed that fossil fuel energy is responsible for the downward trend in economic growth. Finally, their study concluded that there is a greater need for sustainability in energy transitions in less developed countries. However, energy transition requires massive financing, where least-developed countries are lacking. Surprisingly, the study by Ref. [20] revealed that even as the share of clean energy increased, polluting energy sources continued in most of the world. Therefore, the current trends in energy patterns require significant shifts in public policy.

In another study [21], explored the connections between income growth, energy consumption, and CO2 emissions. Their findings demonstrated that economic growth supports environmental quality in high-income countries. However, these economies have shifted their fossil industry to poor countries. This shift has increased employment levels in host countries and improved the environment in developed nations. They also discovered that upper-middle-income countries' environmental conditions worsen due to rising fossil energy utilization. In a similar analysis [21], examined the short- and long-term impacts of economic growth, FDI, and fossil fuel consumption on CO2 emissions in fifteen emerging Asian nations. Their findings demonstrated that efforts to promote economic development in these developing economies increase CO2 emissions and that using fossil fuels worsens the local environment by increasing CO2 emissions. Their empirical findings supported the Pollution Haven hypothesis by showing that foreign direct investment contributes to environmental degradation and increases domestic CO2 emissions.

The study by Ref. [22] examined the impact of population and electricity production from fossil fuels on environmental degradation in G-7 countries. In this regard, using panel data from 1996 to 2019, this study divides economic growth into production inputs like labor and capital. The study found that the effects of working people on environmental degradation are significantly positive. Finally, fossil fuel energy positively affects carbon dioxide emissions in both the short and long term. Furthermore, their study supported the environmental Kuznets curve theory. Researchers looked into how energy use and economic expansion affected carbon emissions in the newly formed Silk Road economic region [15]. This study used panel data (1995–2014) from 24 middle-income nations along the Belt and Road for its empirical analysis. The findings highlighted the effects of economic growth, renewable energy, and non-erasable energy on carbon emissions. Their study concluded that using non-renewable energy sources is a more significant obstacle to reaping the most remarkable economic rewards. The study by Ref. [23] found that the impact of fiscal imbalance on the environment is critical. Their study observed significant effects of fiscal imbalances on CO2 emissions. However [21], revealed two types of FDI impacts on CO2: diverging in developed economies and converging in developing economies. Moreover, their study found a significant connection between FDI and CO2 emissions. It is positive in emerging economies; however, it is found to be negative in developed economies.

2.2. Research gap

After reviewing the previous studies, it is clear that many of them utilize a single indicator to measure environmental sustainability. No studies have so far applied comprehensive indicators to measure the environmental sustainability gap. Therefore, this study intends to fill this research gap evident from previous studies. Accordingly, this study develops an environmental sustainability gap index using forestry, life expectancy, and household carbon emission variables. To do so, the study uses entropy weighting and creates weighted environmental sustainability, which shows the degree to which the country's environmental sustainability has been met. Then, a comprehensive indicator of environmental sustainability is created, which is a measure of the magnitude of the environmental sustainability gap that needs to be filled to achieve environmental sustainability. Moreover, it can also be seen from the previous literature that there is a gap regarding the analysis of environmental sustainability using the income levels of countries. While this study's main objective is to analyze the sustainability gap for the whole panel of G20 countries, this study also separates this panel into high-, upper-, and lower-middle-income countries for comparative analysis, which makes this study even more unique. Furthermore, the study uses important indicators such as economic growth, energy mix, FDI, and population growth to see how they affect the environmental sustainability gap. The study follows the theory of the Environmental Kuznets Curve (EKC) and includes both GDP and its square. Unlike other studies, which use either nonrenewable or renewable energy variables, this study uses the energy mix variable, which is a combination of renewable and non-renewable energy sources. As such, this study intends to fill several research gaps existing in the empirical literature, specifically for G20 economies. In line with the pollution haven or pollution halo hypothesis, this study also includes foreign direct investment as a critical factor influencing the environmental sustainability gap. Moreover, the population has also been included in this study, which can significantly affect this sustainability gap following the work of [24].

3. Emperical framework

We start our research on how economic growth affects the gap in environmental sustainability in the specified G20 countries using balanced panel data from the World Development Indicators (WDI). These G20 nations are then divided into three panels based on the income level criteria of the World Bank: lower-middle income, upper-middle income, and high-income countries. This study period is based on the availability of annual data, which suggests that data on the energy mix, sustainable environment, and foreign direct investment are particularly scarce. Nonetheless, we were able to acquire yearly balanced panel data without the need for data approximation approaches for seven upper-middle-income, two lower-middle-income, and ten high-income nations for the years 2002–2019. The concluding selection of countries is as follows: i. Argentina, ii. Australia, iii. Brazil, iv. Canada, v. China, vi. France, vii. Germany, viii. India, ix. Indonesia, x. Italy, xi. Japan, xii. Republic of Korea, xiii. Mexico, xiv. Russia, xv. Saudi Arabia, 16. South Africa, 17. Turkey, 18. the United Kingdom, and xix. The United States. Though distinct, these countries share some common features, including high dependence on fossil fuel consumption, rising populations, top carbon-emission rankings, and an accelerated pace of industrialization over the past three decades. The study uses balanced panel data to analyze the impact of economic growth, energy mix, and foreign direct investment on the environmental sustainability gap in the G20 countries. To examine the long-run relationship between dependent and independent variables, an Augmented Mean Group technique is used.

3.1. Theoretical rationale

The climate crisis is now occupying the central stage in political regimes, both in national and international contexts [25]. In this context, this study explains the environmental sustainability gap in G20 nations, focusing on economic growth, energy mix, foreign direct investment, and population to address the climate crisis of these nations. The relationship between environmental sustainability and economic growth is very well defined by the theory of the Environmental Kuznets Curve (EKC). This theory was proposed by Grossman and Krueger in 1991 [26]. The EKC theory states that economic expansion first increases the environmental sustainability gap, eventually reaches a tipping point, and then begins to reduce the sustainability gap. EKC shows how, once a nation reaches a certain level of economic development, its citizens view environmental health as a desirable product and are willing to pay for high-quality care. Therefore, EKC states an inverted U-shaped relationship between economic growth and environmental sustainability. However, there is a possibility that this relationship can be U-shaped where economic growth first reduces environmental sustainability, and after a certain threshold, this growth starts to increase environmental sustainability [27].

In this study, the theoretical foundations are based on the EKC model. In Fig. 5, an inverted U-shaped EKC is shown, further separated into two stages. The first phase is identified as the deterioration phase, which indicates the expansion of economic growth. However, expanding economic growth increases carbon emissions. In this stage, a direct relationship is observed between growth and emissions (in this case, the environmental sustainability gap). However, in this form of EKC, the second stage is called the maturity stage, which indicates that the expansion of economic growth is inversely related to environmental deterioration. This expansion speed means that the efficiency of economic growth has improved and is moving towards sustainability.

Energy is critical to both economic development and environmental quality. In G20 nations, a large part of their economic expansion comes from the use of fossil fuels. The abundance of natural resources provided these economies with an added advantage to accelerate economic expansion, in addition to these other factors. As the economies of these countries developed and their living standards improved, the average age of the population began to increase. However, as these nations have developed based on fossil fuels, carbon emissions are having a negative impact on the environment. The energy demand of the industrial sector is increasing due to globalization, and current energy development is insufficient to reduce emissions at this level. As such, there is a need to shift the energy mix of these countries toward renewable energy sources to reduce emissions and minimize the environmental sustainability gap. Therefore, it can be expected that the energy mix will have a significant impact on environmental sustainability in G20 economies.

This study also focuses on foreign direct investment and population as critical factors for minimizing the gap in environmental sustainability. All of the member states of the United Nations agreed to the Sustainable Development Goals (SDGs), which were established in 2016 to address the climate crisis [28]. However, even after setting the SDGs for 2030, the focus is on “simple development” rather than “sustainable development” in industrialized and developing countries. Likewise, this may be the primary justification for maintaining lax national regulations to create a soft legal framework that attracts foreign capital. Such an adaptive framework has accelerated industrial growth and increased the amount of foreign direct investment (FDI) but at the cost of the health of the local population and the environment. Furthermore, studies such as [21] have explained how foreign direct investment (FDI) raises energy consumption in host nations by promoting the growth of transportation, industry, and the manufacturing sector. The impact of FDI on energy consumption is evident in most countries, and the findings demonstrate that FDI is a major cause of high energy consumption. However, there is still much debate on how foreign direct investment (FDI) affects carbon emissions in both industrialized and developing nations. Analyzing how foreign direct investment affects the environmental sustainability gap is an important project because it makes it possible to assess the harm that FDI causes and test the "pollution haven" theory in particular countries. Furthermore, population growth can intensify the problems of urbanization and industrialization and cause the deterioration of the natural environment [29]. Therefore, population growth is considered to negatively affect the environmental sustainability of G20 nations.

In light of this contextual background, it is important to examine how these indicators affect environmental sustainability differences using a theoretical framework that accounts for evolutionary effects over a given period. This study used panel data following

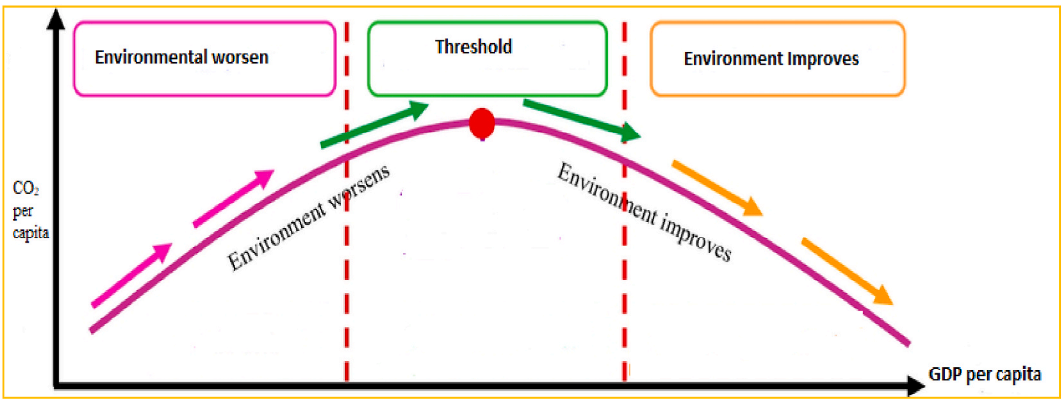

Fig. 5. EKC shape.

the methodology of [30]. However, the analysis period of this study is 1995–2018. The functional form of the econometric model in this study is based on previous studies such as [21] and can be described as follows:

$$ESG = f\left(EG, EG^2, \varnothing\right) \tag{1a}$$

Here ∅ shows an unknown factor (such as energy mix, foreign direct investment, or population growth) and their potential influence on carbon emissions. In light of this contextual background, it is important to examine how these indicators affect environmental sustainability differences using a theoretical framework that accounts for evolutionary effects over a given period. This study used panel data following the methodology of [30]. However, the analysis period of this study is 1995–2018. The functional form of the econometric model in this study is based on previous studies such as [21] and can be described as follows:

$$ESG = f\left(EG, EG^2, \varnothing\right) \tag{1b}$$

Here ∅ shows an unknown factor (such as energy mix, foreign direct investment, or population growth) and their potential influence on carbon emissions.

This study introduces an index of the environmental sustainability gap (ESG) (dependent variable) as a novel step in the literature. Environmental sustainability is seen as a holistic concept. However, according to Ref. [31], unidimensional cues are limited in accessing information about the state of the environment. Environmental sustainability can be assessed flexibly using a dashboard of individual metrics. On the other hand, it is more difficult to comprehensively compare and characterize sustainability for individual metrics [32]. In this sense, the multidimensional approach overcomes the shortcomings of previous techniques.

It has emerged as the standard method for evaluating environmental sustainability and integrates several factors to provide a single value. However, a comprehensive assessment of environmental sustainability taking into account multiple dimensions, including forestry, life expectancy, and carbon emissions, is currently lacking. In addition, studies have used deforestation, life expectancy, and carbon emissions as proxies for environmental sustainability [33,34], and [21]. All selected variables for ESG have a unique aspect of the environment, but incorporating these variables into one value makes ESG a multidimensional approach." This index shows a specific value for a country's environmental sustainability that the country has achieved so far. In this index construction process, entropy weightage is used. In this regard, weighted environmental sustainability (WES) is created as follows:

$$WESx, t = \sum\left(W1 * FRS + W2 * LE + W3 * CO_2\right) \tag{1c}$$

The variable description for equation i is given in Table 1, where W1, W2, and W3 refer to the weight of forestry (FRS), life expectancy (LE), and household carbon emission (CO2). This study used entropy weighting to be unbiased in deciding which variables contributed more. Here, x refers to country, and t refers to time (year). The WES value will show the degree to which the country's environmental sustainability has been met. In Equation (ii), we arrive at the Composite Environmental Sustainability GAP Index through the following process:

$$\mathrm{ESG} = 1 - W E S\mathrm{G} \tag{1d}$$

By deducting WESG from 1, one can determine the environmental sustainability gap (also known as ESG) that a nation needs to

Table 1
Variables representations.

Name	Variables	Description	Transformation	Reference	Data Source
ESG	Environmental Sustainability Gap	Forestry (as a percentage of all-terrain) (FRS) Total life expectancy at birth in years (LE) Household emissions of carbon dioxide per capita (CO_2)	Index (0–1)	[35] [33] [21]	UNDP WDI, IEA
EM	Energy mix	(Non-renewable Energy/Renewable Energy Consumption) *100	Ratio	[36]	WDI, IEA
FDI	Foreign direct investment, net inflows (% of GDP)	The term "foreign direct investments" refers to net investments made to purchase a long-term management stake (10 percent or more of voting stock) in a company that operates in a different economic system from the investors. According to the balance of payments, it is the total equity capital, reinvestment of earnings, and additional long-term and short-term capital. Net inflows of foreign capital (new investments, fewer outflows) into the reporting economy are shown in this GDP-broken data.	Natural log	[8]	World Development Indicators (WDI)
EG	GDP per capita	GDP is the sum of the gross value added by all resident producers in the economy, plus any product taxes and minus any subsidies not included in the value of the products. GDP is calculated without considering the depreciation of fabricated assets or the depletion and degradation of natural resources. The data are in constant 2010 US dollars.	Natural log	[21]	
POP	Population, total	The total population is calculated based on the real definition of population, which includes all residents regardless of citizenship or legal status.	Natural log	[8]	

close. This index shows how much of the environmental sustainability gap needs to be closed to achieve environmental sustainability. Keeping in mind equation (1), the econometric model that is used to estimate the outcomes can be expressed as follows:

$$ESG_{it} = \beta_0 + \beta_1 EG_{it} + \beta_2 EG_{it}^2 + \beta_n \varnothing_{it} + \mu_{it} \quad (2)$$

In the present study, we note energy consumption, foreign direct investment, and population growth as important factors that may influence the generation of carbon emissions and the quality of the environment in the G20 economies. The extended form of equation (3) can therefore be written as follows:

$$ESG_{it} = \beta_0 + \beta_1 lnEG_{it} + \beta_2 EG_{it}^2 + \beta_3 EM_{it} + \beta_4 FDI_{it} + \beta_5 Pop_{it} + \mu_{it} \quad (3)$$

Here, 'ln' stands for natural log; β is the coefficient of given variables; EG is economic growth; EM is energy mix; FDI is foreign direct investment; and POP is the total population." For detailed variable definitions, the following table is presented in Table 1.

3.2. Methodology

3.2.1. Cross-sectional dependence test

The dataset structure defines the empirical methodology's application. For this purpose, cross-sectional dependence (CSD) is essential for empirical analysis. The CSD paradigm assumes that dependency can originate from several cross-sectional units and can lead to inadequate and incorrect results. Due to dependency issues, the result cannot display the precise and actual relationship between the given variables. The study [20] indicated that this issue arises due to regional interdependence and a fossil fuel-based economic structure. Therefore, the Pesaran [37] CSD test is used in this study. This test has the null hypothesis that there is no cross-sectional dependence. The following equation provides the statistics for the Pesaran test specification:

$$CSD = \sqrt{\frac{2T}{N(N-1)}} \left(\sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \widehat{\rho}_{ij} \right) \sim N(0,1) \quad (4)$$

Where $\widehat{\rho}_{ij}$ is the sample estimate, N stands for cross-sectional dimensions while T represents the time dimensions of the panel.

3.2.2. Unit root tests

To account for CSD, this study uses second-generation unit root techniques. The cross-sectionally augmented IPS (CIPS) method is used; it was developed by Ref. [38]. This test asymptotically eliminates the CSD by appending the first differences for each unit and the cross-sectional averages of the lag levels to the ADF regressions. It takes into consideration both CSD and the serial correlation of the error terms [39]. The CIPS test can be expressed as follows:

$$CIPS\ (N,T) = \left(\frac{1}{N}\right) \sum_{i=1}^{N} t_i(N,T) \quad (5)$$

In equation (5),the CD-ADF statistic is represented by the term$t_i(N,T)$.

3.2.3. Westerlund cointegration test

The cointegration method can help identify long-term correlations across the examined variables, which denotes that the variables move forward continuously over time. As a result, it implies that the selected model may be able to predict the long-period stability process. This research employed the Westerlund cointegration technique, as suggested by Ref. [40].

When there is cross-sectional dependence, Pedroni and Fisher's first-generation cointegration tests cannot sufficiently confirm the long-term relationships between variables. Thus, to solve this problem, the Westerlund cointegration method is applied. The null hypothesis states that there is no cointegration. The Westerlund depends on mathematically based error-correcting procedures as follows:

$$\Delta Y_{it} = \alpha_i + {}'\delta d_{\ t} + \eta_i (Y_{i,t-1} - \beta_i X_{i,t-1}) + \sum_{j=0}^{p_i} \eta_{ij} \Delta y_{i,t-j} +) + \sum_{j=0}^{p_i} \gamma_{ij} \Delta x_{i,t-j} + \mu_{it} \quad (6)$$

In this case, i stands for the cross-sections, t for observations, dt for deterministic components, and ηi for the convergence rate to the equilibrium state after an unanticipated shock.

3.2.4. Augmented mean group (AMG)

An augmented mean group (AMG) is used in this study to address the issue of cross-sectional dependence (CSD). The technique used in the study [41] as well as [42] recommends this test. This method can be used in addition to CSD to manage heterogeneity. Following [41], the equation that represents the augmented mean group method is as follows:

$$\Delta ESG_{it} = \delta_0 + \delta_1 \Delta EG_{it} + \delta_2 \Delta EG_{it}^2 + \delta_3 \Delta EM_{it} + \delta_4 \Delta FDI_{it} + \delta_5 \Delta POP_{it} + \sum_{t=1}^{T} c_t D_t + \partial_i UCF + e_{it} \quad (7)$$

$$\mathrm{AMG} = \frac{1}{N}\sum_{i=1}^{N}\partial_i \tag{8}$$

Here, D_t represents the dummy variables, which are the time variables. Δ represents the difference operator, and UCF is the unobserved common effect. The ordinary least squares of equation (7) generate the AMG of equation (8), where ∂_i is the slope parameter of independent variables.

4. Results and discussion

4.1. Empirical results

Table 2 presents the cross-sectional dependence test of [37]. The result shows that in the G20 economies, the null hypothesis of no cross-sectional dependence is rejected. It means that there is cross-sectional dependence (CSD) in the whole panel.

The HIC group also shows evidence of CSD, while the UMIC and LMIC groups show no evidence of CSD, as the null hypothesis cannot be rejected. After confirming cross-sectional dependence, Table 3 presents the estimated values for the CIPS, showing that the majority of variables are stationary across samples.

After confirming cross-sectional dependence and stationarity, Table 4 presents the results of the Westerlund cointegration test.

The Westerlund cointegration technique is a very suitable method that significantly overcomes the problem of cross-sectional dependency constraints [40]. The Westerlund panel cointegration result indicates that all models are cointegrated, as the null hypothesis of no cointegration is rejected for all samples.

Table 5 presents the AMG test results for the G20 countries as a whole and the three subsamples. The results obtained using the extended mean group are interesting and varied. First, results from the overall G20 panel show that a 1% increase in economic growth (EG) reduces the environmental sustainability gap (ESG) by 0.202%. In addition, the empirical results of quadratic economic growth (EG2) show that a 1% increase in EG2 increases ESG by 1.304%. These overall G20 panel findings are consistent with high-, upper-, and lower-middle-income countries. These empirical results support a U-shaped relationship between economic growth and environmental sustainability gaps in the analyzed countries. This shows that initially, increasing economic growth reduces the environmental sustainability gap, but later, after a certain threshold, increasing economic growth increases the environmental sustainability gap. These findings contrast with the presence of EKC in the entire panel as well as in three subsamples. In Fig. 6, the U-shaped relationship between economic growth and the environmental sustainability gap is presented.

The energy mix (EM) has a positive impact on ESG in the overall G20 panel. Specifically, a 1% increase in EM increases ESG by 0.0483%. These findings of EM are consistent in upper-middle and high-income countries. However, in lower-middle-income countries, a negative relationship with the environmental sustainability gap can be seen. The impact of foreign direct investment on ESG is significant and positive for the overall G20 panel. In this regard, the impact and relationship of FDI are consistent in their direction toward high- and upper-middle-income countries. However, discrepancies can be found in lower-middle-income countries, as they show a negative and significant impact on ESG.

Finally, the population growth (POP) result shows a statistically insignificant relationship with ESG in the overall G20 countries. Results for LMIC and UMIC show a negative impact on ESG, while only UMIC shows a significant impact. The higher income model shows a positive but insignificant effect on ESG.

4.2. Discussion

This study examines how the economy, energy, population growth, and foreign direct investment relate to environmental sustainability. First, the results obtained from the overall G20 panel showed that increasing economic growth decreases the environmental sustainability gap. However, empirical results also revealed that an increase in the square of economic growth increases the environmental sustainability gap. The U-shaped quadratic effect of economic growth contradicts the existence of the EKC theory and supports the idea that long-term economic growth eventually leads to an increase in the environmental sustainability gap. The economic growth and the environmental sustainability gap, in particular, are found to have a U-shaped relationship in this study, effectively disproving the EKC theory and suggesting that the environmental sustainability gap will continue to grow. In this view, the study by Ref. [43] supports the current findings and further reveals that global environmental change is rooted in patterns of human existence and economic activity. Climate change is said to have been introduced during the Industrial Revolution, which began around 1750. Carbon dioxide emissions are much lower than before the start of industrialization. The amount of greenhouse gases in the

Table 2
Cross-sectional dependence test.

Models	Overall (G20)	HICs (G20)	UMICs (G20)	LMICs (G20)
Pesaran	7.65***	4.07***	−0.37	1.11
Prob.	0.00	0.00	0.71	0.26

H_0: No cross-sectional dependence exists in the selected model.
Note: *** and ** show significance levels at 1 percent and 5 percent, respectively.

Table 3
Results of CIPS unit root test.

Variables	Overall (G20)	HICs (G20)	UMICs (G20)	LMICs (G20)
ESG	–	–	–	–
ΔESG	−4.07***	−3.33***	−4.40***	−3.46***
EG	–	–	–	−2.97***
ΔEG	−2.91***	−3.32***	−3.47***	–
EM	–	–	–	−2.89***
ΔEM	−4.01***	−3.90***	−4.24***	–
FDI	−3.28***	−3.10***	−3.47***	−2.86***
ΔFDI	–	–	–	–
POP	–	–	−2.39**	2.64***
ΔPOP	−2.25*	−2.22*	–	–

Note: *** and ** show significance levels at 1 percent and 5 percent, respectively. Δ denotes unit root test at deference.
H_0: series has a unit root.

Table 4
Result of westerlund cointegration test.

Westerlund Cointegration Test	Overall (G20)	HICs (G20)	UMICs (G20)	LMICs (G20)
Variance ratio	−1.81**	1.89**	−1.79**	−1.36*

***, **, * shows significance level at 1%, 5% and 10% respectively.
H_0: No cointegration.

Table 5
Result of Augmented Mean Group (AMG) estimation technique.

Variables	Overall G20	LMICs	UMICs	HICs
EG	−0.202*** (0.0732)	−2.624*** (1.58e-05)	−0.920*** (9.81e-06)	−0.394*** (0.118)
EG^2	1.304*** (0.324)	11.95*** (0.000775)	4.190*** (1.61e-05)	0.826** (0.420)
EM	0.0483*** (0.0158)	−2.12e-06** (8.45e-07)	1.40e-07 (6.19e-07)	0.0560*** (0.0151)
FDI	0.000840** (0.000399)	−2.38e-06*** (5.31e-07)	1.31e-07 (6.30e-07)	0.000848** (0.000407)
POP	1.073 (4.377)	−0.0124 (0.0104)	−0.000356*** (7.67e-05)	2.539 (4.116)
Constant	−4.259 (12.77)	−53.88*** (0.0275)	−20.10*** (0.000190)	−8.565 (12.12)
Observations	331	34	123	171
Number of Countries	19	2	7	10

Note: *** and ** show the significance levels at 1 percent and 5 percent, respectively. Standard errors are in parentheses.

atmosphere has increased dramatically since the beginning of the industrial age. For example, in 2019, the concentration of carbon dioxide in the atmosphere reached 409.8 ppm (parts per million), the highest in at least the last 800,000 years. This study's empirical results are not surprising since fossil fuels are considered important for economic growth and driving the world's energy needs. The G20 economies are a group consisting of high-, upper-middle-, and lower-middle-income countries. These countries, especially the upper-middle and lower-middle-income countries, face many economic challenges and are still working to raise the standard of living of their people.

Despite the threat of global warming, unfortunately, many industrialized countries continue to generate a significant amount of their energy from coal and oil. In this regard, the findings of this study show increasing economic growth in the overall G20 economies at the expense of environmental sustainability gaps. In particular, low- and upper-middle-income countries are still making priority efforts to increase their fossil-based industrial activities [25]. Since the Industrial Revolution, these countries have rapidly increased their reliance on fossil energy to produce more goods and services. The best example of this is China's economy, which has a rapidly increasing carbon footprint as its total carbon emissions rose from 3.4 billion metric tons in 2000 to 13 billion metric tons in 2018. This is due to China's policies supporting fossil-based industrial development [44]. In this respect, lower-middle-income countries are following the same path regardless of global warming concerns and still welcome fossil-based economic growth. In this view, India is an example of a low-income country where environmental pollution has increased along with economic growth. In particular, India raised its carbon emissions from 2.3 billion to 2.7 billion metric tons in the same period.

Second, the energy mix has a positive effect on the environmental sustainability gap across G20 economies as a whole. Moreover, this effect is similar to that of high- and upper-middle-income countries. The findings of this study show how the energy transition activities of industrialized countries are very slow and hurt environmental quality. In particular, high- and upper-middle-income economies are still expanding their fossil-based infrastructure, leaving environmental sustainability priorities behind. In this regard [36], found that energy consumption induces a positive effect on environmental deterioration for full samples as well as individual

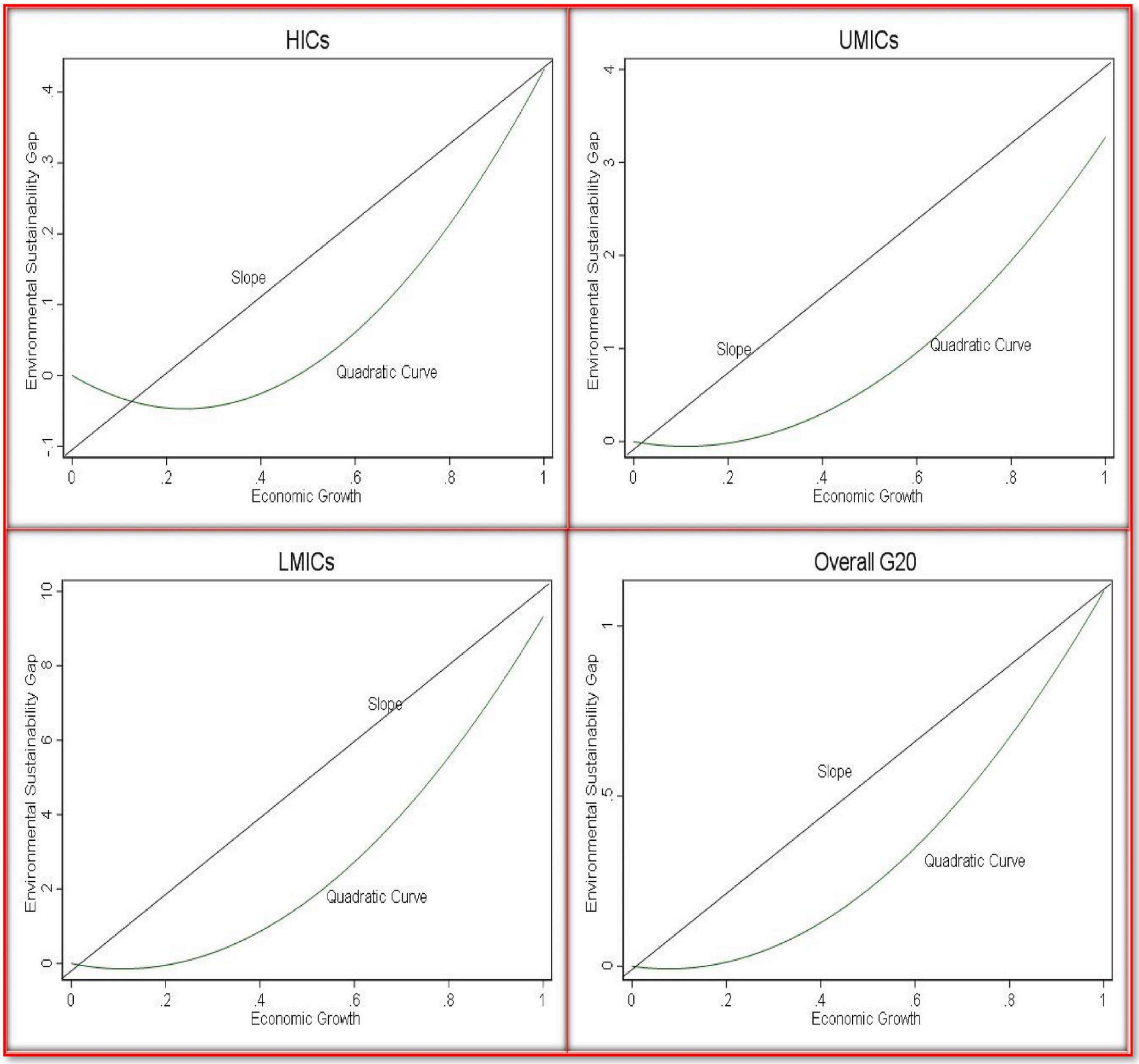

Figure: 6. Quadratic Relationship of the economic growth and Environmental sustainability gap.

samples. This is also seen in Ref. [16], where the authors find that energy adoption cannot improve environmental sustainability. The degradation of the environmental sustainability gap increases with the increase in the level of fossil-based industrialization, and this process leads to an increase in energy consumption in parallel. However, the effect of the energy mix on the environmental sustainability gap is negative in lower-middle-income countries.

Third, the impact of foreign direct investment on the environmental sustainability gap is significant and varies across the samples. The results for overall G20 countries and particularly high-income countries are consistent with their impact and relationship. In this regard, foreign direct investment indicates a positive and statistically significant relationship with the environmental sustainability gap for selected high- and overall G20 countries. These results support the Pollution Heaven theory in these panels, indicating that foreign direct investment is a substantial source of high carbon emissions and environmental degradation. The relatively lenient environmental rules of industrialized countries have increased their income but have had a significant positive impact on the ecological sustainability gap. This corroborates the finding of [21], where the authors found that for emerging Asia, FDI is hurting environmental sustainability. The results for lower-middle-income countries show that FDI narrows the gap in environmental sustainability, while the upper middle class shows no significant impact.

Finally, the results for the effect of population growth on the environmental sustainability gap show a statistically insignificant relationship in the overall G20 countries. Moreover, this effect is similar in high- and lower-middle-income countries. However, the impact of population growth on the environmental sustainability gap is negative in upper-middle-income countries. Specifically, a 1 percent increase in population significantly reduces the environmental sustainability gap by 0.0004%. This indicates the population has a favorable impact on environmental sustainability in the upper middle-income group, while other groups cannot utilize their population to minimize this environmental sustainability gap. The upper middle-income result matches the result of [16] yet again, where the authors showed that urbanization causes a decline in CO2 emissions in the short and long run.

5. Conclusion and policy implications

This study empirically analyses the environmental sustainability gap of G-20 economies and their high-income, upper-middle-income, and lower-middle-income groups. This study analyzes the G20 countries as a whole, and then, for the robustness of the analysis, this study separates these G20 countries into three sub-panels for comparative study. The distribution of these panels is based on World Development Bank indicators with income level specifications. These groups are named as lower-middle, upper-middle, and high-income countries. In this regard, the impacts of economic growth, energy mix, population, and foreign direct investment on the ecological sustainability gap are examined. The analysis employed panel data from 2002 to 2019. The study uses pre-diagnostic tests such as cross-sectional dependence, stationarity, and cointegration tests. As the main technique, the current research employs an augmented mean group for long-run estimation.

Based on the findings of the study, the following policy implications are suggested: It is advised that G20 nations change their economic structures to incorporate more renewable energy as economic growth widens the gap in environmental sustainability. The panel as a whole indicates that the energy mix increases the disparity, so these governments need to give clean energy sources top priority when making investments. In this regard, the banking sector has a critical role to play in easing loans for clean energy firms. Governments can implement strict carbon pricing tools to mitigate the environmental degradation of these countries. Although some of the developed countries have already implemented this tool, it should be extended to sectors with high carbon emissions that must charge a high carbon tax. Since FDI harms environmental quality, governments should ensure that clean technology-using firms invest in the G20 economies. The government should also educate its citizens regarding environmental awareness and ecological welfare so that they can utilize the population to favor environmentally sustainable policies.

This study has some limitations regarding data availability for G-20 countries and econometric techniques. Data on environmental sustainability gaps, economic growth, energy mix, foreign direct investment, and population data for recent years are missing. These results are estimated using only augmented mean group econometric techniques. This study considers only the G20 panels. However, when the data becomes available, future studies can extend the environmental sustainability gap indicator to multiple countries to provide insights into how this gap can be minimized across developing and developed countries. Moreover, future studies can apply new techniques, such as the cross-sectionally augmented ARDL technique, as well as recent Granger causality approaches, to examine the environmental sustainability gap.

Data availability

Data are available upon request from the corresponding author.

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Originality

This manuscript is original, and its publication does not infringe any copyright. As the corresponding author, I declare that the manuscript has not been previously published, in whole or in part, in any other journal. Also, considering the second part of your comment, this study has some limitations.

CRediT authorship contribution statement

Lei Wang: Supervision, Software, Investigation, Formal analysis. **Muhammad Javeed Akhtar:** Writing – original draft, Supervision, Software, Formal analysis, Data curation, Conceptualization. **Mohd Naved Khan:** Writing – review & editing, Investigation, Formal analysis. **Nabila Asghar:** Writing – review & editing, Validation, Methodology. **Hafeez ur Rehman:** Writing – original draft, Supervision, Conceptualization. **Yifan Xu:** Writing – review & editing, Investigation, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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