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RESEARCH

The dynamic impact of human capital, energy consumption, economic growth and urbanization on ecological footprint: evidence from Brunei Darussalam

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Abstract

This study examines the impact of human capital on ecological footprint, controlling for energy consumption, economic growth and urbanization in Brunei Darussalam over the period 1990–2024. The analysis employs robust econometric techniques, including the Phillips–Perron and Augmented Dickey–Fuller tests, which confirm a mixed order of integration. Structural breaks are addressed using the Zivot–Andrews test, while the Bounds testing approach confirms the existence of a long-run relationship among the variables. The Autoregressive Distributed Lag (ARDL) model is applied to estimate both short and long-run dynamics. The model stability is ensured through diagnostic tests while the robustness of long run results are validated through fully modified ordinary least squares (FMOLS) technique. The findings reveal that human capital significantly reduces ecological footprint in both the short and long run, highlighting its critical role in enhancing environmental sustainability. Energy consumption exhibits a negative long-run effect, suggesting efficiency gains and improved energy utilization. Economic growth initially increases environmental degradation; however, its squared term is negative and significant, confirming the inverted U-shaped Environmental Kuznets Curve (EKC) hypothesis in both the short and long run. Urbanization increases ecological footprint in the long run, reflecting rising consumption and infrastructure pressures, although short-run effects indicate temporary efficiency gains. The error correction term is negative and significant, indicating a rapid adjustment towards long-run equilibrium. By employing ecological footprint as a comprehensive proxy for environmental sustainability, this study provides novel insights for Brunei Darussalam and highlights the importance of human capital development in sustainable growth strategies and efficient energy use.

Keywords Human capital · Ecological footprint · Economic growth · Energy consumption · Urbanization · ARDL · Environmental kuznets curve

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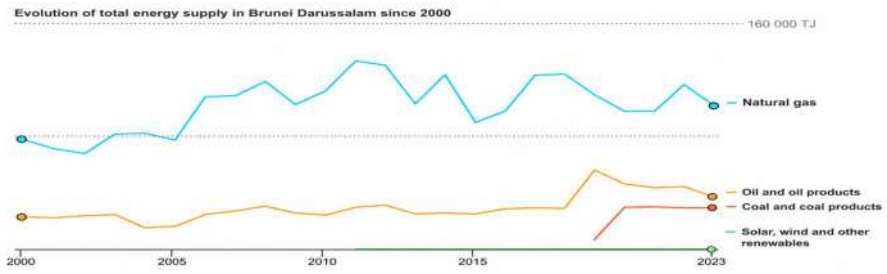
Introduction

Sustainability has emerged as a central concern in contemporary development discourse that aimed at protecting the environment through climate mitigation measures to promote global economic and social progress through cooperative framework (Khan et al. 2025a, 2026a). In 2015, countries around the world came together to adopt the 17 Sustainable Development Goals (SDGs), marking a shared commitment to move towards a more sustainable future. These goals were designed not just to protect the planet, but also to improve people's lives, promote peace, strengthen partnerships and ensure long-term prosperity without jeopardizing the environmental quality. The 2030 Agenda reflects a broad vision that connects human well-being with the health of the environment, offering hope for a more stable, prosperous and harmonious world for present and future generations. The shared commitments of both developing and developed economies towards environmental sustainability are to be met by 2030 by reducing the pressure on ecology and planet earth. Brunei Darussalam's endorsement of the 2030 Agenda for Sustainable Development during the 70th Session of the United Nations General Assembly with the other Member States marked its commitment to this shared vision, especially to tackle climate change by 2030. For the effective realization of these commitments Brunei adopted the long-term strategic program, Wawasan Brunei 2035, aiming to develop a dynamic and sustainable economy while aspiring to position Brunei Darussalam as a nation recognized globally for its educated, highly skilled and accomplished people, ensuring a high quality of life (NDC 3.0, 2020).

According to International Energy Agency (IEA), in 2022 share of modern renewables in total final energy consumption of Brunei Darussalam was merely 0.03% despite a 50% increasing trend from 2011 to 2022, however share of electricity generation from renewables showed an 85% increasing trend from 2011 to 2023 and stood at 0.099% in 2023. To witness an impressive increase in renewable energy Brunei adopted a strategic plan in 2014 to achieve 10% share of renewable energy by 2035. The figure below presents the total energy supply in Brunei since 2000; it is evident from the figure that major contribution to energy supply comes from natural gas while the renewable energy being the lowest source of energy supply that too from 2011 onwards.



Source: Authors' extraction from International Energy Agency website

The economy of Brunei Darussalam is heavily dependent on the fossil fuel based energy resources as natural gas was 61% of its total energy and remained the largest source of total energy supply in 2023. This has badly impacted Brunei by raising the temperature by 0.25 °C per decade since 1970 and mean temperature by 0.4 °C per decade (Brunei Climate Change Secretariat 2020). The high dependence on non-renewables increases the inefficient energy consumption that consequently raises the environmental degradation (Hassan et al. 2024). This view was further affirmed by Xuan 2025 in his study on Brunei by finding that high energy consumption and economic growth rates are associated with increased levels of carbon emissions and consequently the environmental degradation during the empirical period of 1990 to 2023. Despite setting goal to reach net zero emissions by 2050, the levels by which emissions are reduced a gap persists in Brunei policy set up (International Monetary Fund, 2023) which needs a targeted intervention to realize the environmental sustainability.

According to the 2025 Nationally Determined Contribution (NDC 3.0) third report of Brunei Darussalam, Brunei's economy has traditionally relied heavily on its natural resources, particularly the oil and gas sector. In 2023, the oil and gas industry accounted for 58% of GDP, and about 92% of the nation's exports with primary exports being crude oil, petroleum products and Liquefied Natural Gas (LNG). The report further says that its residents who are mostly concentrated in urban areas enjoy the high standard of living due to significant revenues generated from non-renewables as such economic growth of country is mostly reliant on oil and gas production. The heavy reliance on fossil fuel based energy consumption has considerably raised the environmental degradation in Brunei Darussalam in the form of carbon emissions (Hassan et al. 2024). Brunei's total gross GHG emissions stood at 14.60 MtCO2e (Million tonnes CO2 equivalent) in 2023 with consistent rise in energy sector driven by activities in the oil and gas industry, transport and electricity generation. Albeit, energy sector is dominant but not the sole contributor to the environmental degradation as IPPU (6.1%), Waste (1.3%) and Agriculture (0.3%) follow the emission generation (NDC 3.0, 2025). To assess environmental quality, various metrics are used like carbon emissions but ecological footprint is more comprehensive to evaluate the environmental sustainability while analysing the role of human capital in the investigated economies (Khan et al. 2025b). The ecological footprint measures impact on the environment through activities like mining, agriculture and manufacturing i.e. the human pressure exerted on planet earth and the ecological resources. Unlike CO2

emissions, which traditionally dominate climate change discussions, the ecological footprint provides a broader and more comprehensive indicator of environmental degradation.

Given the importance of environmental sustainability, particularly in a resource-rich economy such as Brunei Darussalam with considerable human capital, this study is relevant for policymakers and researchers alike. The contribution of this study is threefold. First, the nexus between human capital and environmental sustainability has been scarcely examined, and mostly through limited proxies such as carbon emissions; this study instead employs ecological footprint as a more comprehensive measure. Second, despite being resource-rich, Brunei's heavy reliance on energy consumption exacerbates environmental degradation, posing challenges for achieving the Sustainable Development Goals by 2030. Third, by focusing on a single-country case, the study addresses the generalization issues inherent in cross-sectional analyses (Hayat and Tahir 2021). As Brunei diversifies beyond oil and gas, understanding these linkages is essential for informed policy, offering insights for a balanced and sustainable development trajectory.

Review of literature

Theoretical framework

Consistent with the objective of examining the impact of human capital on the Ecological Footprint (EFP) as a proxy for environmental sustainability, while controlling for energy consumption, economic growth and urbanization, this study is grounded in endogenous growth theory, the Environmental Kuznets Curve (EKC) hypothesis, the energy–growth nexus and urban transition theory. Endogenous growth theory, particularly the contributions of Romer (1990) and Lucas (1988), highlights the role of human capital and technological progress as key drivers of long-run economic growth. Human capital enhances labour productivity, promotes innovation, and facilitates the adoption of cleaner technologies. Beyond its growth effects, higher levels of education and skills can improve environmental outcomes by increasing environmental awareness and strengthening institutional capacity. The latest empirical evidences also suggest that improvements in human capital are associated with reduced ecological pressure and improved environmental sustainability (Khan et al., 2026c, Khan et al. 2026a). The study also relies on the Environmental Kuznets Curve (EKC) hypothesis, which proposes an inverted U-shaped relationship between economic growth and environmental pressure. In the early stages of development, rising income tends to increase environmental degradation; however, beyond a certain income threshold, further growth supported by technological progress and structural transformation may improve environmental quality (Grossman and Krueger 1995). To capture this nonlinear relationship, both GDP and its squared term are included in the empirical model. The energy–growth nexus emphasizes the importance of energy structure for environmental sustainability. Renewable energy consumption can help decouple economic growth from ecological pressure by reducing dependence on fossil fuels and lowering carbon intensity (Hasanov et al. 2021). Finally urban tran-

sition theory opines the pivotal role of structural transformation in enhancing the sustainability in urban areas through energy demand and infrastructure development (Wang and Dong 2019). Overall, these theoretical perspectives provide a conceptual framework linking human capital (HC), energy consumption (EC), economic growth (GDP) and urbanization (URB) to promote environmental sustainability, measured through the ecological footprint (ECF) in the context of Brunei Darussalam.

Empirical review

The relationship between economic growth and environmental sustainability has been widely examined within the Environmental Kuznets Curve (EKC) framework since the seminal work of Grossman and Krueger (1995), later refined by Stern (2004). The EKC hypothesis suggests an inverted U-shaped relationship in which environmental degradation initially increases with economic growth and declines after reaching a threshold level of income. This framework has been extensively tested across countries by the researchers. However, empirical findings remain inconclusive. While several studies confirm the EKC hypothesis (Zafar et al. 2019; Ahmed et al. 2020; Khan et al. 2025a; Khan et al. 2026a), others report no evidence of nonlinearity (Dietzenbacher and Mukhopadhyay 2007; Çamkaya et al. 2026). These mixed results indicate that the growth–environment relationship is conditional on structural factors such as energy composition, technological progress and institutional quality. Energy consumption plays a central role in linking economic growth with environmental outcomes. It causes economic expansion through increased energy demand, thereby exerting pressure on environmental quality depending on the composition of the energy mix (Sharif et al. 2020; Usman et al. 2022; Pata and Balsalobre-Lorente 2022). In one of the recent study Çamkaya et al. 2025a found that fossil fuel consumption deteriorates the environment quality in E7 countries. In earlier studies as well it was confirmed that fossil fuel consumption is consistently associated with increased environmental degradation (Rahman and Kashem 2017; Usman et al. 2022; Feng 2022), whereas renewable energy contributes to environmental improvement by reducing emissions and environmental pressures through technique, composition and awareness effects (Anwar et al. 2021; Khan et al. 2025a; Çamkaya et al. 2025b; Shahbaz et al. 2025). The latest study of Çamkaya et al. 2026 further complemented this finding and concluded that renewable energy controls the fossil material footprint in G7 economies however this view is contradicted by Çamkaya and Karaaslan 2024 in US where renewable energy did not improved the environmental quality.

Beyond energy consumption, human capital has emerged as a crucial determinant of both economic growth and environmental sustainability. However, its environmental implications remain underexplored and empirically ambiguous. Whilst human capital is not only pivotal in increasing the finance and banking (Sheergujree and Khan 2026a) but is instrumental is abating environmental degradation caused by human actions (Sheergujree and Khan 2026b), financial development in turn plays an instrumental role in decreasing the environmental degradation (Shahbaz et al. 2025; Khan et al. 2025c). A strand of literature suggests that human capital—through education, skills, and awareness—facilitates the adoption of cleaner technologies and environment friendly production techniques, thereby reducing emissions (Bano et al.

2018; Çamkaya et al. 2023; Khan et al., 2026c). This view was further supported by Çamkaya and Karaaslan 2024 in United States who found that human capital significantly enhances the environmental quality during the investigated period of 1965 to 2018. In contrast, other studies report that human capital may increase environmental degradation, particularly in developing regions where economic expansion dominates efficiency gains (Hazwan 2021; Dong et al. 2022; Khan et al. 2025b). Recent studies have adopted the ecological footprint (EFP) as a more comprehensive measure of environmental sustainability. Exploring the link between the human capital and environmental pollution in Turkey during empirical period of 1980 to 2018 Çamkaya et al. 2023 found that human capital decreases the environmental pollution by reducing both carbon emissions and ecological footprint. The more recent evidence in this context comes from Khan et al. 2025a from their study in India and China wherein they found that ecological footprint is a wider representative of environmental sustainability and found that human capital reduces it in investigated economy. They further support this view in their study in India as found mitigation of ecological footprint with the aid of human capital fosters sustainability (Khan et al. 2026).

Lastly the relationship between urbanization and environmental degradation has been a subject of extensive research, with mixed findings. Some studies suggest that urbanization despite fuelling the economic growth exacerbates environmental challenges due to increased energy consumption, vehicular emissions, and industrial activities (Shahbaz et al. 2016; World Bank, 2023; Lee et al. 2023). Khan et al. 2026b conducted a study in major Asian economies and found that urbanization individually causes environmental degradation. This finding is confirmed in the study of Sheergujree and Khan 2026b in India who found a positive impact of urbanization on environmental degradation. The positive association between urbanization and is confirmed in African countries in the study of Shahbaz et al. 2025. Conversely, other studies argue that urbanization can reduce environmental degradation through economies of scale in public services and the adoption of energy-efficient technologies that reduce carbon emission and pressure on the ecological reusources or due to the positive externalities of human capital (Satterthwaite 2009; Phetkeo and Kaneko 2010; Shahbaz et al. 2025; Khan et al. 2026b). Exploring this nexus is important for Brunei Darussalam which holds its large chunk of population in urban areas.

Against this backdrop, exploring the interconnected dynamics of human capital, energy consumption, economic growth and urbanization in shaping the ecological footprint is particularly relevant for Brunei Darussalam. Despite these advances, limited attention has been given to the role of human capital in ensuring the environmental sustainability within the EFP framework, particularly in the context of Brunei Darussalam.

Research hypotheses

H1 (Human Capital Hypothesis): Human capital negatively influences the ecological footprint.

H2 (Energy consumption Control Hypothesis): energy consumption enhances the ecological footprint.

H3 (Economic Growth Control Hypothesis – EKC): Economic growth exhibits a nonlinear (inverted U-shaped) relationship with the ecological footprint.

H4 (Urbanization Control Hypothesis): Urbanization increases the ecological footprint.

Data and model

This study employs annual time-series data for Brunei Darussalam spanning the period 1990–2024 to examine environmental sustainability within the ecological footprint (EFP) framework, with particular emphasis on human capital. The study period from 1990 to 2024 was selected based on the availability and consistency of data for all variables included in the investigation. Additionally, this period captures the major economic, environmental and human capital transitions experienced by Brunei Darussalam, thereby providing a comprehensive framework for examining the long-run relationship among the variables. EFP is used as a comprehensive indicator, capturing the total ecological pressure exerted through demand (Khan et al. 2025a; Khan et al. 2026a), with data sourced from Footprint Data Foundation. Human capital is proxied by the Human Capital Index and data is extracted from the Penn World Table (PWT 10.0). The data on energy consumption, GDP per capita (constant 2015 US$) and urban population are obtained from the World Development Indicators (WDI), World Bank, to account for energy-mix effects, structural transformation and to test the EKC hypothesis (Grossman and Krueger 1995; Sarkodie, et al. 2018; Khan et al. 2026a). The squared term of GDP is included to capture nonlinearity. All variables are transformed into natural logarithms.

Following the existing literature, the empirical model is constructed to examine the effects of human capital, energy consumption, economic growth and urbanization on environmental sustainability.

$$EFP_t = f\left(HC_t, EC_t, GDP_t,\ GDPS_t, URB_t\right) \tag{1}$$

Where,

EFP_t represents Ecological footprint, HC_t denotes human capital index; EC signifies energy consumption GDP_t measures economic growth; and $GDPS_t$ is the square of economic growth to capture potential non-linear effects and $\mathrm{URB_t}$ denotes the urban population. The empirical form of the model, specified as

$$EFP_t = \beta_0 + \beta_1 HC_t + \beta_2 EC_t + \beta_3 GDP_t + \beta_4 GDPS_t + \beta_5 URB_t + \epsilon_t \tag{2}$$

Where β_0 is the intercept, β_1, β_2, β_3, β_4, β_5 are coefficients, and ε_t is the error term. Following Shahbazet al. (2012), a log-linear specification is adopted as presented in Eq. (3). The natural logarithms reduce heteroscedasticity, normalize skewed variables and improve estimation efficiency, while enabling coefficients to be interpreted as elasticities.

$$lnEFP_t = \beta_0 + \beta_1 lnHC_t + \beta_2 lnEC_t + \beta_3 lnGDP_t + \beta_4 lnGDPS_t + \beta_5 lnURB_t + \epsilon_t \tag{3}$$

This framework facilitates a robust analysis of the relationships, aligning with established theoretical and empirical approaches in the literature.

Econometric techniques

Unit root test

The Augmented Dickey–Fuller Test **(ADF)** and Phillips–Perron Test **(PP)** unit root tests are employed to examine the stationarity properties of the time series variables in determining long-run relationships. However, a key limitation of these conventional tests is that they do not account for possible structural breaks in the data, which may lead to biased and unreliable results. To address this limitation, the Zivot–Andrews Unit Root Test with a structural break is also applied. This test endogenously determines the break point in the series and allows one structural break in each variable. The Zivot–Andrew's test considers three models.

Model A:

$$\Delta y_t = \mu + \alpha y_{t-1} + \gamma DUt + \sum {}_{j=1}^{k} \delta_j \Delta y_{t-1} + \epsilon_t \tag{4}$$

Model B:

$$\Delta y_t = \mu + \alpha y_{t-1} + \theta DTt + \sum {}_{j=1}^{k} \delta_j \Delta y_{t-1} + \epsilon_t \tag{5}$$

Model C:

$$\Delta y_t = \mu + \alpha y_{t-1} + \gamma DUt + \theta DTt + \sum {}_{j=1}^{k} \delta_j \Delta y_{t-1} + \epsilon_t \tag{6}$$

Where:

$\mathrm{D}U_t = \begin{cases} 1 & if\ t > TB, \\ 0, & otherwise, \end{cases}$ captures a one-time change in the intercept,

$\mathrm{D}U_t = \begin{cases} t - TB, & if\ t > TB \\ 0, & otherwise, \end{cases}$ captures a one-time change in the intercept, otherwise.

TB is the break year determined endogenously by the model, ϵ_t is a white-noise error term.

ARDL bound testing approach

To examine the long-run and short-run dynamics among the variables, this study employs the Autoregressive Distributed Lag (ARDL) bounds testing approach developed by Pesaran and Pesaran (1997), Pesaran and Shin (1999), and Pesaran et al.

(2000, 2001). The ARDL technique is preferred over conventional cointegration methods because it can be applied regardless of whether the underlying variables are integrated of order I(0), I(1), or a mixture of both. Moreover, the ARDL approach provides more efficient estimates in small samples and allows for endogeneity among explanatory variables (Pesaran & Shin, 1999).

The ARDL model for the present study is specified as follows:

$$\begin{aligned}\Delta EFP_t =& \beta_0 + \beta_{1k} \sum_{k=1}^{n} \Delta EFP_{t-k} + \beta_{2k} \sum_{k=1}^{n} \Delta HC_{(t-k)} + + \beta_{3k} \sum_{k=1}^{n} \Delta EC_{(t-k)} + \\ & \beta_{4k} \sum_{k=1}^{n} \Delta GDP_{(t-k)} + \beta_{5k} \sum_{k=1}^{n} \Delta \mathrm{GDPS}_{(t-k)} + \beta_{6k} \sum_{k=1}^{n} \Delta URB_{(t-k)} + \\ & \lambda_1 EFP_{(t-1)} + \lambda_2 HC_{(t-1)} + + \lambda_3 EC_{(t-1)} + \lambda_2 GDP_{(t-1)} + \lambda_3 GDPS_{(t-1)} + \lambda_6 URB_{(t-1)} + \epsilon_{1t}\end{aligned} \tag{7}$$

where Δ denotes the first-difference operator, β_0 is the intercept term, and ε_t is the error term. The coefficients β_1–β_6 represents short-run dynamics, while λ_1–λ_6 captures the long-run relationship among the variables. To test for co-integration, the null hypothesis of no long-run relationship is formulated as:

$$H_0 : \lambda_1 = \lambda_2 = \lambda_3 = \lambda_4 = \lambda_5 = \lambda_6 = 0$$

Against the alternative hypothesis:

$$H_1 : \lambda_1 \neq \lambda_2 \neq \lambda_3 \neq \lambda_4 \neq \lambda_5 \neq \lambda_6 \neq 0$$

The joint significance of the lagged level variables is evaluated using the F-statistic and compared with the critical bounds values provided by Pesaran et al. (2001). If the calculated F-statistic exceeds the upper bound critical value, the null hypothesis of no co-integration is rejected. If it falls below the lower bound, no co-integration is confirmed, while values between the bounds yield inconclusive results. The Akaike Information Criterion (AIC) is used to select the optimal lag length. Once evidence of co-integration is established among ecological footprint, human capital, energy consumption, economic growth, squared economic growth and urbanization, the long-run coefficients are estimated using the following equation:

$$\Delta EFP_t = \delta_0 + \delta_1 EFP_{t-1} + \delta_2 HC_{t-1} + \delta_3 EC_{t-1} + \delta_4 GDP_{t-1} + \delta_5 GDPS_{t-1} + \delta_6 URB_{t-1} + \mu_t \tag{8}$$

If a long-run relationship exists, the short-run dynamics are estimated through the error correction model as follows:

$$\begin{aligned}\Delta EFP_t =& \varphi_0 + \varphi_1 \sum_{i=1}^{0} \Delta EFP_{t-1} + \varphi_2 \sum_{i=1}^{0} \Delta HC_{t-1} + \varphi_3 \sum_{i=1}^{0} \Delta EC_{t-1} + \\ & \varphi_4 \sum_{i=1}^{0} \Delta GDP_{t-1} + \varphi_5 \sum_{i=1}^{0} \Delta GDPS_{t-1} + \varphi_6 \sum_{i=1}^{0} \Delta URB_{t-1} + + \mathfrak{n} EC_{t-1} + \mu_t\end{aligned}$$

The error correction term EC_{t-1} measures the speed of adjustment toward long-run equilibrium after a short-run shock. The coefficient ψ is expected to be negative and statistically significant, indicating the proportion of disequilibrium corrected in each period.

Robustness check through fully modified ordinary least squares (FMOLS)

The long run coefficients estimated through the autoregressive distributed lag are examined for robustness by applying fully modified ordinary least squares method (Phillips and Hansen 1990). Besides checking the robustness of long run results FMOLS has the ability to well handle the issues of heterogeneity and heterogeneous co-integration (Chandio et al. 2020). In the empirical studies (Chandio et al. 2020), Mukhtarov et al. (2020), Iqbal et al. (2023) and Makur and Sur (2026) FMOLS method has been used to verify the long-run coefficient's accuracy, to assess the accuracy and robustness of the ARDL results. The application of the robustness method as such validates the long run findings of autoregressive distributed lag model.

Stability of the short-run model long and short run (Estimation)

The cumulative sum (CUSUM) and CUSUM of the square test on the recursive residuals are used to assess the stability of the model in the short-run. While the CUSUM of squares test can identify abrupt changes from the constancy of regression coefficients, the CUSUM test can identify systematic changes from the regression coefficients (Brown et al. 1975).

Results and discussion

The descriptive statistics as presented in Table 1 indicate moderate variation across the variables, with ecological footprint (LnEFP) showing a mean of 1.66 and a relatively high standard deviation (0.45), suggesting noticeable fluctuations in environmental pressure over the sample period. The main explanatory variable, human capital (LnHCI) is quite stable, with a mean close to 0.98 and a very low standard deviation (0.04), implying gradual and consistent improvements in human capital. Similarly, energy consumption (LnEC) exhibits limited dispersion (mean = 8.97; SD = 0.13), indicating steady energy use patterns. For the economic variables, economic growth (LnGDP) and its squared term (LnGDPS) display modest variability, reflecting a stable growth trajectory, which is important for testing the nonlinear Environmental Kuznets Curve (EKC) hypothesis. The relatively narrow range between minimum and maximum values further supports this stability. Meanwhile, urban population (LnURB) also shows very low variation (SD = 0.04), suggesting a slow but steady urbanization process as the Brunei is mostly urbanized previously.

Table 1 Descriptive Statistics

Statistic	LnEFP	LnHCI	LnEC	LnGDP	LnGDPS	LnURB
Mean	1.663854	0.981164	8.968964	10.45692	109.3640	4.284245
Median	1.827770	0.980407	8.951364	10.49611	110.1683	4.309919
Maximum	2.100469	1.044547	9.199767	10.69651	114.4152	4.321641
Minimum	0.398776	0.890036	8.729219	10.25938	105.2549	4.185854
Std. Dev.	0.446584	0.041270	0.134431	0.131767	2.755680	0.041905

Authors' Compilation

Table 2 Unit root test results

Variables	Philipps Perron (PP)		Augmented Dicky Fuller (ADF)	
	Levels	Difference	Levels	Difference
LnEFP	−0.335465 (0.9861)	−8.275559 (0.0000)*	−0.752033 (0.9604)	−7.610143 (0.0000)*
LnHCI	−4.924112 (0.0018)*	−2.191360 (0.4785)	−5.360321 (0.0007)*	−4.669781 (0.0041)*
LnEC	−3.781721 (0.0301)**	−8.448711 (0.0000)*	−3.771239 (0.0308)**	−7.616243 (0.0000)*
LnGDP	−2.448716 (0.3498)	−5.804272 (0.0002)*	−2.606393 (0.2800)	−5.785551 (0.0002)*
LnGDPS	−2.466572 (0.3415)	−5.842931 (0.0002)*	−2.630384 (0.2702)	−5.821570 (0.0002)*
LnURB	−5.189059 (0.0002)*	−1.476212 (0.01872)**	−2.994323 (0.0477)**	−1.263186 (0.0876)***

Authors' Compilation. Note: Asterisk mark *, **&*** indicate Significance level at 1%, 5% and 10% levels respectively

Table 3 Structural break tests

Zivot-Andrews test				
	Levels		Difference	
Variables	t-stat	Break Year	t-stat	Break Year
LnEFP	−2.775 (0.002)*	2019	−4.113 (0.000)*	2018
LnHCI	−6.297 (0.153)	2003	−6.471 (0.208)	2005
LnEC	−4.656 (0.024)**	2006	−4.045 (0.169)	2002
LnGDP	−3.186 (0.023)**	2008	−2.648 (0.219)	2004
LnGDPS	−3.204 (0.022)**	2008	−2.648 (0.223)	2004
LnURB	−3.854 (0.004)*	2017	−5.051 (0.001)*	2007

Authors' Compilation. Note: Asterisk mark *, ** indicate Significance level at 1% & 5% levels respectively

The unit root results from both the Phillips–Perron Test and Augmented Dickey–Fuller Test that are tabulated in Table 2 reveal a mixed order of integration among the variables, which is suitable for ARDL estimation. Human capital, energy consumption and urbanization are stationary at levels, implying I(0) order in both the tests while as other variables ecological footprint, economic growth and its square term are non-stationary at level but became stationary at difference indicating order one I(1).

Table 3 presents the structural break results based on the Zivot–Andrews Test that reveal important turning points in the time series that can be plausibly linked to economic, environmental and policy developments in Brunei Darussalam. For ecological footprint significant breaks around 2019 likely reflect the comprehensive measures like undertaking of rejuvenation projects by the Govt. helped to reduce total GHG emissions from 38% in 2015 to 18.1% in 2018. Besides, to accomplish the sustainable development goals (SDGs) for which country's first Voluntary National Review (VNR) was issued in 2020 exhibiting the measures undertaken to mitigate the environmental degradation. Brunei was one of the first ASEAN nations to ratify the Paris Agreement in 2016 that made it more concerned to mitigate the climate change and to reduce the pressure on ecological resources. In contrast, human capital (HCI) does not exhibit statistically significant structural breaks, suggesting a smooth

Table 4 Lag Model Ecological Footprint

Lag	LogL	LR	FPE	AIC	SC	HQ
0	370.5965	NA	1.02e-17	−22.09676	−21.82466	−22.00520
1	615.6530	386.1498	3.34e-23	−34.76685	−32.86220	−34.12600
2	703.9444	107.0198*	1.77e-24*	−37.93602*	−34.39882*	−36.74586*

* indicates lag order selected by the criterion. Authors' Compilation

Table 5 Co-integration results of ARDL bound test

Estimated Model	F-Stat	Lag Order	Cointegration
LnEFP/LnHCI, LnEC, LnGDP, LnGDPS, LnURB	4.731121*	(1, 0, 2, 0, 0, 1)	Yes

*Indicates statistical significance at the 5% level. F-statistic: Tests for the presence of a long-run relationship. Lag order: Shows the selected lags for each variable in the ARDL model. Co-integration: 'Yes' indicates a long-run relationship exists

and gradual accumulation process. For energy consumption (EC) the identified break around 2006 may be associated with structural transformation in the energy sector, including fluctuations in oil and gas production and evolving domestic energy policies towards efficient energy in an economy heavily reliant on hydrocarbons. Similarly, economic growth and its square show breaks around 2008, which can be linked to the global economic slowdown triggered by the global financial crisis of 2008, affecting oil prices and consequently Brunei's GDP, given its dependence on energy exports. Overall, the presence of these structural breaks highlights the importance of accounting for regime shifts in empirical modelling. Ignoring such breaks could bias the estimated relationships between ecological footprint, human capital, energy consumption, economic growth and urbanization in the context of Brunei Darussalam. Following Hashmi et al. 2020, this study controls for the break in the analysis by adding to the model a dummy variable and redo the analysis. Nevertheless, the coefficient of the structural break remained statistically insignificant, suggesting that structural break has no influence on environmental quality in Brunei Darussalam.

The lag length selection results for the ecological footprint model are presented in Table 4 and indicate that lag 2 is the optimal specification. This is evidenced by all major information criteria—Final Prediction Error (FPE), Akaike Information Criterion (AIC), Schwarz Criterion (SC), and Hannan–Quinn (HQ)—reaching their minimum values at lag 2, as marked by the asterisks.

The ARDL bounds testing results presented in Table 5, based on the Bounds Testing Approach, provide strong evidence of long-run relationships among the variables. The reported F-statistics for the model is statistically significant at the 5% level, indicating that model exceed the critical upper bound. This confirms the presence of co-integration between ecological footprint, human capital, energy consumption, economic growth, its squared term and urban population.

The ARDL results presented in Table 6 reveal a clear distinction between long-run equilibrium relationships and short-run dynamics among ecological footprint (LnEFP) and its determinants, with findings broadly supporting the Environmental Kuznets Curve (EKC) hypothesis.

In the long run, the variable of interest human capital exerts a strong and statistically significant negative impact on ecological footprint with 1% increase in human

Table 6 ARDL long run, short run and diagnostic test results

Long run results			Short run results		
Variable	Coefficient	Prob.	Variable	Coefficient	Prob.
LnHCI	−28.459849	0.0003***	D(LnHCI)	−17.904482	0.0008***
LnEC	−1.367678	0.0146**	D(LnEC)	0.299631	0.2341
LnGDP	103.307148	0.0409**	D(LnGDP)	64.991945	0.0771*
LnGDPS	−14.944755	0.0397**	D(LnGDPS)	−9.401951	0.0755*
LnURB	7.653646	0.0833*	D(LnURB)	−52.070136	0.0408**
C	−168.748294	0.0402**	CointEq(−1)	−0.629114	0.0004***

Diagnostic results		
Diagnostic test	F-stat	Prob.
Breusch–Godfrey serial correlation	1.704929	0.2060
Normality test (Jarque Bera)	2.700104	0.259227
Ramsey RESET test	4.086918	0.555
Heteroskedasticity (Breusch–Pagan–Godfrey)	1.197131	0.3431

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D (variable) represents the first difference of the variable. ECT represents the error correction term, indicating the speed of adjustment. ***Significant at 1% level, **significant at 5% level

capital leading to 28% reduction in ecological footprint in Brunei Darussalam, indicating that improvements in education, skills and technological capabilities substantially reduce environmental degradation. The same trend has been exhibited in the short run as with 1% increase in human capital there is a 17% decrease in ecological footprint indicating that impact of human capital is immediate which is enduring in long run with more decrease. This result is consistent with Brunei's policy orientation toward knowledge-based development and human capital enhancement since a long and its high levels of human capital index has benefited its economy with enhancement in sustainability. The results in this context are in consonance with the study of Khan et al. 2025a; Khan et al. 2026a which report a negative relation between the human capital and ecological footprint in the respective studies implying a positive influence of human capital on environmental sustainability. Many reasons can be held responsible for the rising and high levels of human capital in Brunei Darussalam the nation with less than half a million population like prioritizing of universal education to the citizens. The various policy interventions like free and compulsory basic education to all children aged 6 to 14 years through Compulsory Education Act 2007; envisioning of National Education System for 21 st Century (SPN21) in 2009; initiation of 'Strategic Plan for 2018–2022' by Ministry of Education to achieve the potential vision of 'Quality Education, Dynamic Nation' to maximize the talent of students and an appetite for life-long learning aimed at supporting Wawasan Brunei 2035 to build a knowledge based society through increasing opportunities to life-long learning; inception of School and Family Engagement (SAPE) program in 2014 in all pre-schools to involve parents in children literacy developments etc. were instrumental in raising the human capital in the country (Voluntary National Review Report, 2020). These policy interventions were supported by the programs run by non-governmental organizations and other institutions to help country in building the human capital. La Vida's, a local NGO educational support to unprivileged and students in need; providing of assistance to students in need by Chinese Chamber of Com-

merce in Brunei Darussalam through its education fund scheme that has helped many students to complete their tertiary education in Law, Medicine and Management; Bank Islam Brunei Darussalam (BIBD) ALAF program to support life-long learning aspiration of unprivileged and needy students etc. have complemented the effort of Govt. to raise the education and learning of skills capacity of the children (Voluntary National Review Report, 2020). These combined efforts especially the government sponsored policies have helped this small country of Brunei to excel in the OECD's Program for International Students Assessments (PISA) tests and has achieved 3rd rung among participating ASEAN countries in 2018 in these tests implying its students proficiency in Reading, Mathematics and Science i.e., achieving of quality education and not merely the rising enrolments. The emphasis on quality education in this respect has not only raised the per capita income of the masses but also the sustainable approach toward environment in Brunei. A more educated populace is likely to adopt cleaner technologies, improve energy efficiency and support environmentally conscious decision-making, thereby lowering ecological pressure. Apart from these the targeted comprehensive measures were adopted to accomplish the sustainable development goals (SDGs) for which country's first Voluntary National Review (VNR) was issued in 2020 exhibiting the measures undertaken to mitigate the environmental degradation. Brunei was one of the first ASEAN nations to ratify the Paris Agreement in 2016 that made it more concerned to mitigate the climate change and to reduce the pressure on ecological resources. The rejuvenation projects were undertaken by the Govt. to reduce the heavy dependence on fossil fuel based energy that have attributed in reducing the shares of fugitive emissions of total GHG emissions from 38% in 2015 to 18.1% in 2018.

Similarly, energy consumption shows a negative and significant long-run coefficient, suggesting that 1% increase in energy consumption leads to 1.36% decrease in ecological footprint indicating that increased energy use is associated with reduced ecological footprint. The results in this category are in conformity with the findings of (Khan et al. 2025a, 2026a) that state a negative link between the renewable energy consumption and ecological footprint in their investigated economies but contradict with findings of (Sharif et al. 2020; Usman et al. 2022; Pata and Balsalobre-Lorente 2022) which found that increased energy consumption exerted pressure on environmental quality. However in short run there is positive but insignificant relationship between the energy consumption and ecological footprint with 1% increase in energy consumption leads to 0.29% increase in ecological footprint implying that the increased energy consumption in short has a positive but insignificant impact on ecological footprint. Brunei Darussalam is a resource rich country particularly in non-renewable energy source like oil and gas but to realize SDGs particularly the sustainable development goal 7 of affordable and clean energy, has initiated many efforts. Among the various measures include electrification of country and expansion of electric grid through targeted interventions that have helped realization of 99.9% electrification access gained by the population of Brunei. It has been made possible by the highly regulated electricity tariffs as affordable energy cost for residential sector was provided at an average of USD 0.05/kwh and also through the installation of solar powered panel in government buildings (Voluntary Review Report, 2020). Brunei Darussalam has been in international and regional collaboration to diversify its

energy sector that is highly reliant on the oil and gas. Brunei is member international energy agency (IRENA) and has benefited from its collaboration to diversify the energy mix. The regional collaboration with ASEAN and co-hosting of 4th East Asia Energy Forum entitled 'A Low-Carbon Energy Transition in the ASEAN Region' in 2021 have also helped Brunei in this context. Other collaboration to diversify the energy mix include bilateral cooperation with Malaysia, Singapore and other countries in the areas of energy and green economy has helped Brunei to decrease the pressure on ecological resource and to reduce the ecological footprint and overall this performance can be attributed to Brunei's relatively efficient and modern energy infrastructure, along with gradual improvements in energy efficiency and potential shifts toward cleaner energy sources. In an oil-rich economy like Brunei, energy consumption may reflect productive efficiency rather than environmental harm, particularly when supported by better technology and regulatory oversight.

The Table 6 further reports an important finding of the study, economic growth has a positive and significant long-run effect indicating that 1% increase in economic growth in Brunei leads to 103% increase in ecological footprint, implying that initial economic expansion increases environmental degradation in larger proportions due to higher resource extraction, industrial activity and dependence on fossil fuels. The early phase of economic growth is also intensified by the attempts to transform demographic potential into demographic dividend (Ahmad 2023) that is focused mainly of the rising the productivity and employment without any potential preference for clean environmental activities. The larger coefficient of economic growth indicates the heavy reliance of Brunei on fossil fuel based energy consumption which is causing larger environmental degradations. However, after a threshold point the further increase in squared economic growth causes a statistically significant reduction in ecological footprint as 1% increase in squared economic growth leads to 14% decrease in ecological footprint. The smaller coefficient of growth square implies reduction in environmental degradation but comparatively lesser than the degradation caused in initial phase of economic growth. The positive coefficient of economic growth (i.e. $\beta_3 > 0$) and negative coefficient of squared of economic growth (i.e. $\beta_4 < 0$) confirms the presence of an inverted U-shaped EKC relationship in Brunei Darussalam in long run. This implies that beyond a certain income threshold, further economic growth leads to environmental improvements, as higher income enables investment in cleaner technologies, stricter environmental regulations, and sustainable practices. The short run coefficients of economic growth and its squared term also exhibit the same trend that of long run. A 1% increase in economic growth cause 64% increase in ecological footprint and consequently the environmental degradation, while as 1% increase in square of economic growth diminishes the ecological footprint by 9% indicating improvements in environmental quality. The positive coefficient of economic growth and the negative coefficient of its squared term confirm the presence of inverted U shaped EKC in short run in Brunei during the empirical period of 1990 to 2024. The findings of presence of inverted U shaped in both long and short run are in consonance with the finding of (Khan et al. 2025a; Khan et al. 2026a) who report that economic growth initially cause environmental degradation but the subsequent increase in it after a threshold causes environmental quality to improve paving way to achieve the third goal of Wawasan Brunei 2035 to build a dynamic and sustainable

economy. This finding of existence of inverted U curve is contradicted to Çamkaya et al. 2026 who invalidated the EKC hypothesis in G7 economies.

The findings further report that Urbanization exhibits a positive impact on ecological footprint in long-run indicating that 1% increase in urbanization leads to 7.65% increase in ecological footprint, suggesting that urbanization contributes to increased ecological footprint through rising consumption, infrastructure expansion and energy demand. This finding is in conformity with the results of (Shahbaz et al. 2025; Khan et al. 2026b; Sheergujree and Khan 2026b) which found the increased environmental degradation due to increased urbanization. Although a reverse relationship between the urbanization and ecological footprint is observed in short run implying 1% in urbanization leading to 52% decrease in ecological footprint reflects Brunei's controlled and planned urban growth. This implies that short-term urban development may temporarily reduce ecological footprint, possibly due to efficiency gains, improved infrastructure and better resource management in urban areas.

The findings obtained from the ARDL technique are further validated by the results derived from the fully modified ordinary least square (FMOLS) method, which is employed as a robustness check, consistent with Makur and Sur (2026). The FMOLS estimates presented in Table 7 shows that Human capital (LnHCI) exhibits a negative and statistically significant effect on ecological footprint. Likewise, energy consumption (LnEC) shows a negative coefficient, similar to the long-run ARDL results; however, the statistical significance differs, as the FMOLS estimate is statistically insignificant. Economic growth (LnGDP) demonstrates a positive and statistically significant impact on ecological footprint, while the coefficient of squared GDP is negative and statistically significant, consistent with the ARDL long-run estimates. The positive coefficient of GDP alongside the negative coefficient of GDP squared confirms the validity of the Environmental Kuznets Curve (EKC) hypothesis within the FMOLS robustness framework as well. Furthermore, urbanization (LnUP) exerts a positive and statistically significant effect on ecological footprint. Overall the estimates of FMOLS validate the findings obtained from autoregressive distributed lag technique.

The error correction term (ECT) is negative and highly significant (–0.6291, $p<0.01$), confirming the existence of a stable long-run relationship and indicating that approximately 63% of any short-run disequilibrium is corrected within one period. This reflects a relatively rapid adjustment process toward long-run equilibrium in Brunei's environmental system.

The diagnostic tests support the reliability of the model. The Breusch–Godfrey test indicates no serial correlation, the Jarque–Bera test confirms normality of residuals, and the Breusch–Pagan–Godfrey test shows no heteroskedasticity, ensuring that the

Table 7 FMOLS robustness check

Variable	Coefficient	Prob.
LnHCI	−29.01225	0.0002
LnEC	−0.469233	0.2789
LnGDP	101.9815	0.0093
LnGDPS	−15.00585	0.0070
LnUP	10.15925	0.0160
C	−181.8759	0.0031

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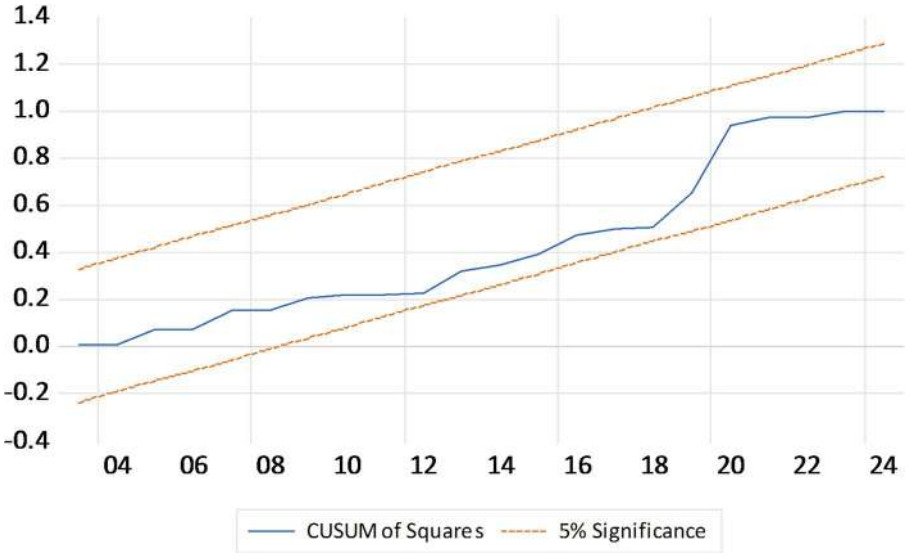
Graph. 1 CUSUM plots



Graph. 2 CUSUM square plots

regression assumptions are satisfied. Overall, the model is statistically sound, and the results highlight the critical role of human capital and structural transformation in mitigating environmental degradation in Brunei Darussalam.

Finally the short run stability is confirmed through CUSUM and CUSUM of square presented in graph 1 and graph 2 respectively, both of which indicate that the

estimated parameters remain stable over the sample period, as the plots lie within the critical bounds.

Conclusion and policy implications

The study examined the impact of human capital on ecological footprint controlled for energy consumption, economic growth and urbanization during the empirical period of 1990 to 2024 in Brunei Darussalam using the ARDL framework. The empirical findings confirm the existence of a stable long-run equilibrium relationship among the variables, supported by the bounds testing results. The analysis reveals that human capital plays a crucial role in improving environmental quality, as evidenced by its strong and significant negative impact on ecological footprint in both the long and short run. This highlights the importance of education, skills and technological advancement in promoting sustainable development. The results further indicate that energy consumption reduces ecological footprint in the long run, reflecting efficiency gains and the relatively modern energy infrastructure in Brunei. However, its short-run effect is insignificant, suggesting that environmental benefits from energy use materialize over time. The relationship between economic growth and environmental degradation follows an inverted U-shaped pattern, validating the Environmental Kuznets Curve (EKC) hypothesis. Economic growth initially exacerbates environmental pressure due to reliance on fossil fuels, but beyond a certain threshold, higher income levels facilitate environmental improvements through technological progress and stronger regulations. Urbanization exhibits a mixed impact, increasing ecological footprint in the long run due to rising consumption and infrastructure demands, while contributing to environmental improvements in the short run through efficiency gains and better resource management. The error correction mechanism confirms a relatively fast adjustment toward long-run equilibrium, highlighting the dynamic stability of the system. Overall, the findings emphasize that structural transformation, particularly through human capital development and sustainable growth strategies, is key to mitigating environmental degradation in Brunei Darussalam.

Based on the empirical findings, several policy implications emerge for enhancing environmental sustainability in Brunei Darussalam. First, the strong negative impact of human capital on ecological footprint suggests that sustainability is largely driven by knowledge, skills and technological capability. Policies should therefore emphasize environmentally oriented human capital development through education, green skills training, and support for research and innovation should be aligned with Wawasan Brunei 2035. The curriculum of the country should be aligned with the environmental sustainability to raise awareness among the educated population that in the race of raising economic growth and competing to land in top 10 nations with high standard of living, the quality of environment is not compromised. The high human capital index of Brunei must continually depict the enhancing of awareness effect harnessed from it as country is still relying more on the natural gas and oil in meeting its energy demands. The human capital benefits should be externalized towards the diversification of industrial sector which is the back bone of the economy and leaps towards the non-pollution

emitting sectors like services sectors must be harnessed through the high levels of human capital index. Although energy consumption underpins economic activity, reliance on non-renewables threatens environmental quality. Brunei's progress in energy diversification and efficiency improvements should be strengthened by promoting cleaner energy and efficient use rather than restricting consumption, ensuring decoupling of growth from environmental harm. The investments in the green energy sectors should be increased both by making special provisions in the domestic budget and with the support of international and regional organizations like International Energy Agency and Asian Development Bank. The country must make cooperation with economies that lead in technical expertise in various forms of renewable energy and make collaborations with such countries to enhance these pro environmental forms of energy. Like making collaborations with China which leads in global solar PV manufacturing can help Brunei to gain momentum in solar energy. This will help Brunei to reduce dependence on fossil fuel based energy that is major source of environmental degradation and to make a transition towards renewable energy that is sustainable and having ability to spur innovations that increase employments and transcends towards a green economy. The inverted U-shaped relationship between growth and ecological footprint, consistent with the Environmental Kuznets Curve, indicates a transitional phase. Policymakers should accelerate the shift to sustainability through stricter regulations, clean production incentives and economic diversification. The country shall design economic plan that focus on the diversification of economic activities outside the realm of traditionally dependent activities based on oil and gas sector which can provide a sustainable employment to the population of the country. The country should not compromise this strategy even to the international investments entering the country in the form FDI from multinational companies. Brunei can no longer benefit from the industrial activities based on the fossil fuel energy as the current gains in the form of increasing income are based on compromising the environmental quality. The country shall also explore the employment generation in agriculture, forestry and fishing sectors for sustainable development. Urbanization, while initially efficient, may increase long-term environmental pressure. This necessitates sustainable urban planning focused on resource efficiency and integrated systems. The 74% of Brunei's population is residing in the urban areas which resonates the modernization and infrastructure upscale by policies adopted in Brunei but is yet be a sustainable one. The focus of policy framers should shift towards the green urban planning for which the gains of human capital can be harnessed. The human capital induced urbanization can reduce the consumption and production based on non-renewable energy to make Brunei sustainable economy. The country shall intensify its efforts to realizes the objectives of sustainable urban planning, enhancing air quality through strengthening transboundary cooperation with neighboring economies, sustainable construction and waste management as envisioned by Brunei in its address to 81st session of united nation economic and social commission for Asia and Pacific (ESCAP). Overall, achieving sustainability in Brunei requires a balanced approach integrating human capital, energy efficiency and coherent environmental and economic policies.

Limitations and potentialities for future research

Despite providing important insights, this study faces some limitations that are acknowledged to address the future prospects of research. The study relies on a restricted set of variables of human capital, energy consumption, economic growth, urbanization and ecological footprint, which may not fully capture the complexity of environmental degradation. Future investigations can incorporate other relevant factors such as load capacity factor, technological innovation, institutional quality, renewable energy and trade openness to capture comprehensively the complexity of environmental concerns. While structural breaks and diagnostic tests are considered, the ARDL framework may not fully account for all potential nonlinearities and regime shifts in the data. The testing of inverted load capacity curve (ILCC) hypothesis can be an added advantage over conventional EKC in the forthcoming studies along with employing of advanced nonlinear or panel techniques to provide more comprehensive and generalizable results.

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Data availability Upon reasonable request the relevant author shall provide the data supporting the conclusions of the study.

Declarations

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