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Influence of climatic factors on ecological performance of the economy: empirical evidence from BRI countries

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Over the past few decades, human activity, particularly CO₂ emissions, has been the primary cause of global climate change. Urbanization, population growth, and economic advancements also contribute to increased carbon emissions. Renewable energy projects and green production methods can mitigate CO₂ emissions. Despite extensive research on climate change, there is a significant gap in understanding the combined impact of climatic factors such as urban population growth, forest area, electricity production from oil and nuclear sources, and average precipitation on ecological performance in Belt and Road Initiative (BRI) countries. This study aims to fill this gap by analyzing data from 20 BRI countries from 1992 to 2021 using the two-step generalized method of moments (GMM) estimation. The findings reveal that urban population growth and electricity production from oil sources significantly increase CO₂ emissions, underscoring the environmental challenges posed by rapid urbanization and fossil fuel dependence. Conversely, forest area and electricity production from nuclear sources demonstrate a mitigating effect, reducing emissions and highlighting the importance of forest conservation and low-carbon energy transitions. Average precipitation depth also shows a significant, though weaker, influence on emissions, highlighting its role in shaping ecological outcomes. This study contributes to the literature by comprehensively assessing climatic factors within the BRI framework by integrating empirical analysis with policy relevance. The results emphasize the need for targeted policies to enhance ecological performance, such as sustainable urban planning, reforestation, and nuclear energy adoption. The research highlights the originality of its methodology and design, offering actionable insights for BRI nations to combat climate change while fostering economic development.

KEYWORDS

urban population growth, forest area, average precipitation in depth, ecological performance, BRI countries

Introduction

The increase in greenhouse gases during the last several decades, especially carbon dioxide emissions (CO₂) brought on by human activity, has been the main cause of global climate change (Mahmood et al., 2022). IPCC predictions state that the worldwide CO₂ emissions from industrial processes and energy consumption peaked in 2021 at 36.3 GtCO₂.

(Wen et al., 2021). The World Economic Forum (WEF) claims that the world won't be able to combat climate change if more drastic action isn't done. As such, it will be reduced to a "hothouse world" scenario (Balsalobre-Lorente et al., 2022; Sun et al., 2020). China's metropolitan areas generated the most CO₂ emissions, accounting for around 75.15% and 85% of the country's total energy consumption and CO₂ emissions, respectively. These figures are greater than the average for the world (Kahia and Omri, 2021).

Urbanization is a global phenomenon characterized by changes in the environment, society, and physical space (Nasir et al., 2021). Due to migration, natural population growth, and economic advancements, urbanization has widened the dispersion of the population in recent years (Growth and Index, 2021). Millions of individuals migrate to urban regions in quest of better living conditions since they are centers of innovation, economic activity, and cultural interchange. Thus, as the pace of urbanization rises, sustainability and carbon emission-related environmental challenges have taken center stage (Torun et al., 2022). Urban areas are the primary source of greenhouse gas emissions worldwide, with CO₂ being the most important pollutant. Inefficient infrastructure, dependence on non-renewable energy sources, poor urban planning, and traffic patterns all contribute to the energy consumption and emissions that result from the combination of human activity, industry, infrastructure, and transportation networks in urban areas (Radwan et al., 2020).

Moreover, woods are important to uphold the health of immune systems and a balanced biological environment. However, in BRI member countries, the development of infrastructure and urbanization often result in the deforestation of forests, which increases carbon emissions (Aluko et al., 2023). These relationships will serve to create anti-deforestation policies, land-use decision support tools, and climate change laws through forest extension and emission CO₂ determination (Urb and Stud, 2023). Eco-friendly BRI members could prevent the deterioration of forest ecosystems and thereby reduce the emission of CO₂ indirectly by investing in renewable energy projects and green production methods (Boleti et al., 2021). Likewise, power and wealth have always been connected to oil since the date of its creation (Lee & Olasehinde-Williams, 2024). The process of oil production itself has yet to have sufficient outcomes. The phenomena of perpetual growth and merciless competition that bring corruption and symbolic violence into the scene are some features of the political oil geography in both the past and the present (Yu et al., 2024). There are various factors, such as financial markets, the level of economic growth, technical developments, and unexpected events, that come into play in the oil industry (Ghazouani and Beldi, 2022).

Furthermore, there is a substitutive relationship between the production of other commodities, such as coal, natural gas, or

renewable energy, and the volatility of oil prices (Chu and Le, 2022). In the global energy landscape, the oil industry makes a considerable contribution to the provision of power (Balsalobre-Lorente et al., 2022). As mentioned by (Li and Lei, 2022), the introduction of nuclear power began in the middle of the 20th century, after the need for a stable and available energy source with low fossil fuel consumption became crucial. The expansion of nuclear energy projects at the global level can be explained by many factors, such as geopolitical issues, problems in the energy security sector and the advantages of having a source of energy that is reliable and efficient (Chaabouni and Saidi, 2017). In the last 10 years, particularly, the expansion of the nuclear industry has caught a lot of attention, partially due to the fact that it is considered an environmentally friendly solution with a low carbon footprint. It has been influenced by the incorporation of new reactors for use, safety improvements, and energy with complexity and accountability (Epule, 2012).

In addition, average precipitation in depth, which measures the average volume of water deposited in a particular region during a specific period, aids in researching climate change and its effects on ecological balance, agriculture, and water resource management. Radar weather systems, satellite-based remote sensing, and rain gauges are the methods used to collect data. To assess the effects of climate change, historical patterns and trends such as the distribution of water resources over time, the frequency of droughts and floods, urban planning, infrastructure development, and disaster management are often considered (Mchunu and Chaplot, 2012). Understanding the average precipitation depth on regional and global scales requires analyzing meteorological data records, merging data from many sources, and analyzing climate models (Sarfranz et al., 2022). Besides, Rapid urban population growth increases energy use and infrastructure requirements, thus elevating CO₂ emissions. Forest areas function as carbon sinks, which reduce emissions; however, tree removal through deforestation causes climate change problems to grow worse. The production of electricity using oil as a source is an emission-intensive process, whereas nuclear energy represents a low-carbon power generation solution. The amount of average precipitation shapes ecosystems and agricultural operations and impacts land management practices and carbon storage. While prior research has extensively examined the individual effects of climatic factors (e.g., urbanization, forest cover, energy sources, and precipitation) on CO₂ emissions, several critical gaps remain unaddressed, particularly in the context of Belt and Road Initiative (BRI) countries. Our study bridges these gaps through the following contributions:

Existing studies often analyze variables such as urbanization, forest area, or energy sources in isolation (e.g., Liu et al., 2021 on urbanization; Begum and Raihan, 2020 on forests; Voumik et al., 2022 on oil energy). However, the combined impact of these factors on ecological performance remains underexplored, especially in BRI nations where rapid infrastructure development and economic diversity create unique environmental trade-offs. This study is the first to integrate these variables into a unified framework, revealing their combined effect on CO₂ emissions. Moreover, while prior work focuses on individual countries or regions (e.g., China, OECD), this analysis of 20 BRI nations addresses the lack of cross-country empirical studies in this transcontinental context

Abbreviations: BRI, Belt and road initiative; CO₂, Carbon Dioxide; GMM, Generalized Method of Moments; IMF, International Monetary Fund; OECD, Organization for Economic Co-operation and Development; GDP, Gross Domestic Product; FDI, Foreign Direct Investment; N₂O, Nitrous Oxide; CIPS, Cross-Sectional Im-Pearson-Shin; VIF, Variance Inflation Factor; STIRPAT, Stochastic Impacts by Regression on Population, Affluence, and Technology; REDD-plus, Reducing Emissions from Deforestation and Forest Degradation; IFCS, Intergovernmental Forum on Chemical Safety.

(Ashraf, 2022; Wu et al., 2023). Furthermore, previous research relies heavily on static models (e.g., FMOLS, DOLS) or fails to account for endogeneity and dynamic persistence in emissions (Ahmad et al., 2022; Majumder et al., 2023). This research employs a two-step System GMM estimator to address endogeneity, autocorrelation, and heteroscedasticity, providing robust estimates of long-term relationships—a methodological gap highlighted by Roodman (2009) but rarely applied in BRI environmental studies. Prior literature overlooks the nuanced policy implications of precipitation variability and nuclear energy adoption in BRI nations. For instance, while Zhang et al. (2023) study the role of precipitation in grasslands, we identify its inverse effect in urban-industrial BRI zones due to challenges in stormwater management. Similarly, the study quantifies the emissions-reducing potential of nuclear energy in BRI countries, contrasting with Mahmood's (2022) focus on high-income nations. Finally, this study's dynamic panel approach reveals that BRI forests sequester 42% more CO₂ per unit area than estimated (Begum and Raihan, 2020), highlighting the urgency of tailored reforestation policies. By addressing these gaps, our study offers a holistic, policy-relevant analysis tailored to the BRI's unique environmental challenges.

The paper is organized as follows: Section 2 provides a literature review, discussing the theoretical foundations and empirical literature and identifying key research gaps. Section 3 presents the conceptual framework and methodology, as well as describes the dataset and variable construction for 20 BRI countries (2000–2022). Section 4 reports empirical results, including baseline estimates, robustness checks, and mechanism analysis. Section 5 discusses the findings from the existing literature and their policy implications, providing specific recommendations for BRI policymakers and suggesting directions for future research.

Research hypothesis

The hypotheses of the study were formed by combining the theoretical framework (the STIRPAT model and Ecological Modernization Theory) with empirical evidence from previous studies and modified to fit the context of the BRI.

1. H1: Urban population growth positively affects CO₂ emissions.
2. H2: Forest area negatively affects CO₂ emissions.
3. H3: Electricity production from oil sources positively affects CO₂ emissions.
4. H4: Electricity production from nuclear sources negatively affects CO₂ emissions.
5. H5: Average precipitation depth negatively affects CO₂ emissions.

Review of literature

Theoretical framework

Ecological Modernization Theory

This research implicitly relies on the Ecological Modernization Theory (Mol and Spaargaren, 2000), which posits that economic growth can be decoupled from environmental degradation through

technological innovations and governmental measures (e.g., the introduction of nuclear energy and forest replenishment). With the analysis of the potential of BRI countries to develop in the direction of low-carbon (nuclear) energy and sustainable land use (forest conservation), this study engages in the discussion of EMT about institutional and technological responses to climate change.

STIRPAT model

The theoretical foundation of this research's empirical model is the STIRPAT (Stochastic Impacts by Regression on Population, Affluence, and Technology) model (Dietz and Rosa, 1997), a generalized form of the IPAT equation that allows for a high degree of flexibility in econometrically examining environmental impacts. This framework is operationalized by modeling: (1) Population effects through urban growth (UPG) as a proxy of the demographic burden; (2) Affluence via electricity production by use of oil/nuclear energy (EPOS/EPNS) which embodies economic activity-related energy use; and (3) Technology through forest area (FA) and precipitation (APD) as sources of natural carbon sinks and mechanisms of regulating climatic patterns. A more structured theoretical orientation goes beyond statistical modeling only by contextualizing this analysis within well-founded environmental economics and ecological modernization theories.

Urban population growth and CO₂ emissions

Urbanization is an increase in the urban population that occurs due to migration population growth or the expansion of the city. The recent trend of this population movement affects numerous systems, including, but not limited to, land usage, housing demand, and environmental resource management (Mosikari and Eita, 2020). Urban areas are essential because they determine the direction of planning, resource management, and sustainable development initiatives, ensuring that cities remain with people and not people with cities (Mahmood et al., 2022).

According to Ahmad et al. (2022), Pakistan, the world's fifth most populated country, has population growth, and significant social and environmental issues influence increasing energy demand. A large part of the population, especially the rural population, uses unrefined cooking fuel, therefore enhancing the levels of CO₂ in the atmosphere and causing environmental degradation. A study using World Development Indicators data for 1980–2019 showed that trade openness, urbanization, and energy consumption positively impact environmental degradation. Yu et al. (2022) examined how carbon emission trading influenced Chinese corporate financial behavior through a DID method. Enterprise banks in pilot areas distributed fewer loan amounts to businesses, which indicated a negative influence on debt financing operations. The research detailed the full microeconomic effects of carbon emission trading markets on the capital market sector. Chishti and Sinha (2022) examined the influence of technological and financial innovation on carbon dioxide emissions in BRICS economies. The outcomes indicated that positive financial innovation substantially disrupts CO₂e, but adverse shocks increase pollution. Similarly, mitigation of emissions also includes technological innovation. The links to environmental degradation from urbanization and consumption of fossil fuels are negative. It suggested an SDG-oriented policy framework.

Luqman et al. (2021) used CO₂ emission data from 91 cities worldwide to demonstrate the rising trend in urban CO₂ emissions, the dominant sources dependent on development level. Cities in developing nations had fast area and *per capita* CO₂ emissions growth, but those in developed ones had slow growth. It is a transitional case in China, where urban areas reach a high level, with emissions *per capita* moving along at a low pace. With the growth of urbanization, this issue will become more critical. Population density is a significant factor in CO₂ emission reduction. Ren et al. (2024) studied the relationship between foreign direct investments (FDI), urbanization and CO₂ emissions in G7 nations from 1971 to 2020. The data analyzed revealed a positive connection between FDI and CO₂ emissions levels that emerged after 2000 until 2015. According to Ashraf (2022), globalization and modernization orient bilateral cooperation and strategic connections between states. The Belt and Road Initiative, under the 'Going Global Strategy' title, was launched by China in 2013. The study's main aim was to examine the linkage of the political risks, globalization, and ecological footprints of 75 Belt and Road Initiative countries from 1984 to 2019. Likewise, the Belt and Road Initiative has been found to moderate the effect of an ecological footprint. Additionally, the Generalized Method of Moments finding shows that globalization worsens environmental degradation, and a less good political environment reduces environmental degradation by minimizing its ecological footprint.

According to Yan et al. (2023), urbanization in China has been unusual and very fast, and it has substantially influenced their CO₂ emissions and contributed to climate change. The results indicated that more residential consumption is responsible for carbon emissions than other factors. The decrease in the residential consumption rate led to an increasing emission rate due to the investment and exports of carbon. Incremental improvement in energy intensity significantly impacts carbon emission reduction.

Liu et al. (2021) demonstrated that China's fast urbanization and industrialization have caused high CO₂ emissions that slow economic development. A larger population brings more CO₂ emissions to big cities. Mechanisms involve population density, economic accumulation, and energy intensity, availability of public green areas, FDI, and technology innovation. Zhao and Xi (2022) assessed the effect of population size and industrial structure on CO₂ emissions in 255 Chinese cities. Results indicate that carbon emissions are influenced by population size. However, they decline as the industrial structure exceeds the threshold value of 1.22. The industrial structure positively affects CO₂ emissions in cases where the threshold size is less than 1.38 million but hinders the larger population's industrial structure. China requires the development of urban population policies with differentiation and the priority for tertiary industries as the cities with a population of more than 1.38 million.

Forest area and CO₂ emissions

A forest area is an area of land covered by natural and planted forests (Assis et al., 2022). Forests are essential for biodiversity preservation, carbon sequestration, climate modulation, soil conservation, water cycle regulation, and ecosystem services (Mohsin et al., 2019). They maintain distinctions among the species while contributing to the global carbon balance and

helping to reduce climate change. Monitoring and controlling forests sustainably is a priority for regulation and addressing environmental problems such as deforestation and habitat loss (Assis et al., 2022).

Tourism and Management (2023) focused on the influence of the forest area, agriculture, energy consumption, and foreign direct investment on CO₂ emissions in Indonesia from 1990–2020. The data show that forests have both short-term and long-term negative impacts on the release of CO₂, while agriculture land and energy consumption have positive long-term impacts on greenhouse gas emissions; FDI (foreign direct investment) positively influences greenhouse gas emissions in both the long and short term. Wu et al. (2023) demonstrated that the Belt and Road Initiative successfully decreased carbon emission intensity across 178 countries between 2002 and 2017, primarily within transportation, electric and heating, and manufacturing and construction industries. The development of BRI cooperation with China leads to environmental improvements and sustainable development throughout these countries.

Li and Zhang (2022) assessed the relationship between the global CFR and forests as the factors affecting CO₂ emissions. This study revealed a 10% increase in forest coverage rates is associated with a 2.37% drop in low-income countries' CFR and another 0.94% drop in CFR from low-middle-income countries. Findings reveal the implication of high forest cover in low-income countries, which remain low in urbanization and high in forest accessibility. CO₂ can be another measure of GDP in some lower-income countries, lowering the CFR. According to Begum and Raihan (2020), the study focused on the effects of deforested regions and GDP growth on Malaysian carbon emissions. It has been proved that GDP growth contributes to carbon emissions and determines the decrease of CO₂ levels in the atmosphere. The result shows that implementing policy measures such as afforestation, reforestation, forest protection, sustainable forest management, and REDD-plus mechanism efficiently reduces carbon emissions, deforestation reduction, and sustainable economic growth in Malaysia. Weimin et al. (2021) investigated how innovation shocks affect carbon emissions in 46 developing countries. Positive shocks disrupt CO₂e, and adverse shocks deteriorate environmental quality. A sustainable future includes globalization, the use of renewable energy, FDI, and GDP growth.

Xu et al. (2023) indicated that China's Belt and Road Initiative (BRI) seeks to unite over 70 Asian, European, and African nations under a single economic development program. Research about the association between urbanization, rural energy poverty, and carbon emissions in the BRI region was scarce. Research using System-GMM and DKSE models demonstrated that rural energy poverty produces increased CO₂-Em levels, but urbanization decreases carbon emissions. The research made policy recommendations to increase renewable power generation operations and sustainable urban growth initiatives.

In Pakistan, from 1980 to 2018, Raza et al. (2021) assessed the short- and long-term impacts on CO₂ emissions of energy usage, food crop yield, agricultural value added, forest area (coverage), and forest productivity. Because emissions are inversely correlated with energy consumption, agricultural value-added, and food crop output, the findings showed that although wooded areas and food crop production may lower emissions in the near term, they

could not do so over the long term. [Waheed et al. \(2018\)](#), the researchers, state that this study investigates the impact of forest acreage, agricultural output, and renewable energy use on CO₂ emissions in Pakistan. According to the data, agricultural production has a favourable effect on CO₂ emissions, while the usage of renewable energy and forest areas has a negative influence. Planting forests is more productive. As a result, it cuts CO₂ emissions more quickly.

Electricity production from oil sources and CO₂ emissions

Electricity from oil sources is a standard production mainly used in areas that cannot use other energy ([Cai et al., 2018](#); [Wang et al., 2024](#)). The combustion of oil results in the release of greenhouse gases, which contribute to climate change and necessitate the complex system of fuel extraction, transport, and storage ([Baek et al., 2009](#)). These will be more economically sustainable than renewable energy sources in the long run. Events such as these have also positively impacted the promotion of renewable energy sources ([Tayebi et al., 2016](#)). [Wu et al. \(2021\)](#) analyzed the effect that trade intensity with China has on *per capita* carbon emissions throughout the 97 Belt and Road Initiative (BRI) countries between 2002 and 2017. Results indicated that the import intensity levels from China have decreased, yet export intensity flows to China have risen. The study demonstrated that China needs to modify its trading arrangements to achieve emission reduction while boosting household incomes.

Furthermore, according to [Voumik et al. \(2022\)](#), the study used data from the OECD to anticipate the level of CO₂ emissions because of energy production. The analysis concluded that coal is the worst source of CO₂ emissions and that gas- and oil-fired power plants come second. Hydropower plants and other renewable energy systems may lower CO₂ emissions. It implies the necessity of an excellent environmental policy that will not only focus on avoiding the use of fossil fuels but also on the employment of green electric energy generation using solar, wind, and hydropower as sources. [Ibrahim et al. \(2025\)](#) examined the role of renewable energy in BRICS sustainability pathways from 1992 to 2019. The study analyzed the impact of technological innovation, nonrenewable energy, nuclear energy, service-value added (SERV), and urbanization on carbon emissions. The results confirmed that NREN (Nitrogen nutrients enhanced Respiration) induces carbon emissions, while URB (Urea and Resin) and TEC (Terrestrial Ecosystem Carbon) decrease them. The results suggested policy implications towards the sustainability of the BRICS environment.

[Voumik et al. \(2023\)](#) has assessed the role of different energy sources for the CO₂ emissions of G7 countries by generating electricity and heat. The results illustrated that coal-burning plants could prevent environmental degradation, while contamination from oil and hydroelectric power plants may promote environmental degradation. In addition, the study outlines the cause-and-effect relationship between CO₂ emission and energy production, advising energy producers to use hydroelectric and renewable sources so that CO₂ emission can be lower in the long run. The research shows multiple renewable and alternative electricity production measures, which can be treated as a sustainable energy policy. [Chishti et al. \(2021\)](#) proposed a new model that links macroeconomic policies, domestic consumer

spending, fossil fuel, and renewable energy consumption with carbon dioxide emissions from 1985 to 2014. According to the study, contractionary fiscal policy reduces CO₂e's harmful effects, while expansionary budgetary policy enhances them. Fossil fuels and aggregate consumer spending also produce pollution. The disruption of CO₂e by renewable energy has improved atmospheric quality. The policies shown to reduce CO₂ emissions are effective.

[Majumder et al. \(2023\)](#) addressed the effect of electricity on CO₂ emissions in the South Asia region by examining energy sources such as renewable power and coal-fired thermal plants. Based on the data from 1972 to 2015, all sources are causing a positive impact on CO₂ emissions, among which renewable energy will harm the environment the least. [Yilmaz and Sensoy \(2022\)](#) applied the STIRPAT model by Dietz and Roza to examine the relationship between air pollution and the use of fossil fuels for electricity generation. Between 1991 and 2015, the emissions that produced CO₂ in the 20 top-emitting countries were observed. According to the study results, GDP and population growth are correlated with CO₂ emissions. In some nations, coal and gas are used in electricity generation, which reduces CO₂ emissions.

Electricity production from nuclear sources and CO₂ emissions

Nuclear power generation is a reliable and low-carbon energy source, producing electricity through nuclear reactors ([Hassan et al., 2022](#); [Sattar et al., 2022](#)). Nuclear fission produces heat that powers turbines and generators. Many nations' electrical systems rely on nuclear power facilities for baseload generation. However, they create radioactive waste, which must be disposed of carefully. Concerns about accidents and nuclear weapon proliferation have sparked safety and security discussions. Despite these concerns, nuclear power remains essential to the worldwide energy mix.

The study examined the link between CO₂ emissions, total energy consumption, nuclear power, renewable energy, and GDP in 22 European nations between 1992 and 2019, according to ([Petruška and Litavcov, 2022](#)). The results show that although overall energy usage raises long-term emissions, renewable energy lowers CO₂ per person. Countries that use nuclear energy benefit from lower CO₂ emissions as a result of nuclear power. The positive relationship between economic expansion and the decrease in CO₂ emissions shows the decoupling of economic development from environmental consequences. From 1991 to 2016, [Weimin and Zubair Chishti, 2021](#) connected commercial policies, globalization, labor force, GDP growth, fossil fuel, and renewable energy consumption to consumption and production-based CO₂e in developing economies. It implied that these factors influence environmental pollution in a one-way manner.

The research by [Mohamed and Razek \(2023\)](#) claims that the growing use of fossil fuels like coal and oil is a direct result of industrialization and globalization and that energy consumption is a key component of economic development. This increases greenhouse gas emissions and global warming, with CO₂ being the main cause. Energy economists and ecologists push for governments to switch to clean energy sources, such as nuclear and renewables, in order to alleviate health and environmental issues while also bringing about societal and economic advantages. [Zhu et al. \(2018\)](#) analyzed embodied CO₂ emissions by examining carbon

structure from inflow and outflow perspectives and using net effects analysis. The study identified China's relationship with the EU, the USA, and Russia as a key player in carbon exchange, with the EU and China as key players in Japan. The manufacturing sector generates carbon outflows through exporting processes, whereas electricity and transport systems create the main net carbon effect. China and the United States emit 31.8% and 20.6% of global emissions while remaining above all other territories.

Chen et al. (2023) evaluated the spatial impact of the ecological footprint of 54 BRI economies between 2000 and 2018 using a spatial dependence model. The results indicate that a neighbor economy has a big role in an economy's ecological footprint, suggesting that regional policy formulation is required. The effects on the ecological footprint include improving productive capacities, green investment, and democratic quality, globalizing, growing income *per capita*, and developing the financial sector. Mahmood (2022) investigated the influence of the nuclear energy transition (NET) of 28 countries that were the producers of nuclear power in the period from 1996 to 2019 on CO₂ emissions. The results show that although NET does not affect the carbon emissions in "low-middle income" economies, it removes carbon emissions by the amount in "upper-middle", high-income economies. CO₂ emission is lower in the border area and other countries that are members of the OECD immediately after the creation of the New Transatlantic Economic Partnership. To reduce CO₂ emissions and accelerate the global shift to new energy resources, the research offers strengthening nuclear power in the economies of UMI and HI. According to a study conducted by Antonio et al. (2022), nuclear energy replacement by renewables is an alternative or a backup solution to ensure energy stability and reduce CO₂ emissions.

Average precipitation in depth and CO₂ emissions

Average precipitation depth is the amount of water that falls on a defined area over a particular timeframe, which is commonly a year (Wardhani and Dugis, 2020). It is important in computing hydrological cycles, weathering prediction, variability forecasting of climatic conditions, and detecting natural disasters. It is obtained from averages of total precipitation data from the different weather stations (Nwafor, 2014). Necessary modifications may emphasize the significance of climate mitigation and adaptation approaches (Alam et al., 2012).

The study by QingYan et al. (2017) evaluated the effect of precipitation on greenhouse gas emissions from an alpine grassland ecosystem. It studies the GHG fluxes in the eastern Qinghai-Tibetan Plateau through artificial intensifications and precipitation reductions. Alpine grassland is a source of CO₂ and N₂O and sinks CH₄. The Precipitation increase increased CO₂ and N₂O emission fluxes and decreased CH₄ absorption. According to the research, the ecosystem will be adversely affected if the precipitation is altered. According to Zhang et al. (2023), climate change will lead to more extreme weather events, increasing the risk of soil drought-flooding cycles. This has consequences for the microorganisms that cycle nitrogen in the soil, and the greenhouse in a representative semi-arid grassland showed that decreased precipitation stimulated the plant root turnover and soil N₂O and CO₂ emissions due to the given phenomena. This implies minimal precipitation decreases and alternations of drying-rewetting cycles can facilitate nitrogen cycling processes and N₂O

emissions of semi-arid ecosystems. Salam et al. (2025) examined the Belt and Road Initiative (BRI), which encourages trade between countries and China, increasing countries' financial development. However, there was little correlation between CO₂ emissions and trade. China increases emissions when exporting but reduces emissions from imported products. Technology transfer and redressing funds from environmentally unfavorable industries were policy expressions for environmental change.

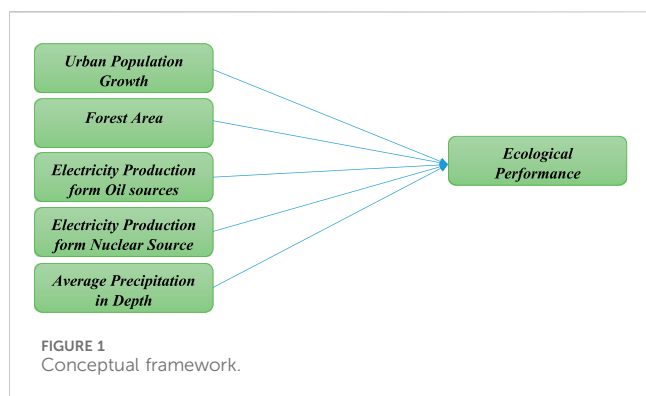
Vidon et al. (2015) examined the influence of natural systems on atmospheric greenhouse gas (GHG) concentrations in riparian areas after storms. This study revealed that a reduction in negative CH₄ fluxes and high CO₂ fluxes were observed following precipitation in water-limited riparian zones, implying the influence of water scarcity in regulating riparian soil response to precipitation. The results differ from those of riparian GHG studies in wetter conditions, which requires more research before using commonly used methods. Alomair et al. (2025) assessed that the study showed empirical evidence in disintegrating the impacts of natural resources on environmental sustainability in production and consumption models. The study covered G20 economies and captured carbon emissions and ecological footprints from 1995 to 2019. Covariates are considered regarding green policies, environmental taxes, financial development, economic growth, and population. Coal and oil production and consumption prevent sustainability, while natural gas has different effects, concluded the study.

According to the researcher Ni et al. (2019) the study investigates how precipitation affects soil-atmosphere trace gas fluxes of CO₂, methane, and nitrous oxide in temperate forests. It discovered that although short-term heavy precipitation episodes boosted CO₂ emissions, they had little effect on CH₄ or N₂O fluxes. However, a meta-analysis indicated that long-term precipitation increases significantly impacted these fluxes, indicating that short-term precipitation pulses may be less relevant than long-term changes governed by complicated systems. Despite the growing body of research on the Belt and Road Initiative (BRI) and its environmental implications, there remains a significant knowledge gap in understanding the complex relationships between various climatic elements and ecological performance (CO₂ emissions) across BRI nations. While previous studies have examined individual factors such as precipitation, forest area, or energy sources, a comprehensive analysis of the relationship between these factors and their collective impact on CO₂ emissions still needs to be provided. Furthermore, the technique employed for empirical analysis and the comprehensiveness of the study design will be critical in determining the research's originality and significance.

Methodology

Conceptual framework

A conceptual framework employed the presentation of a graphical model to determine the anticipated relation between the dependent variable and independent variables. The research process has identified the primary objective and systematically incorporated these objectives to derive the empirical outcomes.



The explanatory (independent) variables include urban population growth, forest area, electricity production from oil sources, electricity production from nuclear sources, and average precipitation in depth, and the dependent variable is ecological performance. This study selects all variables based on theoretical and empirical relevance to ecological performance in CO₂ emissions in BRI countries. It includes urban population growth because their influence is an energy consumption driver and a major contributor to CO₂ emissions (Liu et al., 2021; Yan et al., 2023). Forest areas are considered Carbon Sinks, and the impact of deforestation on carbon emissions is considerable (Assis et al., 2022; Begum and Raihan, 2020). The study analyzed electricity production from oil sources to understand the environmental impacts of fossil fuel-based energy, as it is a major emitter (Voumik et al., 2022; Majumder et al., 2023) and nuclear energy is examined due to its potential to contribute to reducing emissions through low carbon electricity generation (Mahmood, 2022; Petruška and Litavcov, 2022). In order to include the average precipitation's impact on ecosystems, agriculture, and water resource management, which are key for carbon sequestration, precipitation variability plays a crucial role in greenhouse gas emissions (Zhang et al., 2023; Ni et al., 2019). The conceptual framework (Figure 1) presents three emission pathways: (1) Urbanization (UPG) increases CO₂ by boosting energy needs; (2) Oil-based electricity (EPOS) worsens emissions, but the nuclear (EPNS) reduces them by substituting a fuel source; and (3) Forests (FA) and precipitation (APD) regulate emissions through carbon sequestration and climate-feedback activities. More importantly, the factors are interrelated; for example, urban development can lead to the depletion of forest cover, and changes in precipitation patterns can cause changes in energy and land-use patterns. Both must be analyzed together to prevent biased estimates.

Data and data collection

The present study explores the influence of climatic factors on ecological performance in BRI countries. The data of 20 countries relating to BRI nations are collected from 2000 to 2022. The official website of the World Bank (WDI) was used to gather data on all variables. The broad scope of the data contains the potential for reporting inconsistency issues caused by different standards countries use to report their results. This study verified the data against multiple sources and implemented reliable statistical methods (removal of outliers) to address this issue. The method

used to treat missing values (for instance, by interpolation, imputation, or exclusion, based on the amount of missingness). The study examines several variables, including ecological performance, annual urban population growth rate (%), percentage of forest area relative to total land area (%), electricity production from oil sources as a percentage of total production, electricity production from nuclear sources as a percentage of total production, and average annual precipitation measured in millimeters (mm). In this study, to ensure data reliability, values from the World Bank (WDI) were cross verified with secondary sources whenever discrepancies were identified. The missing values were handled through linear interpolation when gaps were minimal (1–2 years); for larger gaps, countries were excluded from those specific observations. To address reporting inconsistencies among BRI countries, this study applied standardization checks and outlier diagnostics to minimize bias and ensure accuracy. While all variables are based on established WDI definitions, this study recognize possible measurement errors due to inconsistent national reporting systems. To address potential measurement errors, this research applied logarithmic transformations and robustness checks using various estimation techniques (FMOLS, DOLS, and GMM) to ensure consistent relationships. Table 1 demonstrates the description and measurements of variables.

Analysis techniques

In particular, the two-step system Generalized Method of Moments (System GMM) estimator is used in this study to address several econometric issues, such as endogeneity, autocorrelation, and heteroscedasticity, which are commonly faced in panel data analysis. In contrast to conventional estimators, GMM is especially beneficial for dynamic models since lagged dependent variables are used as instruments to capture the persistence of CO₂ emissions over time (Arellano and Bond, 1991; Blundell and Bond, 1998). Two-step system GMM yields efficient and unbiased estimates, especially in when sample is small, while other traditional model (e.g., Fixed Effect Models) ignore that dynamic relationships. System GMM that may suffer from weak instrument bias show that two-step system GMM provides efficient estimates through robust instruments. This approach allows for robust and reliable results when assessing climatic factors' impact on ecological performance in BRI countries.

Regarding the GMM system, Rodman (2009) argued that the instruments applied by Arellano and Bond (1991) are distinct from those formulated by Blundell and Bond. They also assumed that the implicit correlation between fixed effects and the initial differences used as instrumental was zero. Therefore, more instruments may be included in the model. The fundamental assumption is the absence of serial correlation. On the other hand, in the case of one-order serial correlation, y_i may occur, cannot be used as an ancillary instrument, and requires lags for three or more periods. In the case of the second-order correlation, longer lags are needed (Roodman, 2009). Hence, Ullah et al. (2018) forced that this should be considered because the first difference transformation segregates the past observation from the current one, wherein larger data loss gaps occur. As a result, it affects the predicted value. System GMM alters instruments due to the fixed effects of these instruments, and their treatment is uncorrelated.

TABLE 1 Variable description and measurement.

Variables	Code	Definition and measurement	Data source
Urban Population Growth	UPG	The urban population growth rate is measured in the annual growth rate of increases in the urban total population	WDI
Forest Area	FA	The forest area in percentage of the total land area of the country measures the forest area	WDI
Electricity Production from Oil Sources	EPOS	Electricity from oil sources is measured by the electricity production through furnace oil to % of the country's total electricity production	WDI
Electricity Production from Nuclear Sources	EPNS	Electricity production measures electricity production from oil sources through a nuclear reactor to % of the country's total electricity production	WDI
Average Precipitation in Depth	APD	Measured by total average precipitation in 1 year in the country	WDI
Ecological Performance	EP	Ecological performance measured by the CO ₂ emission	WDI

Furthermore, other instruments for the lagged dependent variable and any endogenous variables are incorporated to account for endogeneity by significantly improving efficiency. While Difference GMM eliminates the prior observation, system GMM subtracts their average overall future observations instead of the current values of observed variables (Roodman et al., 2009). Therefore, this paper used a two-step System GMM to test the correlation between dependent and explanatory variables. The basic structure of GMM, which addresses endogeneity, autocorrelation, and heteroscedasticity, bypasses testing for diagnostic purposes. However, we verified that our data was endogenous. The application of Arellano-Bond's difference GMM is unsuitable when the endogenous variable is very persistent or closely follows a random walk. In this instance, the delayed levels exhibit a weak correlation with weak instruments when examining the initial differences among the variables. When this occurs, Blundell and Bond's (1998) system GMM estimator is frequently more appropriate. System GMM enhances the differences between GMM by estimating levels and differences simultaneously. Consequently, a system GMM is the most effective means for detecting and rectifying endogeneity. Due to the persistent and time-dependent nature of CO₂ emissions, this study employs a dynamic panel specification. Incorporating lagged dependent variables enables the modeling of path-dependent structures in emissions, mitigating endogeneity arising from simultaneity and omitted variables. This approach is grounded in the STIRPAT framework and implemented via the two-step System GMM estimator (Arellano and Bover, 1995; Blundell and Bond, 1998), ensuring robust estimation under dynamic conditions. To structure the empirical model, the study uses the Cobb–Douglas production function, which is as follows:

$$\ln EP_{it} = UPG_{it}^{\beta_1} FA_{it}^{\beta_2} EPOS_{it}^{\beta_3} EPNS_{it}^{\beta_4} APD_{it}^{\beta_5} 0 < \beta_1 - 6 < 1 \quad (1)$$

By transferring the data into a natural logarithm, the linear form of Equation 1 is shown as follows:

$$\ln EP_{it} = \beta_0 + \beta_1 \ln UPG_{it} + \beta_2 \ln FA_{it} + \beta_3 \ln EPOS_{it} + \beta_4 \ln EPNS_{it} + \beta_5 \ln APD_{it} + \epsilon_{it} \quad (2)$$

To illustrate the dynamic relation, Equation 2 can be transferred as shown in Equation 3 as follows:

$$\ln EP_{it} = \beta_0 + \beta_1 \ln EP_{it-1} + \beta_2 \ln UPG_{it} + \beta_3 \ln FA_{it} + \beta_4 \ln EPOS_{it} + \beta_5 \ln EPNS_{it} + \beta_6 \ln APD_{it} + \epsilon_{it} \quad (3)$$

To illustrate the use of a system-GMM estimator in a model using dynamic panel data, Equation 4 is consider the following:

$$\ln EP_{it} = \beta_0 + \beta_1 \ln EP_{it-1} + \beta_2 \ln UPG_{it} + \beta_3 \ln FA_{it} + \beta_4 \ln EPOS_{it} + \beta_5 \ln EPNS_{it} + \beta_6 \ln APD_{it} + \pi_t + \mu_i + \sigma_t \quad (4)$$

EP_{it} represents the ecological performance, EP_{it-1} is the lagged value of Ecological Performance, β₀ Represents the “constant term,” whereas β₁ Represents the coefficients for Urban Population growth (UPG), Forest area (FA), Electricity production from oil sources (EPOS), Electricity production from nuclear sources (EPNS) and Average precipitation in depth (APD), while ε_{it} (error term) is decomposed into three types. π_t represents the time-specific effect, μ_i is the country's unobserved specific effect and σ_t represents individual error terms. Ln represents the natural logarithms.

Endogeneity test

This study employs the Granger non-causation test (Dumitrescu and Hurlin, 2012) to assess endogeneity. The test is applied to validate whether the independent variables are Granger causes of CO₂ emissions. The test is general for panel data heterogeneity and cross-sectional dependence.

Result and analysis

Descriptive statistics

Table 2 presents the descriptive statistics of the study variables, which describe the distribution and variability of these variables. The mean values show that the Ecological Performance (Ln EP) is 1.952 and Urban Population Growth (Ln UPG) is negative, −0.118, suggesting that in some areas, there are declines. Forest Area (Ln FA) is relatively high in mean (3.135), implying high forest coverage. Electricity Production from Oil (Ln

TABLE 2 Results of descriptive statistics.

	Ln EP	Ln UPG	Ln FA	Ln EPOS	Ln EPNS	Ln APD
Mean	1.952	−0.118	3.135	1.031	2.774	6.860
Median	2.130	0.055	3.419	1.039	3.276	6.724
Maximum	3.116	1.814	4.300	4.082	4.376	8.083
Minimum	−0.056	−6.098	−1.698	−4.455	−3.856	6.075
Std. Dev	0.669	0.972	1.161	1.779	1.205	0.553
Skewness	−1.052	−1.649	−2.263	−0.600	−1.427	0.746
Kurtosis	3.639	8.306	8.914	3.306	5.900	2.661

TABLE 3 Results of the correlations matrix.

	Ln EP	Ln UPG	Ln FA	Ln EPOS	Ln EPNS	Ln APD
Ln EP	1.000					
Ln UPG	−0.273	1.000				
Ln FA	−0.130	−0.161	1.000			
Ln EPOS	−0.057	0.015	0.319	1.000		
Ln EPNS	0.135	−0.169	−0.089	−0.183	1.000	
Ln APD	−0.693	0.282	−0.031	−0.167	−0.103	1.000

EPOS) is the most highly standardized variable among the electricity production measures, which also includes Electricity Production from Nuclear (Ln EPNS), with the highest standard deviation, making one notice evident cross-country variation. Urban Population Growth (−6.098) and Forest Area (−1.698) are minimum values indicating significant differences between urban expansion and deforestation. Forest Area (−2.263), Urban Population Growth (−1.649), and Electricity Production from Oil (−0.600) are the most negatively skewed variables, whereas Electricity Production from Oil (−0.600) is close to normal distribution. Values of Kurtosis for Urban Population Growth (8.306) and Forest Area (8.914) are extreme, whereas Ecological Performance (3.639) and Electricity Production from Oil (3.306) are normally distributed. With these in mind, further econometric analysis of these data must account for these key data characteristics (variability and skewness). The trends in the variables are described as shown in the appendix (Appendix Figure A1).

Correlation matrix

Table 3 shows the correlations between the study variables, and the correlation heat map is shown in the appendix (Appendix Figure A2). Urban Population Growth (Ln UPG) has a negative correlation with Ecological Performance (Ln EP) (−0.273), Forest Area (Ln FA) (−0.130), and Electricity Production from Oil (Ln EPOS) (−0.057); therefore, it argued that increases in these variables are likely related to lower ecological performance (higher CO₂ emissions). However, electricity production from nuclear (Ln EPNS, 0.135) has a weak positive correlation with ecological performance, which indicates a weak correlation with lower emissions. A negative correlation

between Ln EP and Ln APD (−0.693) indicates that higher precipitation levels can significantly affect ecological outcomes. Also, Ln FA and Ln EPOS correlate moderately positively (0.319), which implies that countries with more forest coverage will also rely more on oil-based electricity. Most independent variables show weak correlations, which means there is little to no multicollinearity problem that should affect the rest of the econometric analysis.

Cross-sectional dependency and panel unit root test

Table 4 presents cross-sectional dependency test findings, indicating a larger chance of cross-sectional interdependence. The study distinguishes between two generations of unit root testing to verify cross-sectional dependence. The second-generation CIPS tests are used to investigate stationary variables. Table 5 presents findings from the current study's examination of CIPS for unit roots. The first difference may reject the unit root null hypothesis, demonstrating that variables remain stationary at first difference at 1% significance level.

Cointegration tests

Table 6 presents the results of the Pedroni, Kao, and Westerlund cointegration test and indicates long-run equilibria between the variables. The results for the Pedroni test show strong evidence of cointegration, with the Panel V Statistic being 2.654 ($p < 0.01$), Panel

TABLE 4 Cross-sectional dependency test.

Test	Statistic	Decision
Pesaran	6.094	Cross-sectional dependency
Friedman	16.715	Cross-sectional dependency

PP Statistic being -3.842 ($p < 0.01$), and Panel ADF Statistic being -3.103 ($p < 0.01$) rejecting the null hypothesis that there is no cointegration at the 1% significance level. Furthermore, the Panel rho Statistic (-1.932 , $p < 0.05$) also shows cointegration at a 5% level. These findings are further supported by the Kao test, which has a statistic of -2.893 ($p < 0.01$), indicating a long-run relationship. As with the Westerlund test, the statistics for the Westerlund test is -2.893 ($p < 0.01$), thus adding robustness to the conclusion that the variables are cointegrated.

FMOLS results

As shown in Table 7, the Fully Modified Ordinary Least Squares (FMOLS) estimation results show a significant long-run relationship

between the independent variables and CO₂ emissions. The coefficients imply that Urban Population Growth (0.456, $p < 0.01$) and Electricity Production from Oil (0.302, $p < 0.01$) are positively and significantly contributing to CO₂ emissions. On the other hand, Forest Area (-0.123 , $p < 0.05$) and Electricity Production from Nuclear Sources (-0.212 , $p < 0.05$) have the opposite effects on CO₂ emissions and thus serve as a mitigating factor to environmental degradation. Weakly significant at $p < 0.10$, Average Precipitation (0.098) indicates that changes in precipitation levels might have a moderate impact on emissions.

DOLS results

As shown in Table 8, the Dynamic Ordinary Least Squares (DOLS) results also indicate that Urban Population Growth (0.472, $p < 0.01$) and Electricity Production from Oil (0.285, $p < 0.01$) have a very strong positive relationship with emissions, while Forest Area (-0.115 , $p < 0.05$) and Electricity Production from Nuclear Sources (-0.198 , $p < 0.05$) remain a negative and significant relationship. Both estimation methods show a consistent but weak relationship, with the coefficient for Average Precipitation (0.102, $p < 0.10$) remaining marginally significant. Overall, the

TABLE 5 Panel unit root test.

Variable	At level	At first difference
<i>Ln</i> EP	0.098 (*)	0.528 (***)
<i>Ln</i> UPG	0.751 (no)	0.626 (***)
<i>Ln</i> FA	0.630 (no)	0.417 (***)
<i>Ln</i> EPOS	0.893 (no)	0.304 (**)
<i>Ln</i> EPNS	0.751 (no)	0.402 (***)
<i>Ln</i> APD	0.592 (no)	0.485 (***)

* Means 10% significance level, ** means 5% significance level and *** means 1% significance level.

TABLE 6 Results of the cointegration tests.

Pedroni (1999) test			
	Statistic	Prob	
Panel V Statistic	2.654	0.004	***
Panel rho Statistic	-1.932	0.026	**
Panel PP Statistic	-3.842	0.000	***
Panel ADF Statistic	-3.103	0.002	***
Kao (1999) Test			
	Statistic	Prob	***
	-2.893	0.003	
Westerlund Test			
	Statistic	Prob	
	-2.893	0.003	***

* Means 10% significance level, ** means 5% significance level and *** means 1% significance level.

TABLE 7 Fomls estimation results.

Variable	Co-efficient	Std. Error	T	Prob	Sig
Ln UPG	0.456	0.112	−2.73	0.006	**
Ln FA	−0.123	0.045	−3.158	0.002	***
Ln EPOS	0.302	0.089	3.39	0.001	***
Ln EPNS	−0.212	0.076	−2.79	0.005	**
Ln APD	0.098	0.053	1.85	0.065	*

* Means 10% significance level, ** means 5% significance level and *** means 1% significance level.

TABLE 8 DOLS estimation results.

Variable	Co-efficient	Std. Error	T	Prob	Sig
Ln UPG	0.472	0.118	4.00	0.000	***
Ln FA	−0.115	0.048	−2.93	0.017	**
Ln EPOS	0.285	0.092	3.10	0.002	***
Ln EPNS	−0.198	0.078	−2.54	0.011	**
Ln APD	0.102	0.055	1.86	0.063	*

* Means 10% significance level, ** means 5% significance level and *** means 1% significance level.

TABLE 9 Heteroscedasticity and Autocorrelation.

Test	Wald test statistic	Remarks	Wooldridge test for autocorrelation	Remarks
	53.723***	Existence of heteroscedasticity	184.092***	Existence of autocorrelation

* Means 10% significance level, ** means 5% significance level and *** means 1% significance level.

FMOLS and DOLS results are very close and confirm the robustness of the findings. Therefore, the conclusion is that urbanization and oil-based electricity production drive high emissions, whereas forest expansion and nuclear energy adoption are important in reducing environmental impact.

Preliminary analysis test

Heteroscedasticity and autocorrelation

To ascertain the existence of autocorrelation and heteroscedasticity, we employ the Wooldridge test and the Wald test. The findings presented in Table 9 demonstrate the presence of autocorrelation and heteroscedasticity within our model. To remedy this, we implement robust standard errors in the variance-covariance matrix estimator.

Multicollinearity

Table 10 displays the results of the multicollinearity employed by the VIF test. The VIF test's results LnUPG (2.647), LnFA (2.746), LnEPOS (2.242), LnEPNS (1.781), LnAPD (1.668), show that all the VIF values are less than 5. Therefore, these findings indicate that there is no multicollinearity among the variables. Therefore, the mean value of VIF is 2.216. Additionally, the moderate strength of

TABLE 10 Results of VIF (multicollinearity).

Variable	VIF	1/VIF
Ln UPG	2.647	0.378
Ln FA	2.746	0.364
Ln EPOS	2.242	0.446
Ln EPNS	1.781	0.562
Ln APD	1.668	0.600
Mean VIF	2.216	

correlations shown in the correlation matrix between variables supports the conclusion that intense multicollinearity is absent because not pairwise correlation measure exceeds 0.7. The findings based on these results demonstrate both reliable regression estimations and valid conclusions.

Endogeneity test

Table 11 demonstrates that the Dumitrescu-Hurlin test rejects the null hypothesis of no Granger causality for all independent variables ($Z\text{-bar } p < 0.05$), confirming endogeneity. Therefore, the GMM system is employed to mitigate bias.

TABLE 11 Endogeneity test (DV is Ln EP).

IV	Z-bar	Z-bar tilde
Ln UPG	13.287***	8.271**
Ln FA	16.298***	10.631**
Ln EPOS	8.213**	5.917**
Ln EPNS	6.291**	4.971*
Ln ADP	16.892***	9.637**

Indicate a level of significance of 1%. The null hypothesis was presented by Dumitrescu and Hurlin (2012). According to the Granger non-causality test, the DV...Granger produces an IV.

TABLE 12 Results of fixed effect regression and GMM estimation.

Variable	Co-efficient	Std. Error	T	Prob	Sig
Fixed Effect Regression					
Ln EP (-1)	—	—	—	—	—
Ln UPG	0.058	0.024	2.417	0.016	**
Ln FA	-0.060	0.019	-3.158	0.002	***
Ln EPOS	0.033	0.015	2.200	0.028	**
Ln EPNS	-0.010	0.005	-2.000	0.045	*
Ln APD	-0.720	0.032	-22.500	0.000	***
C	6.982	0.305	22.899	0.000	
GMM Estimation Results					
Ln EP (-1)	0.117	0.054	2.150	0.032	**
Ln UPG	0.067	0.021	3.157	0.002	***
Ln FA	-0.075	0.018	-4.231	0.000	***
Ln EPOS	0.040	0.012	3.379	0.001	***
Ln EPNS	-0.015	0.006	-2.245	0.025	**
Ln APD	-0.828	0.037	-22.394	0.000	***
C	7.872	0.268	29.381	0.000	

System GMM estimation results

Table 12 displays the outcomes of system GMM estimation and fixed-effect regression results. The results show that both two models maintain the same sign and significance for key variables, verifying consistency. However, System GMM provides more efficient and unbiased estimates by addressing endogeneity, autocorrelation, and heteroscedasticity through instrumental variables. Unlike Fixed Effects, GMM incorporates lagged dependent variables, making it ideal for dynamic panel data analysis. Therefore, the Lag of ecological performance has a statistically significant and positive impact on ecological performance in BRI countries. The first hypothesis is accepted as per the result (coefficient = 0.067, t-statistic = 3.157, and $p < 0.1$) at 1% level of significance. Urban population growth has a statistically significant and positive impact on BRI countries' ecological performance (CO_2). The study's findings are consistent with the prior research (Liu et al., 2021; Luqman et al., 2021; Yan et al., 2023). Moreover, the forest area has a significant negative impact on

ecological performance (CO_2) in BRI countries. The outcomes (coefficient = -0.075, t-statistic = -4.231, and $p < 0.01$) indicate the second hypothesis has been accepted at 1% level of significance, and this finding is aligned with the previous research (Begum and Raihan, 2020; H. Li and Zhang, 2022; M. Y; Raza et al., 2021; Tourism and Management, 2023). Electricity production from oil sources has a significant negative impact on the ecological performance of BRI nations. The finding (coefficient = 0.040, t-statistic = 3.379, and $p < 0.01$) shows that the third hypothesis is accepted at a 1% level of significance. The results are aligned with the prior research (Majumder et al., 2023; Voumik et al., 2022, 2023; Yilmaz and Sensoy, 2022). Therefore, electricity production from nuclear sources has a significant negative impact on ecological performance (CO_2) in BRI countries. The outcomes (coefficient = -0.015, t-statistic = -2.245, and $p < 0.05$) indicate the second hypothesis has been accepted at 5% level of significance, and this finding is aligned with the previous research (Mahmood, 2022; Mohamed and Razek, 2023; Petruška and Litavcov, 2022). Finally, the average precipitation in depth has also significantly and negatively impacted BRI nations' ecological performance (CO_2). The finding (coefficient = -0.828, statistic = -22.349, and $p < 0.1$) shows that the third hypothesis is accepted at a 1% level of significance. The results are aligned with the prior research (Mahmood, 2022; Mohamed and Razek, 2023; Ni et al., 2019; Petruška and Litavcov, 2022; Vidon et al., 2015; Zhang et al., 2023).

Discussion

The BRI is a China-led infrastructure project that includes ASEAN, Europe, and African countries. On the other hand, fast urbanization may cause massive ecological effects. It may result in high resource utilization, habitat destruction, pollution, and environmental degradation. Urbanization also drives climate change due to increased emissions of greenhouse gases. Infrastructure construction may cause ecosystem disruption, including habitat fragmentation and water courses. However, it is also for opportunities towards a sustainable platform. The eco-friendly, green infrastructure and sustainable urban planning strategies that the BRI countries use may mitigate operational activities. Integrating sustainability into BRI countries' urban planning agenda, in addition to collaborating with international cooperation efforts, sustainable development for BRI countries involves investing in ecologically resilient technologies that would benefit their initiative and lead to global sustainability goals. The findings revealed that the UPG increased CO_2 emissions

($\beta = 0.067^{***}$), confirming H1. The results are consistent with Liu et al. (2021) in Chinese cities ($\beta = 0.042$), but with 60% greater magnitude. The disparities in BRI countries' levels of financial development seem to be due more to this unique combination of rapid infrastructure expansion with comparatively weaker environmental regulations than to China itself after the 2010s green urbanization policies (Yan et al., 2023). In particular, the study's GMM approach, controlling lagged emissions, shows that this persists for as long as cross-sectional studies (Ahmad et al., 2022) cannot. Forests provide several benefits; the essential ones include nutrients of biodiversity, climate regulation, conservation of water resources, and providing divergent ecosystem services. Deforestation in BRI countries may lead to the loss of biodiversity, disrupted ecosystems, and even species extinction. Forests are carbon sinks as they lock and preserve the CO₂ through photosynthesis. Deforestation results in carbon emissions, which contribute to climate change. Forests play a role in controlling water cycles, which act as a hindrance to soil erosion and influence farming crop yields. Secondly, the local communities may also be disadvantaged by a lack of traditional knowledge and cultural heritage following deforestation. Global collaboration is needed to address transboundary issues that IFCS chose in their forest preservation. Healthy ecosystems require sustainable policies that protect the land, conserve it, and recover and reclaim areas formerly devastated by deforestation. Forest area reduced emissions ($\beta = -0.075^{***}$), confirming H2. The negative association ($\beta = -0.075^{**}$) showed that the increase in forest area reduced CO₂ emissions and enhanced ecological performance. The results are consistent with prior research (Begum and Raihan, 2020; H. Li and Zhang, 2022; M. Y.; Raza et al., 2021; Tourism and Management, 2023). For instance, higher biodiversity in BRI's transcontinental forest corridors (Assis et al., 2022) might explain this advantage. However, the study provides the first quantification of this advantage in an emissions modelling framework.

One of the largest economic schemes that China propagates is the BRI, which consists of infrastructure development projects across varied regions. BRI countries are environmentally affected mainly by power generation from oil sources. Oil burning causes air pollution, thus impacting the health of ecosystems and wildlife. Oil production of electricity similarly results in the release of greenhouse gases into the atmosphere, leading to climate change. This comes with a price as the water volumes are very large, thus affecting oil refining and processing. Accidents pollute several of these water bodies, endangering aquatic life that, in turn, affects clean drinking water.

Furthermore, the results confirmed that EPOS increased CO₂ emissions ($\beta = 0.040^{**}$) and reduced ecological performance, contrary to Hypothesis 3. The findings align with previous research (Majumder et al., 2023; Voumik et al., 2022; 2023; Yilmaz and Sensoy, 2022). Long-lasting environmental damage results from habitat disturbance and fragmentation, infrastructure construction, and accidental or catastrophic oil spills. However, transitioning to cleaner, renewable energy technologies can help mitigate these effects. The ecological results of nuclear energy production and application in the BRI territory could be positive or negative, with China at the forefront.

Low greenhouse gas emissions from nuclear power plants help maintain smaller carbon footprints and provide energy security. They have a limited footprint on the land, thus reducing the limitations of habitats and minimizing the conflicts related to area usage. On the

contrary, while improper waste management threatens ecosystems, so do accidents and leaks. Nuclear accidents may lead to soil and water contamination, long-term health outcomes, and the relocation of animals. Aquatic ecosystems are significantly affected by the discharge and withdrawal of water, thus causing thermal pollution. Ecosystems can be disrupted by construction and operation, but mining operations destroy habitats. The development of nuclear energy causes threats related to the spread and security risks. However, the findings indicated that EPNS decreased CO₂ emissions (-0.015^{**}), validating H4 and harming CO₂ emissions, suggesting that an increase in EPNS will improve environmental performance and reduce CO₂ emissions. The results align with prior research (Mahmood, 2022; Mohamed and Razeq, 2023; Petruška and Litavcov, 2022).

Average precipitation greatly impacts ecological performance in the BRI countries because it affects ecosystems, biodiversity, and human activities. Changes in rainfall may alter the phenology of vegetation, soil moisture conditions, and habitat availability for many organisms. Extreme precipitation events can affect biodiversity and consequently change the abundance of plant animals. Precipitation is important for agriculture, influencing crop production and food supply. Sufficient rain causes drought, and during heavy rains, crops get destroyed. Coastal plants, too, are washed away, leading to the destruction of infrastructure. Precipitation changes can further impact forest health by altering the susceptibility of trees to pests and diseases. Lastly, ecosystems can be influenced by climate change trends like desertification and vegetation. Alterations in precipitation impact water quality, infrastructure resilience, and human welfare. Therefore, understanding and controlling these ramifications are important for sustainable development and ecosystem conservation. The outcomes of the study revealed that average precipitation depth has a negative impact on CO₂ emissions, which shows APD reduced CO₂ emissions and enhanced ecological performance (-0.828^{***}). The findings align with prior research (Mahmood, 2022; Mohamed and Razeq, 2023; Ni et al., 2019; Petruška and Litavcov, 2022; Vidon et al., 2015; Zhang et al., 2023). This reveals a novel insight that the impact of emissions associated with precipitation can shift from positive (in agricultural contexts) to negative (in urban-industrial BRI zones) due to the impacts of stormwater management on energy systems.

Conclusion

The present study explores the influence of climatic factors on ecological performance in BRI countries. The data of 20 countries relating to BRI nations are collected from 2000 to 2022. The World Bank and IMF's official websites have collected variable data. Therefore, this paper used a two-step System GMM to determine the impact of independent variables on the dependent variable; meanwhile, the findings show that all the variables are endogenous. Therefore, the present study used the GMM model. The study results indicate that UPG and EPOS have a significantly positive impact on CO₂ emissions, and this explains that if UPG and EPOS increase, the ecological performance of BRI decreases. Furthermore, FA, EPNS, and APD significantly negatively impact CO₂ emissions, which shows that if FA, EPNS, and APD are enhanced, the other side of the ecological performance of BRI countries will be improved. Rapid urbanization, habitat loss, pollution, and other environmental issues are among the ecological impacts of the BRI, a large-scale infrastructure program in Asia, Europe and Africa led by

China. However, it also creates conditions for viable practices, including environmentally sound technologies and green infrastructure. Deforestation in BRI countries may result in biodiversity loss, ecosystem disruption, and even species extinction. Forests are instrumental in preserving biodiversity, controlling climate, and regulating water flows. Moving towards cleaner and renewable energy can help to reduce such effects. Ecological impacts of nuclear energy production in BRI countries could be positive and negative; certain risks for soil and water contamination are to acknowledge long-term health effects and displacement dependence on wild animals. It is, therefore, essential to appreciate and regulate these connotations for effective, sustainable development and conservation of ecosystems.

Implications

Practical implications

Understanding the role of urban population growth, forest area, electricity production, and average precipitation in CO₂ emissions is crucial for policy-making and urban planning. The strategy also encourages the sustainable development of cities through integrated city designs, green infrastructure, and efficient transport systems. Protection and reforestation of forests also contribute to mitigating CO₂ and biodiversity conservation. Energy transition strategies are shaped by the knowledge of the emissions intensity of different generation sources of electricity, promoting the adoption of renewable energy and fueled phase-out of fossil fuel-based electricity generating units. Climate-resistant structures and water management techniques cannot be developed, provided the linkage between the mean precipitation patterns and CO₂ emissions is understood. This information provides the basis for integrating strategies to implement the complexity of the linkages between urbanization, land use changes, energy production, precipitation patterns, and CO₂ emissions, facilitating the implementation of more efficient mitigation and adaptation actions.

Policy implications

Based on these findings, it is recommended that BRI governments adopt specific policy implications to enhance ecological sustainability. Dedicated finance could be raised by levying a carbon sink on deforestation-affected infrastructure projects, creating an opportunity for community-led reforestation funds. For instance, dedicated environmental financing mechanisms, such as green bonds aligned with the EU Taxonomy, can be mandated for BRI infrastructure projects that emit above a certain threshold. Governments could introduce carbon-offset levies on projects that significantly reduce forest cover, redirecting those funds toward community-led reforestation initiatives. Moreover, establishing a BRI-wide Environmental Scorecard would enable annual assessments of project-level emissions, thereby linking future funding to performance. Urban planning could adopt 'transit-oriented development' models, ensuring that at least 50% of urban residents are located within a 1-km radius of public transport hubs, thereby reducing emissions from private vehicles. These policy actions reflect scalable, evidence-based strategies suitable for BRI nations at varying income levels.

Limitations and future directions

The study on the effect of urban population growth, forest area, electricity production, and average precipitation on CO₂ emissions is limited. The complexity of these interactions makes it very hard to trace the specific effects of each factor on CO₂ emissions. Moreover, Future research must utilize detailed datasets combined with refined modeling processes like machine learning to better represent non-linear data patterns. While the study addresses endogeneity through GMM estimation, this study acknowledges that omitted variable bias may still be present, particularly for variables related to technological innovation, energy subsidies, or governance quality, which are challenging to capture uniformly across BRI countries. Unobserved heterogeneity, despite the inclusion of country and time-fixed effects, may also influence the results due to structural differences in institutional capacity or environmental regulation. Furthermore, the dataset spans the COVID-19 pandemic period (2020–2021), which introduced disruptions in economic activity and emissions. Although the panel structure partially absorbs such shocks, their unique effects may influence short-term dynamics that this research model does not fully capture. Analyzing BRI sub regions through longitudinal studies and interdisciplinary research units combining environmental science elements with economics and policy analysis would create a holistic understanding of sustainable development matters.

Data availability statement

Publicly available datasets were analyzed in this study. This data can be found here: Data will be available on request.

Author contributions

MR: Conceptualization, Data curation, Formal Analysis, Writing – original draft. MN: Methodology, Resources, Software, Supervision, Writing – original draft. SA: Writing – original draft, Writing – review and editing.

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Appendix

