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REVIEW ARTICLE

Sustainable Resource Management and Economic Development: Evaluating the Impact of Rare Earth Mining on Local Economies and Environmental Sustainability in China

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Abstract
Chinese mining is vital to the global economy due to its strategic supply of rare earth elements (REEs) necessary for the production of high-quality technologies such as wind turbines, electric vehicles, and many others. Through direct employment and sources of industries, China, which is a major producer in the global market, has revolutionized the local and national economy. However, similar to many other mining processes, this also creates critical problems of environmental pollution, destruction of habitat, and loss of biological diversity, which raises sustainability questions. The study review assembles prior literature on the economic effects and environmental costs of rare earth mining in China, assesses their sustainable management and suggests the areas for further research. The review covers both empirical papers and theoretical articles, as well as policy documents and environmental reports. This systematic cross-database search of the key terms resulted in the following finding: The implication drawn from the research is that, though the mining of rare earth is beneficial for development, it has negative impacts on the environment. Globally, sustainable management practices have elicited mixed success in managing the impacts of the concerns that arise, thus showing the need to adopt scale-appropriate solutions. However, due to the high level of heterogeneity that has been evidenced from the studies, more refined research and policies are required. For the purpose of furthering the sustainable goal in balance with the economic profit, future research should focus on the longitudinal setting and assess the performance of the sustainable practices within areas of rare earth mining in China.

Keywords: Rare earth mining; Economic impact; Environmental sustainability; Local economies; Sustainable resource management.

Introduction

China's REE mining is central to the world economy as the demand for REE in modern devices like high-performance magnets, green technologies, wind energy, hybrid vehicles, and warfare applications rises (Wu *et al.*, 2024). China has a massive influence over the rare earth industry because it possesses 60% – 70% of the market (Abbas *et al.*, 2024). This form of market control has great economic significance and can be represented through opportunities for employment, regional growth, and foreign exchanges. Similarly to minerals, rare earth elements have been gaining high value in technology and militarized industries, strengthening China's importance in the supply chain (Shuai *et al.*, 2023). However, the social and environmental implications of mining the rare earth in China have been stretched despite the merit that accrues. The environmental effects are soil and water pollution, emissions of gases, and reduction of bio-diversity, as Pradhan et al. 2024 pointed out concerning the extraction and processing of the required rare earth materials. Such processes result in the production of hazardous substances that persistently harm the environment and undermine sustainable development in the concerned areas (Zadokar *et al.*, 2023). However, polluting the environment to this level is a disadvantage that has grown the awareness of the global society on how sustainable mining could be. For instance, a review done by Pradhan et al. confirms that among the concerns raised is that extraction is presumed to use chemicals that affect the environment and are harmful to human health. The study also pointed out that the social impacts of mining rare earth in Global China mean they are also not free from adverse effects. Several mining areas are characterized by weak legal framework and implementation, which leads to unfavourable health conditions and social effects in the world's mining regions (Sager and Wiche, 2024). Several communities also mention displacement and loss of local livelihoods as the negative impacts of mining, mainly when mining is extensive (Li *et al.*, 2024). Lessons such as these social costs can make one appreciate that much debate is in progress as to whether rare earth mining is worth or profitable since, while net benefits are mostly reckoned in terms of profit, costs are reckoned in terms of loss to human and environmental lives. Considering the increasing use of rare earth elements and the associated environmental safety and responsibility issues, it is crucial to reform rare earth mining practices. The academic literature underscores the importance of balancing economic profits with environmental and social responsibility (Diogo *et al.*, 2022). Incorporating immersive technology in extraction methods, strengthening regulatory standards, and fostering global partnerships are vital strategies to mitigate the detrimental effects of rare earth mining while ensuring a steady supply of these metals (Jowitt, 2022). If the global trend towards environmentally sound technologies and sustainable development goals is any indication, the rare earth mining industry has the potential to transform and thrive in the future. Ultimately, the prospect of mining rare earth elements in China is a highly polarized issue, with significant benefits often balanced against extensive negative implications for the environment and social well-being (Liu *et al.*, 2023). In light of these, this paper aims to establish a safer and more sustainable mining method for REEs as the world's demand for the element increases. Policymakers, industries, and academics must recognize the challenges associated with mining these rare elements and take proactive steps to shape the future of this industry. Their collective efforts can lead to the formulation of policies that promote sustainable mining practices and ensure the long-term viability of the rare earth industry. Therefore, this review paper aims to synthesize prior literature on the economic and ecological effects of mining rare earths in China. These include the assessment of the impact that such activities have on local economic boost and the physical environment, examination of the literature to determine the identified or possible sustainable management practices that have been put forward and or can be, and finally, the revelation of critical research area missing in the current knowledge base. Such a review of the existing literature is presented here to guide further research and policy formulation for the sustainable mining of rare earths for economic growth without compromising the environment, emphasizing the urgent need for sustainable management practices.

Review of Literature

Economic Impacts

Similar to other human activities, the research on the economic effects of rare earth mining on the Chinese economy has its strengths and weaknesses. Notably, mining for rare earth has significantly boosted the economies of specific

Chinese provinces, such as Inner Mongolia and Jiangxi province, demonstrating the regional impact of the industry. As highlighted by (Kamenopoulos and Agioutantis, 2013), the mining of rare earth has led to the provision of employment opportunities and improved business circles. This has enhanced the sector's infrastructure and increased local government taxes and royalties. Investment and resource availability means that some areas gain more than others. (Mancheri *et al.*, 2019) analysed China's strategic dominance in the rare earth market and its national economic implications. Rare earth manufacturing allows China to use these resources for economic expansion and geopolitical power. Exports boost the economy by supporting technology, defence, and renewable energy. (Mejame *et al.*, 2022) found that sustainable rare earth mining practices reduce environmental damage and boost long-term economic stability. Sustainable mining can lower environmental cleanup costs and boost the industry's reputation, improving economic outcomes. Rare earth mining employment and income implications in mining localities have been thoroughly examined. (Palle Paul Mejame *et al.*, 2022) discovered that rare earth mining has created many jobs in the mining sector and adjacent businesses like transportation, equipment manufacture, and services. Job creation has raised incomes in some locations, improving local living standards. Mining's socioeconomic effects, according to (Abbas *et al.*, 2024), have increased employment but varied in quality and stability. Workers in low-skilled, transitory mining occupations have little economic security. Workers in mining locations may boost housing and service demand, raising living prices and negating wage increases. (Dou, Xu and Keenan, 2023) advised mining regions to diversify their economies to avoid overdependence on mining. Rare earth mining offers vital jobs, but regions that rely heavily on it may face economic issues if market conditions shift or resources dwindle. Promoting alternative businesses can stabilise employment and income in these communities.

Rare earth mining in China has economic benefits but also concerns that could threaten economic stability. (Wang *et al.*, 2022) noted rare earth market instability. Demand for rare earth elements in the international market, as well as policies and regulations of exporting countries and geopolitical factors, make the price of these elements fluctuate globally. It can be a disadvantage to mining businesses as well as to the regions as it causes fluctuations in revenue. (Jouini *et al.*, 2022) have briefly described a few effects of the mining of rare earth on some places economically. Such communities are at the mercy of the rollercoaster cycles of the extractive industry. Because of dependency, when the mining sector slows down, it leads to unemployment and a decrease in the revenue collected by the local government. Using data from (Zhang *et al.*, 2024), it is evident that mining of rare earth results in economic disparities. It indicated that some places benefit from economic mining, but other places suffer because of the unequal distribution of natural resources and investments. They might cause social tensions and disparities in access to and use of resources, which, in turn, perpetuates regional inequity. (Zhao *et al.*, 2019) pointed out that rare earth mining brings about other problems both for the environment and for the economy. They argued that as much as mining pushes the economy forward, environmental degradation affects residents and the economy negatively in the long run. Such problems require policies that promote economic development and growth while at the same time preserving the environment. Despite numerous challenges, rare earth mining in China impacts the people and economy of China. Employment and income growth are advantages, but market instability, dependency on economic growth, and environmental pollution are disadvantages. Several studies have analyzed the fact that increasing sustainable practices and diversifying the mining region’s economy will help to make positive changes in the region and decrease the negative impact of rare earth mining.

Environmental Impacts

This study's findings indicate that rare earth mining poses high risks to the environment and has negative impacts in areas where mining is intensive. Mining and refining rare earth elements result in the formation of hazardous byproducts, including heavy metals, which affect the environment. The mining of rare earth releases a cocktail of toxic metals into the soil and water, including lead, cadmium, and arsenic, along with radioactive materials such as thorium and uranium. These toxins have the potential to severely pollute water bodies, thereby affecting aquatic life and humans (Baz *et al.*, 2022). It is also emphasized that water pollution could have a significant impact on agriculture and drinking water, leading to the degradation of the environment. It is crucial to note that mining of rare earths is known to contaminate the air as well. The process might involve the use of dangerous dust, which is effectively extracted and processed. Mining airborne pollutants can cause respiratory and other challenges in neighboring communities (Yu and Zahidi, 2023). The study also found that rare earth mining air pollution can precipitate acid rain and damage the soil and water. Mining of rare earths utilities the ecosystem and decreases bio-diversity. Mining habitat destruction displaces species and destabilizes ecosystems. Loss of bio-diversity weakens the ecosystem's capacity to rebound aftershocks; hence, these habitats are easily degraded (da Silva-Rêgo, de Almeida and Gasparotto, 2022).

The issue of rare earth mining is further compounded by the long-term nature of the damage it causes. The presence of numerous toxins, coupled with their significant impacts on ecosystems, makes the rehabilitation of areas affected by rare earth mining a daunting task. It is worth noting that the mining of rare earth leads to the long-term pollution of the soil and water (Drusche and Kretschmann, 2023). Even after mining has ceased, pollutants continue to seep into the environment, perpetuating harm to ecology. The steady and constant decline in soil fertility and water quality lowers the productivity of farmland, and hence food production in the affected countries. The attempt to remediate rare earth mining environmental areas has had some rates of success (Xie *et al.*, 2020). The applications of both soil washing and phytoremediation to deal with contamination of mining sites. These technologies reduce pollution levels, but are capital intensive and require constant maintenance. The research established that the site pollution and the environmental conditions impair the cleanup exercise efficiency. Mining for rare earth affects the ecosystem of soil and water for any region and it is long term damage (Yin *et al.*, 2021). It is indicated that change in ecosystem dynamics of the communities is occasioned by mining-induced loss of biological diversity as well as habitat destruction. These changes can last decades, always negative impact on the species and the communities, which are dependent on the ecosystems. The identified study revealed that ecosystem recovery entails the acceptance, utilization and implementation of effective environmental management strategies (Bielawski, 2020). Although the operation of mining rare earth is slightly different from that of other mining and resource extraction, it also poses special environmental concerns as well as other similar industries. The mining of rare earth is similar to any mining in that it displaces wildlife and degrades soil and water. From the numerous works available to read, it was evident that (Liu *et al.*, 2021) explored the impact of mining on land and the environmental degradation that occurs and in their work, they pointed out that mining such as rare earth mining, coal and metal mining drastically affect land and pollute it. These contaminants and their chronic effects differ in countries, mining methods, and different kinds. As a result of this, it can be noted that, unlike mining of other minerals, rare earth mining has specific environmental implications as a result of the radioactive parts of the ores. (Klinger, 2023) stated that, unlike other mining, rare earth mining and processing present lasting hazards to the environment and human health. This issue needs specialised waste management to maintain the environment and the health of the population. Distinct techniques employed in the extraction of resources have distinct measures of containing the impacts on the external environment. Specifically, (Chen and Zheng, 2019) paid attention to Chinese rare earth mining's measures for environmental protection, such as improved management of waste and more legislation. These efforts are similar to reforestation as well as the treatment processes of water in many other mining industries to assess their effectiveness and applicability. The mining of rare earth leads to contamination, environmental destruction, and long-term disruption of natural habitats. While some of these effects can be mitigated through remediation, the unique characteristics of rare earth mining, such as radiation management and biodiversity, require constant and targeted efforts. Studies on other mining types reveal both common and specific environmental concerns, highlighting the need for ongoing and comprehensive environmental planning in the mining industry.

Sustainable Management Practices

For environmental and resource sustainability reasons, the mining of rare earths in China is now under a sustainable management system. To this end, the Chinese government has integrally addressed the issue of responsible mining from industry players. China's regulations for the mining of rare earth are strict when it comes to environmental standards. (da Silveira Pereira *et al.*, 2023) proposed issues relating to environmental standards such as EIA and limitation of mining chemicals. These policies also set aside sanctuaries to preserve species and cushion the effects of mining on ecosystems. Other legal requirements regarding the industry have also encouraged sustainable mining practices among players within the industry. According to the work of (Li, Li and Pan, 2024), most Chinese mining companies have also embraced international standards such as ISO 14001 in their operations. Such standards help firms to coordinate their environmental obligations better and thus minimize their impact on the environment. China also employs combined processes to optimize the utilization of REEs and to reduce the amounts wasted. Lee and Wen, 2018 presented the idea of recycling garbage and recovery byproducts in order to raise resource productivity and decrease the negative effects on the environment. The following techniques enhance China's circular economy and the country's industrial environmental objectives. China is poised to potentially revolutionize its rare earth mining practices to align with global standards, a move that could significantly enhance the industry's sustainability. This shift could see China adopting stringent environmental policies similar to those in Australia, a country known for its robust mining regulations. (Mehennaoui *et al.*, 2024) evaluated Australia's mine closure and land rehabilitation policy, which restores mining sites to their natural state or repurposes them. This thorough mine closure technique could be a model for China, where poor closure practices have caused long-term environmental damage. Mining sustainability in Canada emphasises community engagement and environmental management. (He *et al.*, 2021) demonstrated how Canadian mining firms work with local communities and indigenous organisations to construct sustainable projects. This collaborative method builds trust and improves community socio-economic well-being, which China may improve to ensure mining activities benefit local development. Chile's mining sector has improved sustainable water management, a major challenge in arid regions. Zhang et al. (2023) noted that Chilean mining corporations use water recycling and desalination to conserve freshwater. Consequently, water scarcity has the potential to worsen environmental effects in Chinese rare earth mining areas, making these practices necessary. Similar methods could reduce mining's impact on the environment and enhance water security. Information opportunities enable an organisation to lessen mining's effects on the environment and enhance its benefits. These include development in areas of using modern techniques in mining as well as developing and implementing proper instruments for achieving increased mining sustainability. These methods help minimise mining wastes and the emission of poisonous gases into the environment. Thus, (Pan, 2023) analysed that sophisticated separation techniques applied for rare earth metals ores decrease the usage of chemicals and enhance mineral recovery. They are effective in minimising pollution to the environment as well as increasing yields, thus making mining more economically viable. The mining industry has expanded the efficiency and effectiveness of mining processes and practices through technology and automation. As pointed out by Mejame et al. (2022), automation leads to low consumption of energy, increased safety of the workers, and efficiency in the utilisation of resources. Mine monitoring is boosted through the use of remote sensing and analytics, which in turn enhance sustainability. There is increasing use of recycling and circular economy options for sustainable mining. (Tian *et al.*, 2020) called for the recycling of REE from e-trash as well as industrial scrap to minimize the effects of mining and the use of virgin raw materials. It suggests that by lessening the social costs of mining, these strategies could assist China in transforming its economy towards being far more sustainable and differentiated.

Methodology

In order to implement a thorough literature review on "Sustainable Resource Management and Economic Development: In the methodological decision to implement the research, titled "Evaluating the Impact of Rare Earth Mining on Local Economies and Environmental Sustainability in China," systematization of the literature search was employed. The aim was to systematically look for, appraise, and integrate relevant studies on the economic and environmental costs of REE mining in China. The search was performed in several databases and search engines such as Scopus, JSTOR, Web of Science, Google Scholar, and PubMed. Each of them was selected for their unique features in indexing articles in various fields such as economics, environment and sustainable development. Based on the search results, the specific key terms used in the research were 'rare earth mining', 'economic benefit', 'environmental cost', 'China', 'local economy', 'sustainable mining', 'environmental impact assessment' and 'socioeconomic consequences'. Since the aim was to search selectively for studies that directly compare the impacts of rare earth mining on both economic growth and ecological health in China, Boolean operators were used to combine these terms. The literature review on "Sustainable Resource Management and Economic Development: Different Study Types was used to gather enough information and comprehend the gist of the topic in the article "Evaluating the Impact of Rare Earth Mining on Local Economies and Environmental Sustainability in China". The review also incorporated empirical works that presented the quantitative and qualitative results of the economic and environmental impacts of rare earth mining to ensure that the impacts on the local economy and sustainability were assessed based on available findings. However, theoretical papers were included to provide conceptualizations of the general underlying theories of the study in relation to the conservation and management of rare earth minerals. Additionally, policy comparisons were performed to assess the effectiveness of current laws and processes that address the extraction of rare earth in China to understand policy improvements. Environmental audits evaluated softer aspects of the effects of mining on ecological balance, like pollution levels, disruption of habitats, and long-term sustainability. The angles chosen in the review aimed at giving a broad perspective concerning the various impacts of rare earth mining in China by including those diverse categories of research.

Inclusion and Exclusion Criteria

Table 1 clearly delineates the inclusion and exclusion criteria, ensuring a focused and relevant literature review on the economic and environmental impacts of rare earth mining in China.

In figure 1, the forest plot also provides a systematic review of ten papers that examine the environmental impacts of rare earth mining in China and the best practices in sustainable forest management. In the context of a meta-analysis, the weight of a study is represented by the measure of the square, which is dependent on the sample size and variance of the study. Thus, each study is depicted by a square. These mean differences in environmental impacts and sustainable management practices vary from research study to research study. However, the studies including Zhao et al., 0.90 and Mejame et al., 1.70 depict positive impacts, revealing that sustainable measures lead to a massive reduction of environmental degradation. Others, such as Mancheri et al., exhibit a negative mean difference (-0.20), which implies a potential increase in environmental impacts. Nevertheless, the confidence interval for this study includes zero, indicating that there is no significant effect. The diamond at the bottom of the plot represents the overall effect estimate, which indicates a statistically significant positive effect of sustainable management practices in mitigating environmental impacts.

Table 1: Inclusion and Exclusion Criteria

Criteria	Inclusion	Exclusion
Publication Type	Peer-reviewed journals	Non-peer-reviewed studies
Publication Date	Studies published from 2000 to the present	Studies published before 2000
Study Type	Quantitative and qualitative studies, including research articles, reviews, case studies, and meta-analyses	Studies not providing substantial data or insights on the economic or environmental impacts of rare earth mining
Geographical Focus	Research specifically focused on China	Studies focused on regions outside China
Content Relevance	Studies addressing economic or environmental aspects of rare earth mining in China	Papers not addressing the economic or environmental impacts of rare earth mining in China

Forest Plot

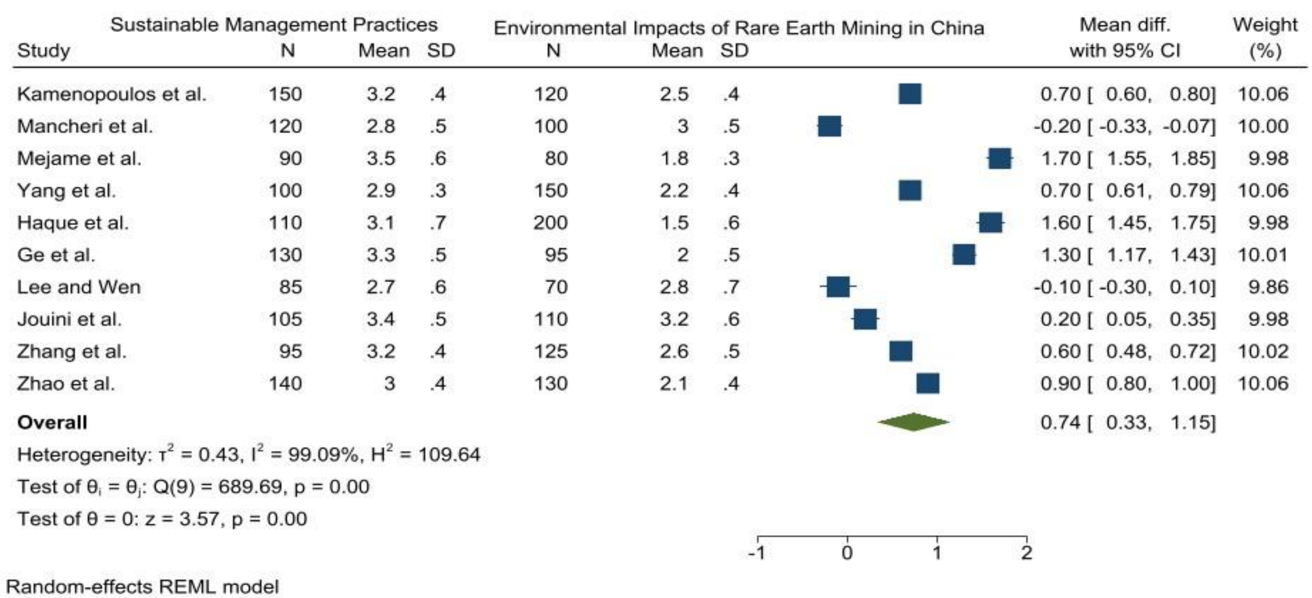

Figure 1. Forest Plot: Environmental consequences of rare earth extraction in China in relation to sustainable management practices

The overall mean difference is 0.74, and the 95% confidence interval comprises 0.33 to 1.15. This implies that, on average, sustainable management practices have a beneficial effect on minimise the environmental harm caused by rare earth mining in China. Nevertheless, the substantial variability in the results, which is likely due to differences in study designs, measurements, or regional contexts within China, is indicated by the high heterogeneity among studies ($I^2 = 99.09\%$). This variability implies that, although sustainable management practices generally have beneficial effects, their efficacy can fluctuate considerably based on the specific local conditions and the specific practices that are implemented.

Gaps in the Literature

Despite the significant body of research on rare earth mining, several gaps remain, particularly regarding the long-term socioeconomic impacts of mining on local communities and the effectiveness of specific environmental policies. While studies have extensively documented the immediate economic benefits and environmental consequences of mining, there is limited understanding of how these impacts evolve over time, especially in terms of social structures, health outcomes, and sustainable development. Furthermore, comparative studies still need to be conducted to assess the overall adverse effects of multiple mining activities and the field testing efficiencies of technologies and policies proposed in achieving these goals. Future research should concentrate on collecting overall assessments of environmental impacts and assessments of the duration of economic and social repercussions, analysing the results with distinctive policies, and empirical tests of policy implications and other technological changes that will address more satisfactory coverage of mining of rare earth metals and its implications and hence forward sustainable mining.

Conclusion

Exploring economic development and environmental sustainability in relation to rare earth mining, the review of the literature suggests the following conclusion. On one hand, rare earth mining has a multidimensional impact positively on local and national economies through employment creation, income and export earnings. On the other hand, it raises a number of environmental issues such as pollution of soil and water, pollution of air and loss of biodiversity. The increased use of sustainable management practices has a varying degree of influence on the alleviation of these environmental impacts, with some of the management practices adopting positive effects. In contrast, others have minimal or even negative impacts. Describing the ten studies on the effect of REEs on EMPs relating to the measures of sustainable management, it was found that on a mean level, the bad impacts of EMPs are lessened, with an overall mean difference of 0.74 and 95% CI from 0.33 to 1.15. However, due to the high level of heterogeneity among the studies that were reviewed in the present paper ($I^2 = 99.09\%$), it could be suggested that the utility of these practices depends on the context. Therefore, it is highly heterogeneous.

The study has the following key implications for policy making, mining stakeholders, and the populace of such regions. More elaborate and rigorous policies on environmental protection need to be formulated and adopted to reflect the regional differences of mining regions and improve the sustainable management policies that are currently in place. The evidence collected indicates that there is impetus for mining companies to take a more strategically proactive stance in adopting and enhancing practices of sustainability, especially those that have been proven to yield the best results in mitigating adverse effects on the environment. These are things like purchasing cleaner production technologies, improving waste management practices, and stepping up environmental monitoring levels. As for the local communities, the focus should be on improving relations with mining companies and policymakers to guarantee that benefits will be provided together with extra care for environmental and societal issues. There is a need for more integrated scientific and social analysis of the concerns surrounding rare earth mining. This comprehensive approach will provide a holistic perspective on the virtual impacts of mining and the long-term socio-economic consequences. It is crucial to synthesize the evidence base that assesses the effectiveness of sustainable management practices in different regions in China. This will enable stakeholders to design precise and efficient measures to reduce the adverse effects of rare earth mining on the environment and promote sustainable economic growth.

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Consent for Publication: All authors have reviewed and approved the final manuscript for publication.

Data Availability: The data generated and analyzed during this study are available from the corresponding author upon reasonable request.

Authors' Contribution: Aliza Tabassam: Conceptualization, Literature Review, Data Analysis, Writing – Original Draft, Corresponding Author. Zulfiqar Hussain: Methodology, Policy Review, Editing, Writing – Review & Editing All authors have read and approved the final manuscript and take full responsibility for the content presented.

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RESEARCH ARTICLE

Enhancing Load Capacity Factor: The Influence of Financial Accessibility, AI Innovation, and Institutional Quality in the United States

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Abstract
The investigation analyzes the impact of financial accessibility, AI innovation, urbanization, and institutional quality on the load capacity factor in the United States from 1990 to 2019. A series of stationarity tests were conducted to detect the presence of unit root problems, revealing a mixed order of integration with no significant unit root issues. To explore the cointegration among variables, the ARDL bounds test was employed, confirming long-run cointegration. The ARDL model's short-run and long-run estimations demonstrate that the Load Capacity Curve hypothesis holds in the United States, with a U-shaped relationship between income and load capacity factor. The results also reveal that financial accessibility, AI innovation, and institutional quality positively influence the load capacity factor in both the short and long run. Conversely, urbanization significantly reduces the load capacity factor over both time horizons. Furthermore, the study utilized further approaches, including Fully Modified Ordinary Least Squares (FMOLS), Dynamic Ordinary Least Squares (DOLS), and Canonical Cointegrating Regression (CCR), all of which validated the ARDL estimation results. Diagnostic tests confirmed the robustness of the model, showing that the variables are free from specification errors, serial correlation, and heteroscedasticity. These findings provide valuable insights for policymakers aiming to enhance load capacity through financial and technological advancements while considering the implications of urbanization.

Keywords: AI Innovation; Financial Accessibility; Institutional Quality; Load Capacity Factor; United States

Introduction

Over the past few years, conservation economics has prioritized ecological problems. Contamination, widespread societal shifts, and habitat loss have endangered natural diversification (Rai & Singh 2020; Raihan et al.,2024e; Raihan et al.,2024g). A rising need for natural resources is contributing to ecosystem issues such as climate change, soil erosion, air and water pollution, biodiversity damage, and the threat of global warming (Azam et al., 2023; Mithun et al.,2023; Raihan et al.,2024f). The USA, one of the six superpowers and the most developed nation in the world, with 52 developed states, is the subject of our study's analysis of environmental deterioration. The US significantly contributes to global carbon dioxide (CO2) emissions, thereby significantly influencing the overall concentration of greenhouse gases in the environment. Between 1990 and 2022, GDP growth causes to a boost in emission level in the 1990s, which peaked in the early 2000s due to changes in efficiency and policy. The 2010s saw a decrease in pollution due to rising natural gas usage, and the 2020s saw further impact from green energy and technological advancements (Dogan et al., 2024). The USA remains the second-largest contributor of CO2 emissions globally, following China (Ozan et al., 2023). However, the US Environmental Protection Agency (2022) indicated that the US has seen a 7% decrease in greenhouse gas (GHG) emissions since 1990. Additionally, the US ranks 7th on the globe for GDP per capita and has the greatest GDP in the world (Khan et al., 2021). Despite the perception that the US financial system is deep and sophisticated, many people still face barriers to financial access. The truth is that 16.7 million Americans are unbanked, meaning that they do not access a standard financial deposit account, and 50.9 million individuals in the US are underbanked, having used Alternative Financial Services (AFS) (Karp and Nash-Stacey, 2015). Furthermore, making use of AI technologies delivers the ability to profoundly revolutionize ways of handling waste in underprivileged areas and improve environmental conditions in the USA (Nwokediegwu & Ugwuanyi, 2024). These worrying statistics for the chosen criteria highlight the importance of the present investigation from a US perspective. The study adopted the load capacity factor (LCF), a vital way to measure a nation's ecological performance. LCF quantifies the extent to which people's actions harm the world and how the ecosystem compensates for it (Kartal et al., 2023). Most analyses focus on CO2 emission and ecological footprint (EF), primarily examining the demand side of ecological issues, potentially overlooking the supply side (Pata and Isik, 2021). An LCF less than 1 jeopardizes ecological sustainability, whereas an LCF above 1 signifies biocapacity exceeding EF and sufficient natural resources for sustainability concerns. Although a thorough study of panel data has not yet taken place, the literature on LCF is developing (Pata and Samour, 2023). Financial industry, commercial activity, population rates, modernization velocity, and usage of new technologies are the primary drivers of environmental pollution and greenhouse gas emissions that the USA must deal with due to its highly developed economy (Khan et al., 2019; Sohail et al.,2019). AI, the key technology of the latest industrial age, is increasingly playing a role in driving societal progress and global economic growth (Borges et al., 2021; Shiam et al.,2024b; Faruk et al.,2024; Abir et al.,2024). AI has demonstrated enormous promise for preserving the environment (Sohail et al.,2018a; Kar et al., 2022; Shiam et al..,2024a). Furthermore, it examines large amounts of past data to generate efficient forecasting models, enhancing the use of green power (Sohail et al.,2018b). In the context of the United States, our inquiry considers financial access, institution quality, and AI innovation as key policy factors, as well as the execution of the advanced ARDL technique. Based on such variables, our work is significant to the existing corpus of recent studies. The global urbanization process is accelerating. The United Nations reports that South America's urban population grew from 37% in 1960 to 82% in 2020 (Nations, 2018). Economic expansion results in a heavy use of power, natural assets, and production inputs, which initially pollutes and puts more strain on the natural world (Nurgazina et al., 2022). However, the finance-environment discourse widely acknowledges that the finance sector plays a crucial role in mitigating pollution by providing appropriate ecological financing (Kirikkaleli et al., 2022). Poor governance in nations may lead to a detrimental impact on GDP development when the governmental sphere is large (Khan et al., 2024). Enforcing laws, regulations, corruption control, and rights of ownership, all of which minimize greenhouse gas emissions while promoting more productive and efficient practices, requires strengthening institutions (Ali et al., 2019; Ahmad et al., 2024b). Our work significantly contributes to the current field in multiple key areas. This investigation is unique as it is the first to directly explore the connection among AI innovation, institutional quality, and the LCF in the USA. The investigation uses ARDL methods to examine patterns and significant areas of study concerning AI, financial accessibility (FA), institutional quality (IQ), GDP expansion, and urbanization (URBA) within the framework of the USA's LCF from 1990 to 2018. By focusing on LCF, this analysis offers new insights for scholars and makes a notable contribution to the field. In order to provide a more thorough study, a comprehensive environmental evaluation should include biocapacity, CO2 emissions, and the EF, which emphasizes humans' demand for natural assets (Pata et al., 2023). Consequently, the LCF is defined as the ratio of biocapacity to EF (Siche et al., 2010). By considering environment related variables from the viewpoints of supply and demand, this technique provides a more comprehensive evaluation (Pata, 2021). This investigation, the first comprehensive examination of the LCF literature, addresses the following questions: What implications do FA, IQ, and AI have on LCF in the US? What additional implications do GDP and urbanization have on LCF? Comprehending these variables might help lawmakers and strategists in encouraging ecologically conscious behavior. Our study additionally uses FMOLS, DOLS, and CCR approaches to verify the robustness of its findings. This research finding is very enlightening for legislators in the United States, as well as for those who work to achieve the SDGs, encourage green growth, and improve ecosystem quality.

The arrangement of the subsequent sections is controlled by the following sequence: Literature evaluations are the primary focus of the subsequent section. The theoretical framework, technique, and information are all provided in the third chapter. The empirical results are illustrated and discussed in the fourth chapter. The final section of the paper examines its conclusion and policy recommendations.

Literature Review

Several empirical studies have explored the implication of financial inclusion, ICT use, and GDP development on the LCF. While many analyses have employed the ARDL model, most have concentrated on the implications of financial globalization and renewable energy on the LCF. The study of ecological degradation in the U.S. context is still relatively new and lacks extensive research. This investigation, however, builds on previous studies to inform the selection of variables and methodologies used in the analysis. Risks related to environmental pollution, air quality, and ecosystems correlate with economic expansion (Awan et al., 2024). Throughout this period, multiple researches have analyzed the link between the natural world and financial prosperity. We need to further look at the relationship between the economic development and LCF in the USA. Covering 1965 to 2017, Pata and Balsalobre-Lorente (2021) conducted a study in Turkey and found an opposite connection between the LCF and GDP growth. Ahmed et al. (2020) using bootstrap causality analysis and the Bayer-Hanck cointegration test performed a work in China. Their findings highlight environmental issues associated with China's economic growth, demonstrating how GDP development leads to an increasing impact on the environment and pollution. Similar findings were made by Pata and Isik (2021) across China, Agila et al. (2022) in South Korea, Shang et al. (2022) within ASEAN economies, Raihan et al.(2024d) within Indonesia, Ridwan et al. (2024a) in South Asia, and Yang et al. (2024) for BRICS zone. Balcilar et al. (2018) carried out an examination of the economic expansion of the G-7 countries in relation to GHG emissions. They argue that rise in GDP is not degrades the ecosystem level in Germany and the UK. Acar et al. (2023) revealed an inverse U-shaped EKC and showed that while the initial boost in GDP led to more biodiversity loss, growth above a certain threshold led to increases in natural health after that.

Environmental degradation and the global warming problem are extremely complicated issues that need cutting-edge and innovative remedies (Nishant et al., 2020; Ridzuan et al.,2023). AI promotes advanced, efficient, and sustainable industrial frameworks (Wei et al., 2021; Hossain et al.,2023; Arif et al.,2024; Ferdous et al.,2023; Rana et al.,2024), which impact atmospheric conditions. Additionally, Dong et al. (2023) examined data from 30 provinces in China to explore the impacts and mechanisms of AI on CO2 emissions. Empirical research indicates that AI significantly reduces CO2 emissions. In order to examine the relationship between AI innovation, urbanization, GDP, stock market capitalization, and banking advancement, Shiam et al. (2023c) examined an analysis conducted in the Nordic region between 1990 and 2020. Utilizing the STIRPAT framework, they determined that progress in AI has an inverse relationship with the ecological footprint in the specified region. Akther et al. (2024) conducted a study in the USA with the ARDL bound test, analyzing data from 1990 to 2019. They discovered a positive correlation between private investment in AI and LCF. Likewise, Ridwan et al. (2024b) conducted an investigation in the USA from 1990 to 2019 to examine the impact of AI on natural health. They employed the ARDL technique and demonstrated that AI-related technology may ensure ecosystem sustainability. In the G-7 region, Ridwan et al. (2024c) did additional research employing the MMQR approach to examine the impact of AI innovation on the LCF. Their findings indicated that the implementation of AI yields beneficial effects at the ecosystem level. Additionally, Hossain et al. (2024) conducted an analysis in the Nordic region utilizing the LCC hypothesis and the ARDL approach. They also noted that AI innovation has beneficial ramifications at the ecosystem level.

Much of the literature indicates that there is conflicting evidence linking finance and environmental concerns. Financial accessibility, on the one hand, provides businesses and green economies with affordable and attractive financing schemes (Le et al., 2020; Islam et al.,2023). Conversely, nations with relatively easy access to financial services and funds are experiencing an increase in industrial activities, leading to high emissions and contaminated atmospheres (Hasanov et al., 2021). By adopting the ARDL framework Raihan et al. (2024b) explore the relationship within FA and CO2 pollutions in the G-7 region covering 1990 to 2019. Their results show that access to finance worsens environmental conditions and raises CO2 emissions. AMG and CCEMG estimates and PMG for testing causality are also used by Ali et al. (2022) to look into how monetary integration affected the environment in ECOWAS countries from 1990 to 2016. They demonstrated that accessibility in finances increases the ecosystem burden. Following the same principles, Hussain et al. (2022) in OECD countries, Anu et al. (2023) in developed and emerging areas, Fareed et al. (2022) in the Eurozone, and Yurtkuran and Güneysu (2023) in Turkiye have indicated that financial accessibility negatively impacts the state of ecosystems. Conversely, Saqib et al. (2023) deployed the implications of FA on developing nations' EF between 1990 and 2019. Using sophisticated panel estimation techniques, they demonstrated that monetary integration reduces environmental harm. Feng et al. (2022) and Zhong (2022) from China also hold similar views. Furthermore, Barut et al. (2023) described that financial accessibility did not affect contamination.

Institutional excellence, which includes factors such as law operation, effective administration, regulation quality, and political stability, has a significant impact on natural assets, temperature rise, and financial growth (Byaro et al., 2024). Therefore, inadequate policies regarding these concerns could potentially threaten ecological stability. Several current studies (Borghi et al., 2023; Chhabra et al., 2023) have highlighted the interaction between quality of institutions (IQ) and environmental sustainability. Similarly, during 1990 to 2019, Aydin et al. (2024) explored the consequences of IQ on 10 European Union nations that invest the most in environmental technologies. They discovered that improved institutional quality raises LCF in Germany and

France and lowers LCF in Austria. Furthermore, they established that the LCC theory applies exclusively to Spain. According to Zakaria and Bibi (2019), a 1% improvement in the IQ in South Asia turns a 0.114% reduction in pollution. According to Ali et al. (2019), in 47 developing nations, organizational excellence, which includes measures of the legal system, bureaucratic superiority, and corruption control, reduces emissions. Beside, Dam et al. (2024) investigate how IQ affects LCF in OECD nations and find that, over time, IQ has favorable consequence on degradation. In a similar way, findings by Anwar and Malik (2022) and Farooq et al. (2023) further confirmed the idea that institutional excellence might reduce environmental degradation. Achuo et al. (2024) additionally highlight how important it is for policymakers to promote legislation by improving institutional quality to foster a sustainable environment.

Urbanization has significant implications for environmental quality. By promoting cost-effective innovation, urban centers, and raising awareness about global warming through marketing and education, URBA has the capacity to enhance the general welfare of ecosystems (Kocoglu et al., 2021). In China scholars like Ahmad et al. (2019) indicate that they are very interested in green technology, suggesting that URBA has a favorable link with the ecosystem. Similarly, Chien et al. (2023) analyzed the implication of URBA on CO2 pollutions in the G-7 nations and found that growing populations reduce pollution in high-emission countries. Moreover, using the dynamic ARDL model, Danish and Hassan (2023) argued that urbanization in Pakistan contributes to pollution control. On the other hand, Raihan et al. (2022b) examined how urbanization has affected CO2 emissions in the USA. They demonstrated that for every 1% increase in urbanization, CO2 emissions increased by 0.56% immediately and 0.20% in the long run. In a similar vein, Tanveer et al. (2024) in Pakistan, Azam and Qayyum (2016) in the USA, and Voumik et al. (2023a) in Kenya also observed that urban growth is harmful for the environment. However, Xu et al. (2022) conducted research in Brazil and discovered that URBA does not affect LCF using ARDL-bound testing. In the same way, Sui et al. (2024) used the ECM model in China to demonstrate that, over time, the growth of urbanization will not deteriorate the ecological environment. Moreover, Ridwan (2023) found that urbanization has no consequences on natural world. Economic growth, urbanization, financial accessibility (FA), institutional quality (IQ), artificial intelligence (AI) innovation, and load capacity factor (LCF) have not been comprehensively examined in the United States. Although these components have been the subject of individual studies in the past, comprehensive assessments have been absent, particularly in the context of the United States' relationship. The appropriate implementation of AI technologies could potentially mitigate climate change by promoting energy efficiency, green technologies, and sustainable urban planning. Furthermore, modern institutions can promote the development of effective pollution-reduction strategies, and financial accessibility can promote conservation efforts. In the United States, an emerging area for analysis is comprised of these three interconnected factors: IQ, FA, and AI. In order to address the research gaps, we implement robust statistical methodologies such as ARDL, FMOLS, DOLS, and CCR. The objective of this investigation is to aid lawmakers in the development of policies that are suitable for the unique ecological and macroeconomic dynamics of the United States, thereby promoting equitable growth by underscoring the importance of LCF in environmental preservation.

Methodology

Data and Variables

The first table is a vital component of this research because it contains a detailed review of all the factors investigated. We derived the LCF statistics for the United States from the Global Footprint Network (GFN), a more appropriate source than other environmental proxies. The study additionally included a large number of independent variables, all of which were based on precisely the information obtained. The World Development Indicators (WDI) provided reliable figures on GDP, GDP squares, and urbanization. We designed Our World in Data to gather statistics on other crucial factors like AI innovation and institutional excellence. However, we collected information about financial accessibility from the IMF. As a result, through enhancing the availability and dependability of the study's approach, extensive proof ensures an explicit and integrated analysis.

Table 1. Source and Description of Variables

Variables	Description	Logarithmic Form	Unit of Measurement	Source
LCF	Load Capacity Factor	LLCF	Gha per person	GFN
GDP	Gross Domestic Product	LGDP	GDP per capita (current US$)	WDI
GDP^2	Square of Gross Domestic Product	$LGDP^2$	GDP per capita (current US$)	WDI
AI	Artificial Intelligence Innovation	LAI	Annual patent applications related to artificial intelligence	Our World in Data
FA	Financial Accessibility	LFA	Financial Institution Access Index	IMF
IQ	Institutional Quality	LIQ	Government Effectiveness, Estimate	Our World in Data
URBA	Urbanization	LURBA	Urban Population (% of population)	WDI

Theoretical Framework

In environmental studies, the load capacity curve (LCC) is a vital tool that sheds light on the complex linkages among ecological health, financial stability, and human development. This emphasizes the equilibrium or imbalance between the planet's ability to recover its resources and its use of human assets. The LCF provides an additional environmental evaluation by contrasting ecological footprint and biocapacity (Dogan and Pata, 2022). A more robust EF and higher LCF are indicators of a more salubrious ecosystem (Pata and Kartal, 2023). Due to the significance of these key features, we choose to utilize the LCF as a substitute for assessing damage to the ecosystem in our analysis.

It is believed that the LCC connects in a U-formation, with income acting as the primary drive. This link highlights the knowledge of how resource utilization expands in tandem with GDP growth and advances in individual affluence as an essential aspect of environmental sustainability (Degirmenci & Aydin, 2024). According to Ulucak et al. (2020), several industries alter manufacturing processes and greenhouse gases; financial growth exacerbates commercial polluting substances; and expanding economies are disadvantaged. We previously mentioned that there might be multiple links between factors such as GDP growth, private investment in artificial intelligence, technical innovation, urbanization, financial globalization, and LCF. We now develop equation (1) for LCC theory to enhance the understanding of previous studies.

$$Load\ Capacity\ Factor = f(GDP, GDP^2, Q_t) \qquad (1)$$

In this case, Q_t denotes other factors changing the LCF, while GDP stands for wealth in equation (1). The 2nd equation attempts to give a deeper understanding of the LCF by including factors such as economic growth, AI innovation, financial accessibility, institutional quality, and urbanization.

$$LCF = f(GDP, GDP^2, AI, FA, IQ, URBA) \qquad (2)$$

The load capacity factor (LCF) is denoted in equation (2), while finance availability (FA), AI innovation (AI), quality of institutions (IQ), and urbanization (URBA) constitute distinctive concepts. The econometric explanation of equation (3) was stated previously.

$$LCF_{it} = \delta_0 + \delta_1 GDP_{it} + \delta_2 GDP^2{}_{it} + \delta_3 PAI_{it} + \delta_4 FGOB_{it} + \delta_5 TI_{it} + \delta_6 URBA_{it} \quad (3)$$

The next equation illustrates the logarithmic values of the factors, which makes statistical information less complicated to interpret and constitute conclusions upon. Moreover, logarithmic scales assist in managing information with different dimensions while tackling obstacles such as heteroscedasticity, which is particularly relevant when working on large datasets. In this case, the research's coefficients are displayed in the parameter range of δ_0 to δ_6 .

$$LLCF_{it} = \delta_0 + \delta_1 LGDP_{it} + \delta_2 LGDP^2{}_{it} + \delta_3 LAI_{it} + \delta_4 LFA_{it} + \delta_5 LIQ_{it} + \delta_6 LURBA_{it} \ (4)$$

Empirical Methods

In the USA, the analysis used the ARDL method for data assessment to explore the link across LCF and variables such as GDP, GDP2, AI innovation, FA, IQ, and URBA. Additionally, we used the FMOLS, DOLS, and CCR approaches to ensure robustness. We conducted unit root assessments (DF-GLS, ADF, and P-P) at the start of the inquiry to explore stationarity. We then applied the ARDL bound analysis, given the nature of the time series data. We then performed estimates for the short and long-term ARDL. Next, we undertook multiple diagnostic tests in addition to the pairwise Granser causality analysis. After a rigorous process of evaluation, we managed to determine which econometric approach was the most precise and effective.

Unit Root Tests

A time series is considered to have a unit root when it displays a stochastic trend (Polcyn et al., 2023). Many studies have recommended running multiple stationarity analyses to assess the sequence integration categorization because the efficiency of such tests varies depending on the sample size (Voumik et al.,2023c).The present study used the ADF (Dickey and Fuller, 1979), the P-P (Philips and Perron, 1968), and the DF-GLS (Elliot et al., 1992) examinations to see if the data set was stationary. Due to its ability to control serial autocorrelation, the ADF technique has grown in favor (Dickey and Fuller, 1981). Compared to the DF approach, the ADF technique is more dependable and appropriate for more complicated tasks (Fuller, 2009).

ARDL Methodology

When variables exhibit stationarity, Pesaran et al. (2001) created the ARDL limits testing technique. Raihan and Voumik (2022a) assert that this technique offers the benefit of deployment in any series integration situation. As a result, the ARDL cointegration method offers precise and effective estimates of the variables' long-term relationship (Raihan and Voumik, 2022b). Moreover, scholars can effortlessly detect dynamic adjustment mechanisms by incorporating lagged terms of variables with ARDL (Raihan et al., 2024c). Therefore, one can apply the ARDL bounds analysis technique regardless of whether the basic returning system separates in I(2) and the cointegration order occurs at I(0) or I(1) (Raihan et al., 2022a; Voumik & Ridwan, 2023). Equation (5) displays the bounds assessment for the ARDL in the following manner:

$$\Delta \mathrm{LLCF_t} = \delta_0 + \rho_1 \mathrm{LLCF_{t-1}} + \rho_2\ \mathrm{LGDP_{t-1}} + \rho_3 \mathrm{L}GDP^2{}_{\mathrm{t-1}} + \rho_4 \mathrm{LAI_{t-1}} + \rho_5 \mathrm{LFA_{t-1}} + \rho_6 \mathrm{LIQ_{t-1}} + \rho_7 \mathrm{L}URBA_{\mathrm{t-1}} + \sum_{\mathrm{i=1}}^{\mathrm{q}} \delta_1\ \Delta\mathrm{LLCF_{t-i}} + \sum_{\mathrm{i=1}}^{\mathrm{q}} \delta_2\ \Delta\mathrm{LGDP_{t-i}} + \sum_{\mathrm{i=1}}^{\mathrm{q}} \delta_3\ \Delta \mathrm{L}GDP^2{}_{\mathrm{t-i}} + \sum_{\mathrm{i=1}}^{\mathrm{q}} \delta_4\ \Delta\mathrm{LAI_{t-i}} + \sum_{\mathrm{i=1}}^{\mathrm{q}} \delta_4\ \Delta\mathrm{LFA_{t-i}} + \sum_{\mathrm{i=1}}^{\mathrm{q}} \delta_4\ \Delta\mathrm{LIQ_{t-i}} + \sum_{\mathrm{i=1}}^{\mathrm{q}} \delta_4\ \Delta\mathrm{LURBA_{t-i}} + \varepsilon_{\mathrm{t}} \tag{5}$$

Pesaran et al. (2001) illustrated the use of the upper and lower bounds as fundamental values to facilitate the comparison of the F-statistics.. If the test results fall within the lowest and highest bounds, they are considered ambiguous (Raihan et al., 2023a; Voumik et al.,2023b). Engel and Granger (1987) established long-term connections before introducing the ECM to assess short-term correlations and ECT. For the long-term evaluation of the ARDL, we use Equation (6).

$$\Delta LLCF_t = \delta_0 + \sum_{i=1}^{q} \rho_1\ \Delta LLCF_{\mathrm{t-1}} + \sum_{i=1}^{q} \rho_2\ \Delta\mathrm{LGDP_{t-1}} + \sum_{i=1}^{q} \rho_3 \Delta GDP^2{}_{\mathrm{t-1}} + \sum_{i=1}^{q} \rho_4\ \Delta\ LAI_{t-1} + \sum_{i=1}^{q} \rho_5 \Delta\mathrm{LFA_{t-1}} + \sum_{i=1}^{q} \rho_6\ \Delta LIQ_{t-1} + \sum_{i=1}^{q} \rho_7\ \Delta LURBA_{t-1} + \theta ECM_{t-1} + \varepsilon_t \tag{6}$$

Robustness Check

We deployed the FMOLS, DOLS, and CCR methods to assess the dependability of the ARDL results. According to Ahmad et al. (2024a), the FMOLS method can produce accurate results and is capable of handling bias resulting from missing variables, variability, serial correlation, error in measurement, and smaller sample sizes. The DOLS method tries to figure out a long-term link in a model where the factors are cointegrated but have different levels of integration, endogeneity and autocorrelation issues (Stock and Watson, 1993; Begum et al., 2020). Furthermore, without requiring any modifications, the CCR regression model applies to both multivariate and single equation regression methods, thereby preserving efficiency (Park, 1992). It separates zero-regularity independent factors from error terms in cointegrating models (Pattak et al., 2023).

Pairwise Granser Causality Test

Granger causality is a theory of statistics that assesses whether previous values of one parameter provide valuable information for finding the other to explore the link between the two variables (Rose and Paparas, 2023). Our work made use the pairwise Granger-causality test Granger, 1969). We say that another time series

X "granser-causes" a time series Y if it can predict the future of the latter (Raihan and Tuspekova, 2022a).However, a bivariate autoregressive model may display the variables Xt and Yt.

$$X_t = \gamma_1 + \sum_{i=1}^{n} \alpha_i Y_{t-i} + \sum_{i=1}^{n} \mu_i X_{t-1} + e_t \quad (7)$$

$$Y_t = \gamma_2 + \sum_{i=1}^{n} \Omega_i Y_{t-1} + \sum_{i=1}^{n} ¥_i X_{t-i} + u_t \quad (8)$$

Here, n denotes the number of lags.

Diagnostic Test

We employed the LM test, the Jarque-Bera test (Jarque and Bera, 1987), and the BPG test (Breusch and Pagan, 1979), to identify significant problems that could directly affect the precision of the predicted coefficients. To ensure that errors do not correlate with time and produce skewed and deceptive calculations, the LM technique examines residuals for serial correlation. Because of heteroscedasticity, the Breusch-Pagan-Godfrey test may produce inaccurate estimates and standard errors. We also check how well the short-term beta coefficients in the ARDL method fit together by comparing the repeated residuals to the CUSUM and CUSUMQ tests.

Results and Discussion

The following section includes actual figures generated from predetermined estimating methods, whereas Table 2 highlights the statistical properties of the variables under consideration. Because every data point had the same number of observations (32), the box delivers an extensive evaluation that includes key statistical measurements, including the mean, median, maximum, minimum, standard deviation, and probability value. Most variables had positive means, except LLCF and LFA, and LGDP2 had the highest mean. Furthermore, the standard deviations of all variables were low, indicating little change over time and a high concentration of data points around the mean.

Table 2. Summary statistics of the variables

Variables	LLCF	LGDP	LGDP2	LAI	LFA	LIQ	LURBA
Mean	-0.835416	10.64393	113.3917	7.505506	-0.129338	0.471661	4.377885
Median	-0.822656	10.71885	114.8942	7.157725	-0.13288	0.444502	4.382195
Maximum	-0.63269	11.15938	124.5318	9.724421	-0.065403	0.692247	4.417309
Minimum	-0.970971	10.08116	101.6297	6.320768	-0.183003	0.243055	4.32148
Std. Dev.	0.093945	0.318778	6.76113	1.035853	0.032861	0.110563	0.027091
Skewness	0.065531	-0.255693	-0.219087	1.155679	0.25722	0.257958	-0.500595
Kurtosis	1.965479	1.888894	1.876795	2.992345	1.75315	2.707801	2.252894
Jarque-Bera	1.449882	1.994763	1.938117	7.123243	2.425709	0.468734	2.08073
Probability	0.484353	0.368844	0.37944	0.028393	0.297347	0.791071	0.353326
Sum	-26.73331	340.6058	3628.534	240.1762	-4.138819	15.09316	140.0923
Sum Sq. Dev.	0.273596	3.150205	1417.099	33.26275	0.033476	0.378947	0.022751
Observations	32	32	32	32	32	32	32

Moreover, the variables LLCF, LAI, LFA, and LIQ exhibited positive skew, whereas the remaining variables displayed negative skew. We executed the Jarque-Bera Normality Test to ensure each factor in this investigation had a normal distribution.

Table 3 illustrates the stationarity tests for the log-transformed factors at both I(0)and I(1) levels. The results demonstrate that financial accessibility, institutional quality, and urbanization are stationary at the level I(0) form. Conversely, LCF, GDP, GDP squared, and AI innovation were non-stationary at the level; however, they became stationary after accounting for the initial difference I(0). Given the heterogeneous order of integration, we can employ the ARDL methodology in further section.

Table 3. Results of Unit root test

Variables	ADF		P-P		DF-GLS		Decision
	I(0)	I(1)	I(0)	I(1)	I(0)	I(1)	
LLCF	-0.588	-5.743***	-0.643	-5.432***	-1.576	-4.110***	I(1)
LGDP	-0.725	-4.148***	-0.359	-4.928***	-1.118	-3.731***	I(1)
$LGDP^2$	-0.416	-5.903***	-0.740	-4.863***	-1.241	-3.655**	I(1)
LAI	-2.061	-4.134***	-1.068	-3.671***	-2.341	-4.061***	I(1)
LFA	-3.871**	-4.071***	-3.703**	-4.021***	-3.771**	-4.052***	I(0)
LIQ	-4.052***	-5.007***	-3.054**	-4.090***	-3.342**	-3.770***	I(0)
LURBA	-4.115***	-7.043***	-7.654***	-8.453***	-3.065**	-4.432***	I(0)

The ARDL bound assessment results reject the null hypothesis of no co-integration at the 1% significance threshold. The F-test statistic result of 8.345 achieved the stipulated value. Consequently, it is feasible to contend that the parameters of the model exhibit specific co-integrating interactions. These attributes facilitate the framework's rapid adaptation to a typical stochastic disturbance. Therefore, we can deduce that the variations in all identified factors influence the LCF in the United States.

Table 4. Results of ARDL bound test

Test Statistic	Value	Signif.	I(0)	I(1)
F-statistic	8.34532	10%	1.99	2.94
K=6		5%	2.27	3.28
Asymptotic: n=1000		2.50%	2.55	3.61
		1%	2.88	3.99

Once the bound testing procedure confirmed the cointegration, we could assess the long-term connection among those factors. Table 5, which incorporates the dynamic ARDL paradigm, illustrates the both period effects of LGDP, LGDP2, LAI, LFA, LIQ, and LURBA on LLCF in the United States. According to the research, the US environment's load capacity appears to go up with GDP growth but falls with economic growth over time. Our findings indicate that due to financial growth, the ecosystem increasingly loses its natural characteristics. The result provides a theoretical explanation because the US economy has grown larger and heavily relies on sources like oil and gas, which damage the natural world. According to Table 5's conclusions, for every 1% expansion in GDP, the LCF declines by 1.687% over the long term and by 0.738% during the short term. Rising economic growth and ecosystem damage are linked to increased consumption and development efforts to meet social

expectations (Raihan and Tuspekova, 2022b). Several studies, such as those by Ridwan et al. (2023), Bekun (2024), Islam et al.(2024), Kirikkaleli et al. (2023), Raihan et al.(2023c) Raihan et al.(2023b) and Wang et al. (2023), back up the idea that GDP and ecosystem degradation are linked in a good way. However, Guo et al. (2024) observed that in China, the effect of per capita GDP on the natural world will eventually lessen. Similarly, Raihan et al.(2024a) aligned with this outcome in India. But Onwe et al.(2024) found asymmetric effect of GDP on environment condition in Japan. In contrast, each unit of GDP2 boost results in a 1.644% long-term and 0.668% short-term enhancement of LCF. Given that the coefficient for LGDP is unfavorable and for LGDP2 is beneficial, both of these are statistically significant, it appears that atmospheric pressure decreases over time, validating the recently proposed LCC hypothesis for the US. However, Dogan et al. (2020) discovered that GDP2 worsens the degree of environmental adaptability in the BRICS.
The LAI coefficients exhibit a positive association with LLCF, predicting a 0.077% long run and a 0.030% short run increase in LLCF for every 1% increase in AI innovation. According to Platon (2024) and Rahman et al.(2024), artificial intelligence is an important component that could improve and hasten the rise of the circular economy. Furthermore, AI reduces carbon emissions in China by strengthening information facilities, advancing green technology innovations, and optimizing industry structure (Chen et al., 2022). In a similar vein, LCF is positively associated with FA in both the long and short runs, and this association is statistically significant.

Table 5. Results of ARDL short-run and Long-run Estimation

Variable	Coefficient	Std. Error	t-Statistic	Prob.
Long-run estimation				
LGDP	-1.687	0.0400	-2.080804	0.000
LGDP2	1.644	0.2359	3.971924	0.000
LAI	0.077	0.0305	1.525705	0.023
LFA	0.602	0.3552	1.696772	0.110
LIQ	0.257	0.1159	2.222973	0.042
LURBA	-1.715	0.6682	-4.765392	0.000
C	7.638	8.4340	6.135154	0.000
Short-run estimation				
D(LLCF(-1))	-0.047	0.0601	-0.7883	0.428
D(LGDP)	-0.738	3.3020	-4.7658	0.003
D(LGDP2)	0.668	0.1505	4.4436	0.005
D(LAI)	0.030	0.0178	3.7343	0.033
D(LFA)	0.853	0.1492	5.7165	0.000
D(LIQ)	0.112	0.0211	5.2924	0.000
D(LURBA)	-1.198	2.1359	7.1157	0.000
CointEq(-1)*	-0.7604	0.0718	-10.5823	0.000

These findings suggest that access to the financial system might be advantageous to the USA ecosystem. Particularly, a 1% development in FA causes a 0.602% long-term rise in LCF and a 0.853% short-term increase.

Similarly, Alam et al. (2024) revealed that financial inclusion minimizes CO2 emissions and improves the environmental quality across oil-producing countries. However, our result is agreed with Le et al. (2020) in Asia, which indicates that the expansion of FA is harmful to biodiversity. Furthermore, having easy access to finance requires more energy, which increases CO2 emissions and harms our planet (Acheampong 2019).

Moreover, there exits an encouraging relationship between LIQ and LLCF, with each 1% increase in LIQ increasing LCF by 0.257% in the long term and 0.112% in the short run, and this result is significant at the conventional level. Our research indicates that strong institutional structures preserve the ecosystem by executing legislation and encouraging green growth. Zheng et al. (2024) in the E-7 economies, Hussain and Dogan (2021) in the BRICS country, and Ashraf and Javed (2023) in the BRI countries have found that enhanced institutional quality contributes to a better atmosphere and significantly reduces pollution. However, Sibanda et al. (2023) within sub-Saharan Africa and Amin et al. (2023) across South Asia have discovered that the rising quality of institutions is contributing to ecological destruction. Conversely, the negative and statistically significant URBA coefficients indicate that both long-term and short-term increases in LURBA negatively affect environmental quality. A 1% expansion in URBA raises LCF by 1.715% in the long run and 1.198% in the short run. Similarly, Voumik et al. (2024) in Bangladesh, Khalid et al. (2022) in the G-7 area, and Ramzan et al. (2024) in China found that population growth boosts CO2 emissions. However, Wang et al. (2021) investigated in OECD territories that urbanization improves environmental sustainability by lowering CO2 emissions.

In Table 6, robustness testing results confirm the findings obtained through ARDL calculations. At the 1% range, the GDP factors in the FMOLS, DOLS, and CCR models are statistically significant and have a negative trend. A 1% rise in GDP diminishes LCF by 1.517%, 1.321%, and 1.508%, respectively. In contrast, GDP2 has an upward and substantial relationship with LCF at the 1% significance threshold in all models. A 1% increase in GDP2 increases LCF by 1.469%, 1.701%, and 1.464%, respectively, implying that greater GDP levels have a favorable impact on LCF.

A 1% development in LAI boosts LCF by 0.041% in the FMOLS model, 0.156% in DOLS, and 0.049% in CCR. This finding highlights that agricultural investment positively influences LCF. Furthermore, an extra 1% in LFA causes an improvement in LCF of 1.012%, 1.387%, and 0.837% in the FMOLS, DOLS, and CCR simulations, respectively. The results reported here are significant at the 1% level and correlate with both term ARDL evidence. According to the FMOLS estimation, a 1% increase in LIQ improves LCF by 0.126%, 0.141%, and 0.147%, respectively. Such results are significant at the 5% level for FMOLS and DOLS, as well as at the 1% level for CCR, which supports the ARDL findings. Conversely, a 1% expansion in LURBA falls to the LCF by 0.801% and 1.504% in the FMOLS and DOLS methods. On the other hand, a 1% spike in LURBA will increase the LLCF by 2.831% in the CCR estimation, resulting in a significant 5% threshold. These outcomes also align with the ARDL short- and long-run estimation.

Table 6. Results of Robustness check

Variables	FMOLS	DOLS	CCR
LGDP	-1.517***	-1.321***	-1.508***
$LGDP^2$	1.469***	1.701***	1.464***
LAI	0.041**	0.156**	0.049**
LFA	1.012***	1.387***	0.837***
LIQ	0.126**	0.141**	0.147***
LURBA	-0.801***	-1.504***	2.831***
C	6.975***	5.968***	6.990***

The insights provided by Table 7 demonstrate the causal links between several kinds of economic variables. The F-statistic of 3.38826 and p-value of 0.0499 reject the null hypothesis of no connection at the 5% significance range, indicating that LLGDP does not cause Granger-cause LLCF. Furthermore, p-values below the standard significance threshold rule out the null hypothesis that there is no linkage in these circumstances, supporting the existence of one-way causality between LGDP2, LAI, LFA, LURBA, and LLCF. However, we found no causative association between LLCF and LIQ. Because p-values above the conventional significance level suggest no significant causal correlations between LLCF and LGDP, LLCF and LGDP2, LLCF and LAI, LFA and LLCF, and LURBA and LLCF, we cannot reject the null hypothesis that there is no causality in these interactions.

Table 7. Results of pairwise Granger Causality test

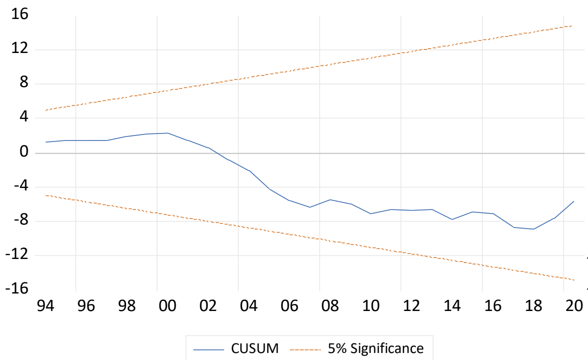
Null Hypothesis	Obs	F-Statistic	Prob.
LGDP $\neq$ LLCF	30	3.38826	0.0499
LLCF $\neq$ LGDP		0.44313	0.6471
LGDP2 $\neq$ LLCF	30	3.4843	0.0463
LLCF $\neq$ LGDP2		0.44696	0.6446
LAI $\neq$ LLCF	30	2.38966	0.0123
LLCF $\neq$ LAI		1.48366	0.2461
LFA $\neq$ LLCF	30	1.20508	0.3165
LLCF $\neq$ LFA		6.46444	0.0055
LIQ $\neq$ LLCF	30	1.81009	0.1844
LLCF $\neq$ LIQ		1.18981	0.3209
LURBA $\neq$ LLCF	30	2.68762	0.0877
LLCF $\neq$ LURBA		5.37891	0.0114

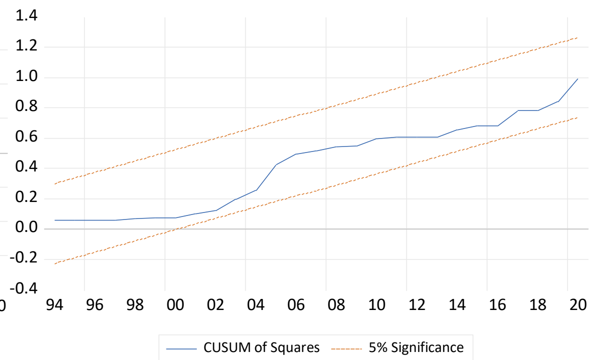
Table 8 shows that none of the diagnostic techniques support the null hypothesis, thus ruling it out. The p-value of 0.4231 from the Jarque-Bera assessment confirms the constant distribution of the residuals. With a p-value of 0.3612, the Lagrange multiplier analysis confirms no serial correlation in the residuals. Ultimately, having a p-value of 0.4123, the Breusch-Pagan-Godfrey assessment validates that the residuals have no evidence of heteroscedasticity.

Table 8. The results of diagnostic tests

Diagnostic tests	Coefficient	p-value	Decision
Jarque-Bera test	2.5671	0.4231	Residuals are normally distributed
Lagrange Multiplier test	1.054	0.3612	No serial correlation exits
Breusch-Pagan-Godfrey test	0.8741	0.4123	No heteroscedasticity exists

Additionally, we apply the CUSUM and CUSUM-SQ statistics to search for structural stability in residuals over both long and short periods. The outcomes are within critical limits, with the CUSUM-SQ plot remaining on the crucial line, as shown in the following figure. This indicates that the parameters are consistent and adequately stated at the 5% level of significance.





Conclusion and Policy Implications

The study investigated the multifaceted connections across economic growth, AI innovation, financial accessibility, institutional quality, and urbanization, as well as their effects on the LCF in the USA between 1995 and 2021. Using sophisticated econometric techniques, the investigation studied the load capacity factor to identify the variables affecting environmental sustainability in the chosen area. We used various unit root analyses, like ADF, P-P, and DF-GLS, to confirm that the factors were not stationary and to make sure the investigation was strong. This created opportunities for assessing the short and long-term influences using the novel ARDL methodology. Robustness testing using FMOLS, DOLS, and CCR confirms the validity and accuracy of the ARDL findings, thereby enhancing the credibility of the results. Finally, we employed three diagnostic tests to check for heterocesdaticity and autocorrelation issues in the selected data set. The ARDL analysis outcomes indicate multiple significant feedbacks. The outcomes showed that GDP growth and urbanization had a negative association with LCF in both the short and long run. These results underscore that the expansion of financial activities and the rise in urban population will lead to increased pollution due to the utilization of more fossil fuels and natural assets. However, GDP squares demonstrate a favorable implication on ecological condition of the USA in both periods, suggesting that a higher GDP can introduce more advanced environmentally-friendly approaches. Similarly, we found a positive association between LCF and AI innovation, financial accessibility, and institutional quality, suggesting that the use of modern AI technologies, improvements in institutional quality, and increased financial inclusion can enhance the natural health of the selected country. The Pairwise Granger causality test revealed a unidirectional causality from LGDP, LGDP2, and LAI to LLCF, as well as from LLCF to LFA and LURBA. However, there is no evidence that LLCF Granger causes LGDP, LGDP2, or LAI. Similarly, we found no causal relationship between LIQ and LLCF, and neither LFA nor LURBA cause LLCF. These relationships highlight the importance of how investments in artificial intelligence, financial accessibility, and good institutions impact the dynamics of ecological sustainability in the United States. Therefore, policymakers can create targeted strategies and regulations to reduce ecological degradation while promoting sophisticated technological innovation, a stable financial system, and standard institutions in the selected area.

The findings of our paper have important policy suggestions for improving the load capacity factor in the United States. Policymakers should give priority to policies that enhance financial accessibility, as research has demonstrated their favorable impact on the load capacity factor. One such approach is to develop strategies that facilitate increased availability of credit and financial services, specifically targeting small and medium-sized firms (SMEs). These enterprises are essential for driving economic growth and maximizing resource utilization. Furthermore, the beneficial influence of AI advancement on the ability to handle heavy loads implies that there should be support for expenditures in technology and innovation. Policymakers have the ability to encourage and support research and development in the field of artificial intelligence (AI), offer tax advantages to corporations that embrace AI technology, and establish a regulatory framework that promotes advancement while also guaranteeing adherence to ethical norms. The study urges the importance of institutional excellence in improving load capacity, emphasizing the requirement for robust governance, transparency, and the implementation of laws that safeguard property rights and encourage equitable competition. Conversely, the disastrous consequences of urbanization on the load capacity factor highlight the necessity for meticulous urban planning and development strategies. Policymakers should take into account the possible burden on infrastructure and resources that rapid urbanization might impose and adopt sustainable urban development measures that alleviate these impacts. This may involve allocating funds towards environmentally friendly infrastructure, advocating for distributed development, and ensuring that urban growth is in line with the available local resources and infrastructure. Policymakers may achieve a balanced approach by considering these factors: financial, technological, and institutional improvements. This strategy will boost the load capacity factor while also reducing the negative impacts of urbanization.

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RESEARCH ARTICLE

How much regulation is optimal for the brick manufacturing industry in developing economies? – Experiences from Bangladesh, India, and Nepal

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Abstract

Brick manufacturing is one of the fast-growing and economically important industries in Bangladesh and the neighboring developing countries. Its growth is synchronized with the increasing demand for bricks in the construction sector of these countries. However, the growth in this industry appears to be unplanned and thus, it is leading to the deterioration of the environment including air pollution, forest destruction, and soil degradation, aligned regulation is also gradually getting more stringent. In this study, the latest and relevant rules and laws have been summarized to highlight the historical development of brick kiln regulations in Bangladesh, India, and Nepal. Nevertheless, Bangladesh has been chosen as a case to understand brick kiln owners' compliance status with applicable regulations in Bangladesh, India, and Nepal. A total of 140 brick kilns were studied from four districts in the country. Socioeconomic factors affecting the degree of compliance of the industry to legal tools have been evaluated using logistic regression. The study shows that every brick kiln violated at least one Section of the Act. Per unit brick production cost has significantly increased due to compliance. This study also reveals that kilns with environmental clearance certificates were more likely to adopt modern technology. However, the kiln's age, penalty, and production cost had a negative relationship with the adoption of modern technology. Total income from brick kilns and possession of an environmental clearance certificate was positively linked to the choice of coal or gas as a fuel rather than wood. In contrast, bribe and production size were less likely to affect the fuel compliance of the kilns. The study has identified the factors that require the attention of policymakers to enhance the practicability of the law at the field level.

Keywords: Brick kilns; Economy; Environment; Industry; Regulation

Introduction

Bangladesh is a developing economy with tremendous economic growth in recent decades aiming to be an upper-middle-income country by 2031 and a high-income country by 2041 (Raihan et al., 2022a). Among the top 12 developing countries with a population of over 20 million, Bangladesh achieved 6-plus percent growth in 2016 (Hussain & Haque, 2017). The country is in transition from an agriculture-based economy to an economy of a mix of light and heavy industries and services (Raihan et al., 2022b). This has led to many infrastructural changes including a flourish in the real estate sector (Hossain et al., 2024). Bangladesh is estimated to construct four million new houses each year to accommodate the growing population (Khan et al., 2021). As a result, in a country with limited natural sources of stones, the boom of the brick manufacturing industry became obvious with a production size of 12 billion bricks a year (Islam et al., 2023). Bangladesh produces 17 billion bricks a year, which is 1.3% of the total Asian brick production (Khaliquzzaman et al., 2020). Being the major building material supplier the industry is generating about 1 million employments and contributing around one percent to the nation's GDP (Talut et al., 2022). However, the growth of the brick manufacturing industry has not been much planned, and thus, there exist many brick kilns that are illegal, unreported, and noncompliant. As of June 2022, Bangladesh possessed 7,881 brick kilns, comprising 3,248 legitimate and 4,633 illegal establishments. Sixty percent of brick kilns in the country are functioning without environmental authorization. Though the brick sector is significantly contributing to the economy, it is a major concern since it is reducing agricultural land, intensifying deforestation, increasing air pollution and greenhouse gas (GHG) emissions along with other social factors including labor right violation, gender discrimination, and social violence (Hossain et al., 2019). According to the Department of Environment (DoE), nearly two million tons of coal and two million tons of wood are combusted in about 5000 brick kilns every year (Muhib & Khan, 2022). With the net reduction and degradation of agricultural land, the brick manufacturing industry is posing strong threats to the country's food security (Haque et al., 2022). The industry is also widely blamed for environmental pollution and human health hazards (Haque et al., 2022). With contrasting issues with the brick kilns, the efforts for regulating this industry have of long regulatory history but with limited success (Brooks et al., 2024). The Government of Bangladesh (GoB) has demonstrated strong commitment by changing its strategies and policies. The first law in the brick sector was introduced in 1989, which saw two rounds of amendment in 1992 and 2001. Despite these amendments, the location requirements have not been enforced, and the use of firewood in the brick kilns could not be checked (Shahen, 2024). As continued effort to conserve environment and forest, the GoB enacted the Environment Conservation Act, 1995 that required environmental clearance certificate (ECC) for the kilns to operate, circulated a gazette notification in 2007 for the kilns to adopt improved technologies by 2010, enacted a new notification in 2010 to eliminate fixed chimney kilns (FCKs) by 2012, issues a final notification in 2012 that required all the kilns to install at least 120-ft high chimneys. This last notification was successfully enforced especially in the vicinity of urban areas where the DoE monitoring of the kilns was quite strong. To take a firmed stand on regulating the brick manufacturing industry, the government enacted the Brick Making and Brick Kiln Establishment (Control) Act, 2013 in July 2013 (Act 2013, hereafter). The law entered into operation in July 2014.

Not only in Bangladesh, but the brick manufacturing industry has also become a matter of concern and is under strong regulation in the neighboring brick-producing countries. Many countries imposed different regulations and set out rules to control pollution from brick kilns. The Government of India has issued notifications of emission standards for brick kilns which include maximum allowable levels for particulate matter concentration in flue gases, minimum stack height, and a proposed ban on the use of moving chimneys (Rajarathnam et al., 2014). In Nepal, various national regulations such as the Environment Protection Act 1997, Environment Protection Regulation 1997, and Industrial Enterprises Act 2004 govern the industrial operation including brick kilns (Thakuri et al., 2024). Industrial Enterprise Act, of 1992 is the main act that governs all types of industries including brick kilns in Nepal (Bhandari et al., 2016). Like Bangladesh and India, Nepal also banned the establishment of movable brick kilns in Kathmandu in 2003 and the restriction was extended throughout the country in 2012 (Thakuri et al., 2024). The country also requires the submission of an environmental impact assessment (EIA) report, soil sources, and land reclamation plan prior to the establishment of a kiln (Bhandari et al., 2016). In Bangladesh, the Act 2013 has been in its initial stage of implementation with varying degrees of success and mixed criticisms from all parties involved – the GoB, the brick manufacturing industry, civil society, and the scientific community. After three years of enactment, the feasibility and enforceability of the provisions of this act are not beyond question (Haque & Sharif, 2021). According to the DoE, this act should be amended in the light of field-level study considering the issues with the participation of all stakeholders (Khaliquzzaman et al., 2020). More than three-decades-long brick manufacturing industry regulation is not so pleasing because of its poor and impractical implementation. Given this, it was enormously important to examine how well the Act 2013 has regulated the brick manufacturing industry. While most of the studies are, in one way or another, inclined towards focusing on how detrimental brick manufacturing industry is to the health, environment, and food security of the nation, technological compliance issue, and technological efficiency of brick production (Hossain et al., 2019; Khaliquzzaman et al., 2020; Aniyikaiye et al., 2021; Ncube et al., 2021; Akhtar et al., 2022; Bajracharya et al., 2022; Haque et al., 2022; Parvez et al., 2023; Shahen, 2024), there is clearly a dearth of any investigation addressing the degree of stringency of this act compared to similar acts in neighboring countries and the level of compliance of the brick manufacturing industry to regulation. That being said, this study was conducted (i) to evaluate the chronological development of regulatory tools governing brick kilns in Bangladesh and neighboring countries, (ii) to examine the status of the compliance of brick manufacturing industry to the Act 2013, (iii) to examine the socioeconomic factors affecting the brick kiln owners' attitudes to comply with the regulation, and (iv) to test the significance of the production cost of such compliance.

Method

Study boundary

The latest legislation that governs the brick industries in Bangladesh, Nepal, and a couple of states in India have been summarized and compared. The Indian states included in the study are Uttar Pradesh (UP), Jammu Kashmir (JK), and Assam (AS). Assuming the existence of similar compliance status in these Southeast Asian countries, Bangladesh was selected as a case to understand the status of brick manufacturers' compliance and attitude towards the regulations. Given this, the study was conducted in four north-central districts of Bangladesh - Brahminbaria, Kishoregonj, Mymensingh, and Netrokona. Mymensingh is 120 km to the north of the country's capital, Dhaka. Netrokona is 134 km to the north, Kishoregonj is 98 km to the northeast, and Brahmanbaria is 76 km to the southeast of Dhaka (Figure 1). These districts constitute a major brick manufacturing zone of the country that harbors 452 of the total of 6000 brick kilns across the country (Muhib & Khan, 2022). The districts are distributed across three administrative divisions - Brahminbaria is in the Chittagong division, Kishoregonj is in the Dhaka division, and Mymensingh and Netrokona are in Mymensingh division – totaling a land area of about 9022 square km. The economy of these districts is largely agrarian having vast areas of farmland and a significant number of rivers flowing through the area. Kishoregonj and Netrokona contain a large area of low-lying wetland, locally known as *haor*, containing Nikli, Austagram, Mithamain, and Birishiri *haors*.

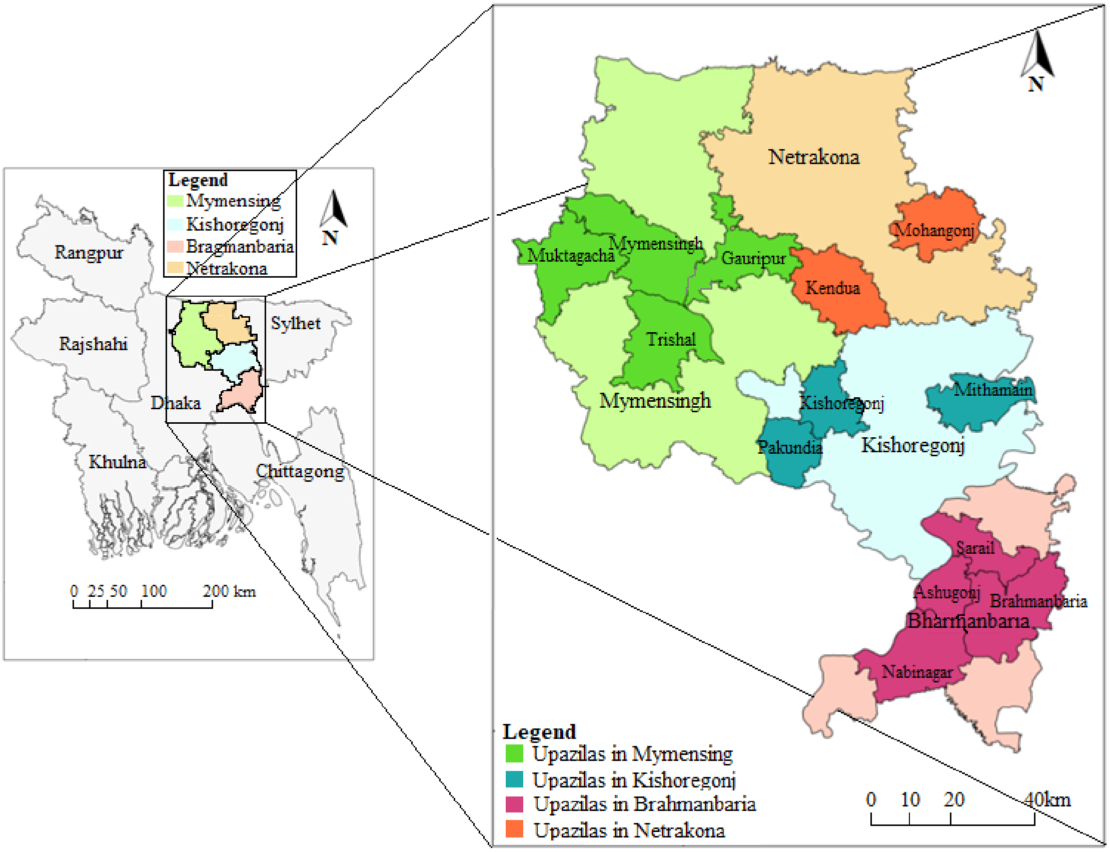

Figure 1. Map of the study area showing studied upazilas under the districts of Brahminbaria, Kishoregonj, Mymensingh, and Netrokona of Bangladesh

Sampling framework and data collection

Of the 452 brick kilns, 142 are in Mymensingh, 123 are in Brahmanbaria, 96 are in Kishoregonj, and 91 are in Netrokona districts. It was planned to select at least 30% of the total brick kilns in the study area for subsequent interviews with the brick kiln owners. Thus, a total of 140 brick kilns (31% of the total) were selected. The distribution of these brick kilns among four districts was done in proportion to the total number of brick kilns available in each of the districts. Thus, 44 brick kilns from Mymensing, 38 from Brahmanbaria, 30 from Kishoregonj, and 28 from Netrokona district were selected (Figure 2). The selection of brick kilns from each district for the final interview was made in such a way that the representation of the maximum number of upazilas under each district could be ensured. That being said, the final field surveys were conducted in the selected brick kilns of Pakundia, Kishoregonj central, and Mithamain upazillas of Kishoregonj district; Ashugonj, Sarail, Brahmanbaria central, and Bijaynagar upazilas of Brahmanbaria district; Trishal, Muktagacha, Mymensingh central, and Gauripurupazilas of Mymensingh district; and Mohongonj and KenduaupazilasofNetrokona district.

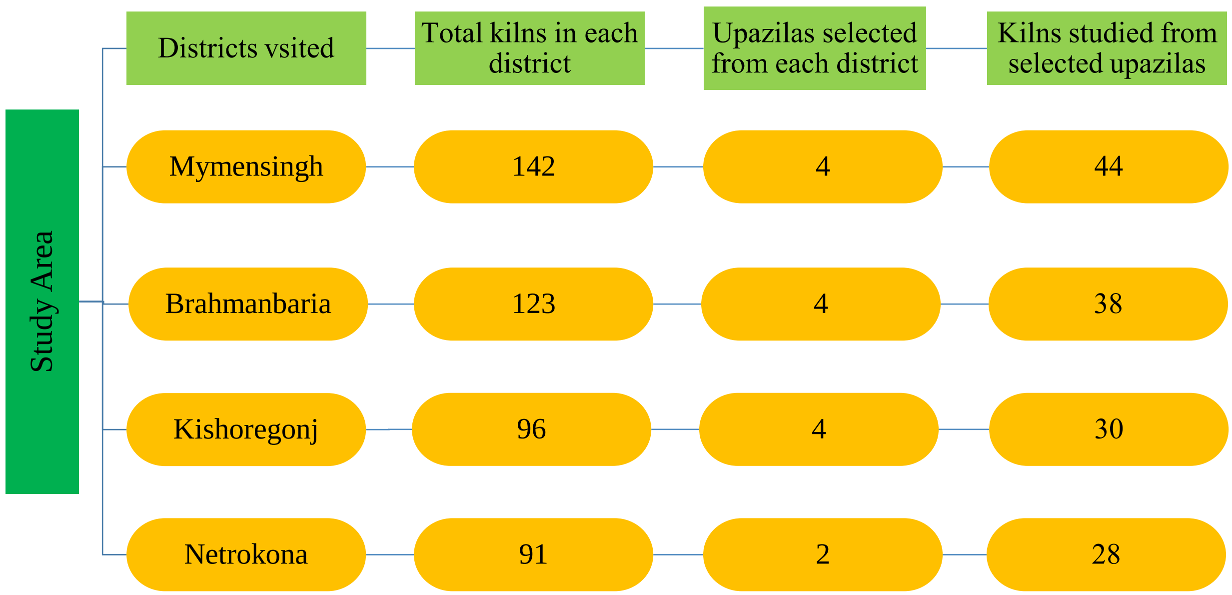

Figure 2. Selection of brick kilns from four districts in the study area

A semi-structured questionnaire was used to collect data from the selected 140 brick kilns. The major variables of interest for the interview have been specified in Table 1. To collect brick kiln-related information, we interviewed either brick kiln owners or the managers of respective brick kilns on the Owners' behalves. In addition to interviewing the brick kiln owners and managers, environment experts, entrepreneurs, secretaries of owners' associations, and brick manufacturing industry-related specialists were consulted to understand their views, opinions, and suggestions to conceptualize their thinking and future strategy toward the development of the brick sector of the country. The fieldwork for this study was conducted over three months, April-June, 2016. Relevant secondary data of the study area were collected from the offices of the Deputy Commissioner Office, the Department of Environment, and brick kiln Owners' Association in each of the districts. Some secondary information was also collected from the World Bank website, government reports, and newspaper articles.

Table 1. Specification and units of measurement of dependent and independent variables

Variable	Definition	Units of measurement
SHIFT_TECH	Brick kiln has shifted to modern technology	Yes=1, Otherwise=0
FUEL_COMP	Brick kilns used only coal and gas	Yes=1, Otherwise=0
ECC	Brick kiln has taken ECC	Yes=1, Otherwise=0
BUSI_LC	Brick kiln has taken a business license	Yes=1, Otherwise=0
AGE	Age of the brick kiln	Years
POL_LEADER	Brick kiln owner is a political leader	Yes=1, Otherwise=0
BRIBE	Bribing the law enforcement authority	Yes=1, Otherwise=0
PENALTY	Penalized ever by the law enforcement authority	Yes=1, Otherwise=0
PROD_COST	The Act-2013 has increased brick production cost	Yes=1, Otherwise=0
RESTRICT_SITE	Brick kiln owner knew legally the restricted locations	Yes=1, Otherwise=0
BRIC_PROD	Quantity of brick production per season	Number
INCOME_KILN	Income from brick kiln per production season	BDT (US$1= BDT80)
DIF_BUSI_LC	Difficulty in getting a business license	Yes=1, Otherwise=0

Analytical framework

Summarizing Acts and Rules enacted in Bangladesh, India, and Nepal

In this study, legal matters related only to brick manufacturing in Bangladesh and a couple of other developing countries have been analyzed. The issues have been discussed in two major segments: (i) Summarizing the chronological development of environmental acts, rules, and ordinances enacted in Bangladesh, and (ii) Comparing the latest regulations governing brick production in Bangladesh, Nepal, and India. In the first segment, how acts and rules were enacted and amended to address the contemporary issues related to the operations of brick kilns and their impacts on forests and the environment have been evaluated. The second segment has been developed to compare the willingness of different developing nations to care for their forest and environment while optimizing the volume and quality of brick production. The latest regulations that govern brick manufacturing in Bangladesh, Nepal, and the states AS, UP, and JK of India have been analyzed and compared. The comparison of the acts and rules in these countries and states was based on the requirement of environmental clearance certificates and business licenses for brick businesses, prohibited and permitted locations, fuel types, and soil sources for brick kilns, raw materials alternative to soil, permitted kiln types and their minimum chimney height, maximum emission level, and provisions for punishment for the law breakers. Through the comparison of all these provisions under the laws of these countries and states, an inference has been drawn on the degree of stringency of brick manufacture-related acts and laws in these countries and states.

Evaluating socioeconomic factors affecting compliance with the Act 2013

We have used a binary logistic regression model to analyze the socioeconomic factors that determine kiln owners' compliance status to the specific technology and fuel, and hurdle to obtain environmental clearance for brick manufacturing. The use of logistic regression is quite common in social science research. Logistic regressions are made up of three components: random, systematic, and link function. The random component identifies the binary dependent variable (*Y=0 or 1*) and its probability distribution, the systematic component identifies the set of explanatory variables (x_i), and the link function identifies a linear relationship between the explanatory variables and their probability function. That is,

$$P_r(Y = 1 \; or \; 0 \mid X = x_i) = \alpha + \beta_i x_i \quad (1)$$

Where X is the vector of socioeconomic attributes of the respondents, $P_i(X \mid X = x_i)$ indicates the probability of respondents' compliance status (compliant = 1, otherwise =0) to regulatory tools for a given socioeconomic characteristic, $X = x_i$, and β_i is the vector of parameters to be estimated.

In the logistic regression model, a *logit-link* function is defined as follows:

$$P_r(Y = 1 \; or \; 0 \mid X = x_i) = log\left(\frac{P_i(x_i)}{1-P_i(x_i)}\right) \quad (2)$$

A combination of equations (1) and (2) gives equation (3).

$$\alpha + \beta_i x_i = log\left(\frac{P_i(x_i)}{1-P_i(x_i)}\right) \quad (3)$$

Equation (3) reduces to (4)

$$p(x_i) = \frac{e^{\alpha+\beta_i x_i}}{1+e^{\alpha+\beta_i x_i}} \quad (4)$$

Now, if$X$ is binary ($x_i = 1 \; or \; 0$), equation (1) yields the following outcomes:

If $x_i = 1, P_r(Y = 1\ or\ 0\ |X = 1) = \alpha + \beta_i$ and if $x_i = 0$, $P_r(Y = 1\ or\ 0\ |X = 0) = \alpha$. Thus, we can estimate the model beta using equation (5):

$$\beta_i = \log\left(\frac{P_i(1)}{1-P_i(1)}\right) - \log\left(\frac{P_i(0)}{1-P_i(0)}\right) \quad (5)$$

Thus, $\beta_i$can be interpreted as the change in the$log\ (odds)$ when x_i changes from 0 to 1. The same also applies when x_i is continuous and changes in an additive fashion. The specifications of all variables evaluated in this study have been described in Table 1.

Testing the significance of compliance cost

One of the major tasks of this study was to validate the claims of the brick kiln owners that the regulation significantly increased their brick production cost. Thus, we compared the mean production costs per brick in two states (with and without environmental regulation) using a t-test. To decide the type of t-test needed for such comparison, we compared the variances of mean production cost per brick to examine whether the variances of the per unit brick production costs in the two states differed significantly. Failure to reject the null hypothesis, that H_0 = the true ratio of the variance of the two groups was equal to one, will lead to conducting a paired t-test to evaluate if the Act 2013 has significantly raised the per unit brick production cost.

Results and discussion

Incremental development of brick manufacturing regulations in Bangladesh

Bangladesh's government has been committed to regulating the ominous side effects of the brick industry, which has led to the promulgation of a series of measures at different times related to the brick sector in Bangladesh. The incremental development of brick production-related legislation has been presented in Figure 3. The very first legislative action taken by the government on brick making back in 1989 was the Burning of Bricks (Control) Act 1989, which focused on the banning firewood, license for brick burning, an inspection of brick fields by the authorities, and the punishment for the violation of the act. Further clarifications were provided through the Brick Burning (Control) Amendment Act, 1992, which prohibited burning ‘dead roots of bamboo’ as firewood, transferred the inspection power to a deputy commissioner, extended a monetary penalty up to fifty thousand takas, and delegated the ‘power of confiscating the fuel wood’ to the court. ‘The Environmental Conservation Act 1995’ also known as the ‘mother law of environmental conservation’ of the country, which emphasized conserving the environment by controlling and mitigating pollution, made an environmental clearance certificate(ECC) mandatory for kiln operation. Later on, the Environmental Conservation Rule 1997 along with fixing the emission standard (1000mg/Nm^3) for stalk emission of Brickfields, categorized brick field as Orange-B and described the procedure of obtaining ECC. In 2001, the Burning of Bricks (Control) Act 1989) was amended which brought some specific changes like committee formation to verify the application for a license, replacing the firewood with fuel, and including imprisonment as a penalty for violating the law. This also prohibited the setting up of brick kilns within three km of the upazila or district center, municipal areas, residential areas (where at least fifty families live), gardens, and the government’s reserve forests. In 2004, Brick burning rules were provoked to reduce aerial pollution, replacing the Bull chimney kiln with a fixed chimney kiln where the use of 120-ft chimneys for brick kilns was set mandatory.

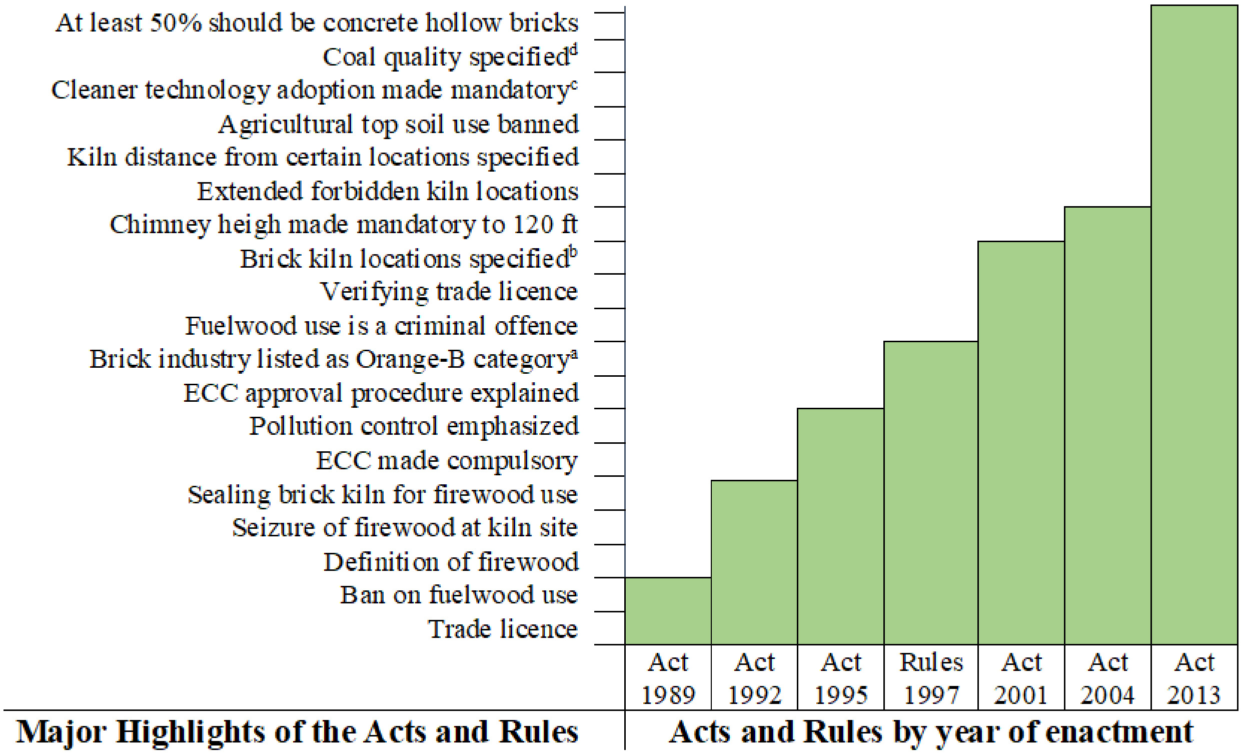

Figure 3. Incremental development of Acts and Rules related to brick kiln operations in Bangladesh

(Notes: Act 1989 =>Burning of Bricks (Control) Act; Act1992=>Burning of Bricks (Control) (Amendment) 1992; Act 1995=>Bangladesh Environment Conservation Act 1995; Rules1997=> Environmental Conservation Rules 1997; Act2001=>Burning of Bricks (Control) (Amendment) Act, 2001; Act2004=>Brick Burning (Control) Rules, 2004; Act2013=>Brick Making and Brick Kiln Establishment (control) Act, 2013; a = In Environmental Conservation Rules, 1997*;* b = Prohibits the establishment of brickfields in residential, protected, commercial and agricultural areas, and also in forests, sanctuaries, wetlands, and Ecologically Critical Areas; c = Cleaner technologies includes Zigzag, Hybrid Hoffman Kiln (HHK) and Vertical Shaft (VSBK) kilns; d=No person shall use coal as fuel, containing sulfur ash, mercury or similar material beyond the prescribed standard, in the brick kilns for burning bricks).

Afterward, in 2013, the Act, 2013 was passed to establish control over brick manufacturing and brick kiln establishment, which came into force from 1st July 2014 (Table 2). The main objective of this law is to protect biodiversity from brickfield-related pollution, which has prescribed different prohibitions and directions regarding the establishment and operation of brick kilns. According to section 4 of this Act, the construction of brick kilns is prohibited without business lice from the Deputy Commissioner's Office. Soil collection from agricultural land, hills, and hillocks has been prohibited in section 5(1) whereas section 5(2) allows soil collection from canals, marshlands, ponds, and rivers after getting permission from the authority.

It is addressed in section 5(4) that, at least 50% of the total bricks should be hollow bricks made of sand and cement along with a restriction on using heavy vehicles for the transportation of bricks and raw materials for bricks. Section 6 prohibits using fuel wood for burning brick whereas section 7 specifies that coal containing sulfur, mercury, or ash beyond permissible limits is not allowed to be burnt in brick kilns. Brick kilns are not allowed within the boundary of residential, protected, and commercial areas, at the headquarters of the City

Corporation, municipality, and upazila, in forests, wildlife sanctuaries, gardens, water bodies, agricultural land, ecologically critical areas, and degraded air-shed, which has been addressed in section 8(1). Per section 8(2), no authority can issue any license or environmental clearance certificate (ECC) in prohibited areas.

Table 2. Summary of environmentally important sections of the Brick Making and Brick Kiln Establishment (Control) Act 2013

Section	Focal Areas	Section-specific statements
4	Business License	Construction of brick kilns is prohibited without business lice from the Deputy Commissioner's Office.
5(1)	Prohibited soil sources	Soil collection from agricultural land, hills, and hillocks is prohibited
5(2)	Permitted soil sources	Soil collection from canals, marshlands, ponds, and rivers is not allowed unless permitted by the authority.
5(3)	Non-soil bricks	At least 50% of the total bricks should be hollow bricks made of sand and cement.
5(4)	Hauling roads	Any road constructed by the local government and engineering department (LGED) should not be used by heavy vehicles meant for the transportation of brick or its raw materials.
6	Fuelwood	Using fuel wood for burning brick is completely prohibited.
7	Coal specifications	Coal containing sulfur, mercury, or ash beyond permissible limits is not allowed to be burnt in brick kilns.
8(1)	Kiln location	Brick kilns are not allowed within the boundary of residential, protected, and commercial areas, at the headquarters of city corporations, municipality, and upazila, in forests, wildlife sanctuaries, gardens, water bodies, agricultural land, ecologically critical areas, and degraded air-shed.
8(2)	ECC control	No authority can issue any license or environmental clearance certificate (ECC) whatsoever for constructing brick kilns in the prohibited locations.
8(3)	Safe distance	Brick kiln construction is not allowed within one km of the prohibited areas, two km of any public forests, half a km of any hill, one km of any educational and research organization, hospital, and railway line, and half a km of any LGED road.
8(4)	Kiln relocation	Any kiln already constructed within the prohibited locations should be relocated to a permitted area within two years of this law being enforced.
9(1)	ECC for License	A business license cannot be issued without an environmental clearance certificate (ECC)
9(5)	Length of license	The license is valid for three years from the date of its issuance.
11(1)	License suspension	The license should be suspended if a criminal offense is committed by the kiln.
11(2)	Voiding license	The license can be voided by the deputy commissioner if the kiln is convicted by any relevant court.

Source: Ministry of Forest and Environment (2016)

Section 8(3) allowed brick kiln construction only beyond one km of the prohibited areas, two km of any public forests, half a km of any hill, one km of any educational and research organization, hospital, and railway line, and half a km of any LGED road. Again, according to section 8(4), any kiln already constructed within the prohibited locations should be relocated to a permitted area within two years of this law being enforced. Sections 9(1), 9(5), 11(1), and 11(2) of the Act 2013assert license related provisions such as environmental clearance certificate (ECC) are mandated for obtaining business licenses, validation, and suspension or voiding of the license are also mentioned in those sections. However, the Act 2013 has highlighted most of the factors that are related to brick kiln-related pollution and its control. But the question remains whether the law is practicable given the socioeconomic conditions that the nation lives with.

Comparison of the brick kiln related Acts and Rules in Bangladesh, India, and Nepal

South Asian countries have more or less similar regulatory tools for the environmental management of brick manufacturing kilns. However, each country or state has also some uniqueness in its regulations. While Bangladesh and Nepal have their central regulatory controls on brick kilns, each of the states of India has its own rules and regulations for brick kiln administration. In all of the five countries and states (Bangladesh, Nepal, and UP, JK, AS of India), it is mandatory to secure an environmental clearance certificate (ECC) and business approval from the appropriate authority for manufacturing bricks (Table 3). As Bangladesh is one of the most densely populated countries in the world with severe limitations on land for agriculture and other purposes, the government has imposed extreme restrictions on shifting agricultural land to any other non-agricultural uses to ensure food security for the nation. This has been reflected in the land's laws too. Unlike Nepal and India, Bangladesh has no provision in its latest brick kiln regulation (Act 2013) to allow the kilns to be used in agricultural and hill soil. While Bangladesh, UP, and AS laws have specific recommendations on using brick raw materials alternative to soil, JK and Nepal have no such recommendations in their legislation. Manufacturing hollow bricks using cement and sand is found as a compliance factor in the Bangladesh regulations only; Nepal and Indian states have no regulatory bindings such as this. Another stringent factor that the kilns are forced and strongly monitored to abide by is not to use vegetative fuel of any sort in the brick kilns in Bangladesh (Table 3). In contrast, UP and Nepal have prohibitions in burning non-vegetative fuel including organic solvent, oily residue, pet coke, plastic, rubber, and leather but JK and AS have no such provision in their laws.

In regards to choosing a kiln type or the preference for the type of kilns JK and AS have no specification, while Bangladesh has made it mandatory to choose among Zigzag, HHK, and VSBK technologies, UP among BTK, DDK, and VSK technologies, and Nepal among BTK, VSBK, and tunnel technologies(Table 3). However, chimney height has been made quite specific in all these countries and states except in JK. Chimney height is at least 36.58m in Bangladesh, 22.30m in UP, at least 30m in AS, and 15-30m in Nepal. In addition, in the case of choosing the kiln locations, the latest regulations have been very specific in Bangladesh and beyond. The prohibited locations for brick kilns in Bangladesh are residential areas, forest and protected areas, commercial areas, agricultural land, and wetlands, in UP are fruit belt areas, in JK are agricultural land, and forest land, in AS are development zones, agricultural land, and in Nepal are forest area and highly populated areas. Again, maximum emission levels have also been specified in all the countries and states except JK. The maximum limits of emission allowed in the laws were 1000mg/Nm^3 in Bangladesh, 750-1000 mg/Nm^3 in UP and AS, and 400-700mg/Nm^3 in Nepal (Table 3). The penalty structures for violating laws also have some variations among the countries according to their dimensions of violations. The lawbreakers are liable to jail time or financial punishment everywhere except in UP. In Bangladesh, the punishment for the law breakers is two to five years of imprisonment or a financial penalty of BDT50,000 – BDT500,000 (US$1 = BDT82). This punishment in JK is two to five years of jail time or a financial penalty of INR50,000 (US$1 = INR64) and in AS is five to seven years of jail time or a financial penalty of INR100,000(Table 3). In Nepal, neither the jail term nor the financial amount of the penalty is explicitly stated. However, production might be halted if the brick kiln owner is convicted. From the comparison of the legal tools in all these countries and states, it is clear that the brick regulation in Bangladesh is excessively tougher than that in other countries and states under study. UP and JK look to have lax regulations than those in other Indian states under study. Nepal's regulation of the brick industry is relatively moderate. It has areas of complaint almost similar to that of Bangladesh. However, the stringency of brick regulation in Nepal is not as high as that in Bangladesh. The degree of stringency might be a major reason for Bangladeshi brick kilns to be non-compliant with brick regulations at a very high percentage.

Table 3. Comparison of brick kiln-related latest legislations in Bangladesh, India, and Nepal

Compliance areas	Act in Bangladesh[a]	Act in UP, India[b]	Act in JK, India[c]	Act in AS, India[d]	Act in Nepal[e]
Environmental clearance	From DoE	From SPCB	From DEIAA*	From SPCB	From SPCB
Business approval	From DC*	From DA* From Panchayet	From PCB	From Panchayet	From PCB*
Prohibited soil sources	Agriculture soil hill soil	NSS	NSS	NSS	NSS
Alternatives to soil	Cement Sand to produce hollow bricks	Stone dust Rice husk ash Mud	NSS	Stone dust Rice husk Ash Red mud	NSS
Prohibited fuel	Firewood	Organic solvent Oily residue Pet coke Plastic & Rubber Leather	NSS	NSS	Wood Rubber Plastic
Permitted kiln type	Zigzag HHK VSBK**	BTK DDK VSK**	NSS	NSS	BTK VSBK** Tunnel kiln
Minimum chimney height	≥ 36.58m	22-30m	NSS	≥ 30m	15-30m
Prohibited kiln locations	Residential area Forest & PAs Commercial area, Agricultural land Wetland ECAs***	Fruit belt area	Agricultural land Forest land	Development zone Agricultural land	Forest Populated areas
Minimum Kiln distance	0.5-1km from: Hill bottom Rail tracks Schools Hospitals	1km from: Residential area School Hospital	NSS	300m-1km from: Residential area Hospital Public building Zoo & Sanctuary	500m-1km from: Populated areas 5 km from Forest
Maximum Emission	1000 mg/Nm^3	750-1000 mg/Nm^3	NSS	750-1000 mg/Nm^3	400-700mg/Nm^3

(PM/SPM)					
Plantation around kiln	NSS	10m wide	NSS	10m wide	Plantation
Punishment (Imprisonment or monetary fine)	2-5years Or BDT 50,000-500,000	NSS	2-5 years Or INR50,000	5-7 years Or INR100,000	Monetary fine Or Halt of production

[a]Brick Making and Brickfield Establishment (control) Act, 2013; [b]Uttar Pradesh Brick Kiln(Sitting Criteria for Establishment) Rules, 2012; [c]Jammu and Kashmir Brick Kiln (Regulation) (Amendment) Act 2016; [d]Assam Brick Kilns Establishment and Regulation Rules, 2013; [e]Protection Act, 2053, the Environment Protection Regulation, 2054 and Industrial Enterprise Act, 2049, *District Administration= DA, District commissioner =DC, SPCB= State Pollution Control Board, Divisional, Pollution Control Board=PCB**Hybrid Hoffman Kiln=HHK, Vertical Shaft Brick Kiln =VSBK, Bulls Trench Kilns=BTK, Down-draft Kiln=DDK, Vertical Shaft Kiln=VSK,***Ecologically Critical Areas=ECAs, NSS=No specific statement, *District Environment Impact Assessment Authority =DEIAA

State of brick kiln owners' compliance to the Act 2013 by sections

Figure 4 represents the summary findings on how the brick manufacturers were responding to the requirements imposed by the Act 2013 as well as their opinions on the applicability of the law in the current socioeconomic setup of the country. While only 52% of the respondents said they had a comprehensive idea about the new law, 10% of respondents had no idea about the law, even after three years of the law in action.

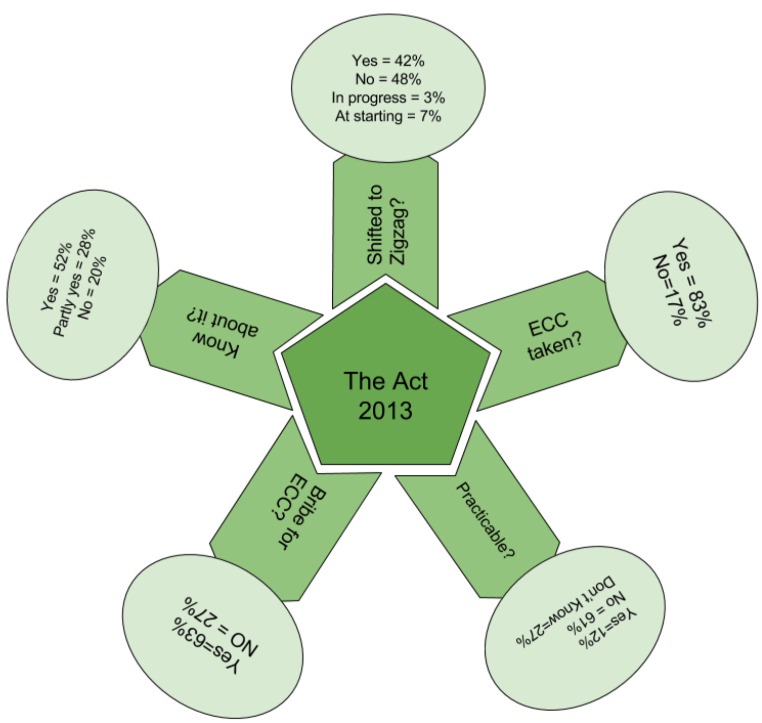

Figure 4. Summary of the state of brick kiln owners' compliance with the Act 2013 in Bangladesh

In addition, another 28% said they had just a bird's eye view of the law. Again, even though obtaining an environmental clearance certificate (ECC) for brick manufacturing is a basic environmental requirement for all industries including the brick manufacturing industry since 1995, 83% of the brick kiln owners said they had it. After more than two decades of such requirements being public, 17% of the studied brick kilns were operating without ECC. This non-compliance might be attributed not only to the purposive inaction of the owners, they might have also found it too costly for the business.
This can be supplemented by the fact that 63% of the owners claimed that they were to offer bribes to get ECC. However, the remaining 37% reported that they obtained ECC without any bribe. The Act 2013 also requires the brick kiln owners to convert their fixed chimney kilns to zigzag kilns. Of all the kilns, 7% were born zigzag, 42% switched to zigzag, and 2% were in the process of adopting the technology. That means, 48% of the surveyed brick kilns were still operating with a production technology that was not legal. Given the existing constraints and opportunities for the brick manufacturing industry in Bangladesh, only 12% of the kiln owners perceived that the Act 2013 is practicable and the vast majority of the owners, 61%, said the law is impracticable and needs immediate amendment. However, 27% had no idea about the applicability of the law. Overall, as evident from the voice of the kiln owners, the compliance status of the brick manufacturing industry does not look so pleasing.

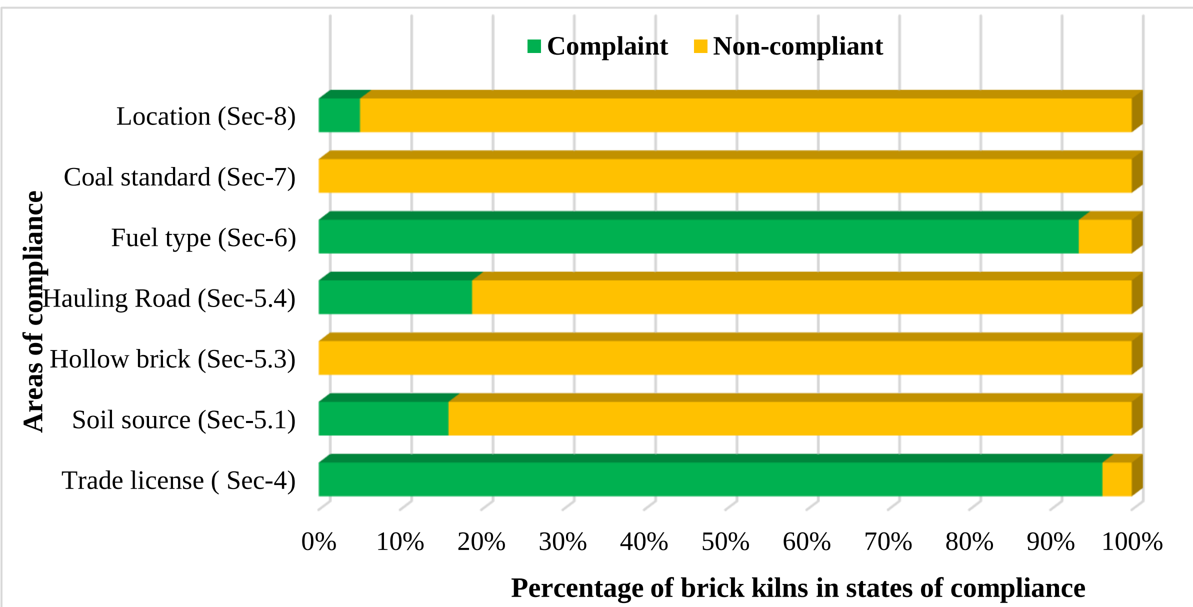

Figure 5. Compliance status of the brick kilns by sections of the Brick Making and Brick Kiln Establishment (Control) Act, 2013

Figure 5 portrays how the Act 2013 could be impracticable in its present form if brick kilns are allowed to continue the business with their present setup. In one way or another, every section of the Act is being violated by most of the brick kilns. The result shows that both Section 5(3) and Section 7 (See Table 2 for Section statement) were being violated by 100% of all the 140 brick kilns studied. While 93.48% of brick kilns were using coal instead of fuel wood just to minimize cost, none of them were using coals with environmental standards as specified in the Act 2013. The responsibility for this noncompliance is equally shared by the Government of Bangladesh since the publicly imported coal was not meeting the legal requirements. Our field data also exhibits that the idea of hollow brick is something that has never been heard of by any of the surveyed brick kilns. The Act 2013 has vehemently emphasized the permitted and prohibited locations for the brick kilns, which has been specified in Section 8. Alarmingly, 94.3% of the kilns were not complying with this Section (Figure 5). Our primary data shows that 88.41% of the brick kilns were located within one km of agricultural land, 61.59% were located within half a km of the LGED roads, and 5.94%, 4.35%, and 3.62% of the brick kilns were within the prohibited boundaries of union or village road, residential area, and educational institute, respectively (Figure 5).

Although the Government's high priority is food security and agricultural land can no way be taken under brick manufacturing activities (Section 5.1), the reality is extremely different: 84.06% of the selected brick kilns were collecting soils from agricultural and other prohibited lands. The brick manufacturing industry consumes around 45 million tonnes of fertile soil – equivalent to around 2,600 hectares of agricultural land- each year (Hossain et al., 2019). An almost similar rate, 81.16%, of non-compliance with Section 5.4 was observed in selecting roads for hauling bricks. The heady trucks loaded with tons of bricks were using the local government-maintained narrow and unpaved roads and creating severe damage to the rural communication networks. However, a satisfactory level of compliance was found with Section 4 (on obtaining a trade license) and Section 6 (on using coal and gas instead of fuel wood). About 96.38% and 93.48% of the brick kilns were found complying with Section 4 and Section 6 of the Act 2013, respectively.

The state of compliance or non-compliance is attributed to many factors. Some of the factors are the size of the Department of Environment, the political power of the kiln owners and corruption, the high fixed cost of switching to the required technology, and the remoteness of the brick kilns. Above all of these, the Act 2013 itself is so tough on the provisions of kiln operations that the kilns could hardly comply with the regulations. The emergence of DoE in Bangladesh is very recent and the total manpower of the Department is less than 500 across the country. They could not have an office in each of the 64 districts in the country. Given this reality, it is not possible to monitor more than 6,000 brick kilns, most of which are located in rural areas, with the human resources they have. Again most of the brick kiln owners are politically strong and they have hardly any incentive to look into the details of the Act 2013 let alone complying with its stringent provisions. Finally, the kiln owners have gone through a series of shifts in kiln types and chimney types in recent years. Switching to expensive kiln types is not possible within the time (two years, which has already expired) they have been given. Thus, most of them were found non-compliant with most of the Sections of the Act 2013.

Factors affecting the brick kiln owners' compliance with the Act 2013

Factors affecting technology adoption

We have found four variables (ECC, BRIBE, PENALTY, and PROD_COST) that significantly affect brick kiln owners' preference for switching to brick manufacturing technologies as specified in the Act 2013 (Table 4). If the brick kiln had ECC, the corresponding *log(odds)* of choosing zigzag technology against fixed technology increased by 0.324. That means brick kilns having ECC were more likely to switch to adopt technology as prescribed in the law. The parameter estimate of BRIBE was -0.247, which was significant at a 1% level. That means hidden cost (need to bribe) was negatively linked to the choice of technology. If the brick kilns needed to offer bribes they were significantly reluctant to adopt better technology as directed in the law. PENALTY was found negatively linked (β = -0.3580) to the choice of a better technology. It turns out that, it was less likely that a penalized brick kiln owner would be willing to adopt modern technology. This finding implies that – the penalty was hardly changing kiln owners' behavior to opt for environment-friendly technology. There might be several explanations behind this: (i) the profit coming through the practice of existing technology was easily offsetting the penalty size and (ii) the fixed cost of shifting to the modern technology was too high for the owners to bear. However, the parameter estimate of PROD_COST was -0.242, which was significant at a 5% level (Table 4). That means the brick kiln owners who opined that the Act 2013 had significantly increased their production cost were less likely to switch to one of the environment-friendly technologies the law advised.

Table 4. Factors affecting brick kiln owner's attitude toward technology compliance

Variables	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	0.564	0.170	3.321***	0.001
ECC	0.324	0.082	3.956***	0.000
BUSI_LC	0.209	0.162	1.294	0.198
AGE	-0.005	0.003	-1.788*	0.076
POL_LEADER	0.051	0.085	0.603	0.547
BRIBE	-0.247	0.073	-3.381***	0.000
PENALTY	-0.358	0.064	-5.606***	0.000
PROD_COST	-0.242	0.077	-3.150***	0.002
RESTRICT_SITE	0.021	0.057	0.366	0.715

Notes: ***, **, *Significant at 1% level, 5% level, and 1% level, respectively; Dependent variable = SHIFT_TECH (1 if shifted to technology specified in the Act 2013 and 0 otherwise)

Factors affecting fuel compliance

Table 5 explains the factors that identify the likelihood of a brick kiln using the fuels (gas and coal, and not fuel wood at all) as specified in the Act 2013. Of the seven variables tested, four were found to significantly affect the kiln owners' willingness to use recommended fuels.

Table 5. Factors affecting owner's attitude towards fuel compliance of brick kiln

Variables	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	0.972	0.136	7.127***	0.000
ECC	0.157	0.058	2.709***	0.008
BUSI_LC	0.020	0.115	0.173	0.863
BRIC_PROD	-0.007	0.002	-2.690***	0.008
AGE	-0.001	0.002	-0.568	0.571
INCOME_KILN	0.001	0.000	2.009**	0.046
BRIBE	-0.050	0.004	-2.135**	0.025
POL_LEADER	0.007	0.065	0.115	0.908

Notes: ***, **, *Significant at 1% level, 5% level, and 1% level, respectively; Dependent variable = FUEL_COMP (1 if using coal or gas and 0 otherwise)

The parameter estimate of the variable ECC was 0.157, which was significant at a 1% level. Since ECC approval requires a kiln owner to complete a large environmental checklist, it was expected that kilns with ECC were more likely to comply with the fuel requirement of the Act 2013. The parameter estimate of the variable BRIC_PROD was -2.690, which was significant at a 1% level. That means brick kilns with a higher number of brick production per production season were less likely to comply with the Act 2013 as far as fuel use was concerned. Similarly, as expected, the beta estimate of the variable BRIBE was negative (-0.05) at significance at a 5% level. The brick kilns that bribed the monitoring authority were more likely to survive in the market yet after using illegal fuels (fuel wood and low-standard coal). The parameter estimate of INCOME_KILN was 0.001, which was significant at a 5% level. That means large brick kilns with larger income per production season were more likely to comply with the provision of gas and coal uses of the Act 2013.

Cost of compliance with the Act 2013

Since the F-statistic is not significant, we failed to reject the null hypothesis (Table 6). This means that the variances of the mean production costs per brick in the two states (with and without environmental regulation) didn't differ significantly.

Table 6. Comparison of the variances of cost per brick with and without regulation and the mean costs per brick with and without regulation

	With Regulation	Without Regulation	df	Statistics	p-value
Variance*	0.6297	0.5782	139, 139	F = 1.0891	0.6181
Mean**	5.8928	5.4040	139	t = 6.0805	0.0000

* H_0: True ratio of variances of cost per brick with and without regulation is equal to 1; ** H_0: True difference of mean cost per brick with and without regulation is equal to 0.

Again, the t-statistics of the mean of the differences were significant at a 1% level. That is, the mean cost per brick with regulation differed significantly from the mean cost per brick without regulation. Since the mean cost per brick with regulation (BDT5.8928, where BDT80=SU$1) was greater than that without compliance (BDT5.4040), it can be concluded that the Brick Burning Control Act 2013 has significantly increased the per unit production cost of bricks. Thus, the increase in cost per brick was BDT0.4888, which might be attributed to environmental compliance.

Recommended policy interventions for development prospects and probabilistic

The DoE proposed policy interventions aim to transition the brick sector in Bangladesh towards a sustainable enterprise, including social, environmental, and economic dimensions.

Revamp the policy on bricks

The Brick Kiln Policy 2008 sought to regulate the unrestrained building of brick kilns by the issuance of environmental clearance certificates by the DoE, in accordance with the Bangladesh Environment Conservation Act, 1995. This strategy was implemented to direct the environmental clearance process for the brick kiln project. This policy guideline outlines the overall procedure for environmental clearance and monitoring, while also addressing pertinent concerns related to brick-making, including locational considerations, environmental pollution management, and research and development components. Over 11 years have elapsed since the adoption of this policy. The government has adopted the Brick Manufacturing and Brick Kiln Establishment (Control) Act, 2013, without revising the Brick Policy. The administration has initiated amendments to the Act. Before amending the statute, a Brick Policy for the next decade should be developed, taking into account the social, environmental, and economic concerns of the brick industry.

Amendment of the Brick Kiln Establishment (Control) Act, 2013

The Brick Manufacturing and Brick Kiln Establishment (Control) Act, 2013 was enacted in 2013 and came into force in July 2014. The primary objective of this act is to regulate pollutants emanating from brick kilns during the production process in technologically advanced facilities. Nonetheless, the regulatory authorities have numerous challenges in implementing this statute. The Act has significantly impeded the development of efficient brick-making technologies in Bangladesh due to restrictions on establishing brick kilns in certain regions and designated buffer zones. This Act should be changed to facilitate initiatives for sustainable brick manufacture.

Develop ancillary regulations in accordance with the 2013 Act

To enable the implementation and enforcement of the Act, a subordinate regulation under the Brick Manufacturing and Brick Kiln Establishment (Control) Act, 2013 should be established.

Draft comprehensive technical specifications for the brick manufacturing process

Technical guidelines must be developed for the approved brick-making technologies, covering the complete cycle of brick production, which includes clay extraction, green brick manufacturing, firing procedures, production organization, and business administration.

Enhancing capabilities

The shift to sustainable brick production necessitates substantial alterations in the regulatory agency's management of the brick-making sector. Regulatory authorities require enhanced methods, equipment, and capabilities for "state management" functions, including emissions measurement, environmental monitoring, clay resource management, planning, and the advancement of the brick-making business.

Launch a brick-based data service

The transition to a sustainable brick sector necessitates that policymakers establish a "foundation for decision-making," which can be accomplished by facilitating the conversion of accessible information and solutions into actionable measures. To ensure effective policy implementation, a brick information service must be built, providing trustworthy data on current circumstances and processes related to brickmaking, clay resources, energy efficiency, emissions, environmental impact, and enterprise economics.

Training and education

To ensure the sustainable development of the brick sector, the promotion of converting available knowledge and solutions into actionable measures is essential. Contributions in this context encompass: training programs; dissemination of plans, guidelines, and tools; technical support and field services for brick manufacturers; in addition to policy instruments and capacity enhancement for regulatory bodies.

Experimental and scalable methodology for environmentally friendly brick manufacturing

The development of model brick production small-scale enterprises (SMEs) utilizing various efficient technologies should be supported by the government. The models' information must be recorded and differentiated.

Research and development

Research and development facilities ought to be established inside pertinent research institutions, such as Housing and Building Research institutions. Emphasis should be placed on green brick manufacturing technology, including efficient firing methods and renewable materials for brick production.

Modernization of the brick industry

Profitability differentials exist among brick-making technologies, with less efficient technology outperforming more efficient alternatives. In this context, converting the brick industry from seasonal and sporadic production to industrial brick manufacturing utilizing continuous brick-firing kilns and year-round production will facilitate a more environmentally sustainable brick industry in Bangladesh.

Technological uniformity in kilns

The relevant authorities should standardize brick kiln technologies.

Advance the resource-efficient brick (REB) market

The utilization of resource-efficient bricks (REBs) can lead to a decrease in the resources consumed during brick production and firing. The advancement of REBs, including hollow and perforated bricks, necessitates the management of both supply and demand, the formulation and implementation of supportive policies, and the establishment of financially viable brick production units.

Mechanizing the brick industry selectively

Bangladesh has a longstanding history in brick manufacture; however, this experience has been confined to antiquated techniques for kiln design and construction, as well as traditional molding and fire processes. There is a contemporary demand for an alternative method of brick production that accommodates diverse designs, dimensions, and hues. This can solely be accomplished by mechanization in brick production.

Build a setting that supports eco-friendly brick production

A conducive climate for sustainable brick production is essential. It entails the institutional establishment, expansion, and distribution of solutions, methodologies, and programs that must be formulated and tested through a collaborative manner. The cooperative strategy involves enhancing the policy framework, specifically by establishing a platform for public-private collaboration, creating a "sustainable brick-making support unit," promoting the formation of a brick-makers association, aiding the formalization of SMEs, and propagating the sustainable brick-making methodology.

Facilitate the acquisition of business funding

The strategy to enhance access to finance entails establishing connections between brick SMEs and lending institutions; alleviating lending risks associated with brick SMEs through the implementation of a risk-sharing mechanism in the form of partial guarantees; providing banks with technical assistance to assess new technology brick projects and to subsequently oversee and monitor the loans issued; and creating a low-interest, long-term revolving fund utilizing government or international donor resources.

Keep employees safe and healthy

The brick business in Bangladesh has historically been a polluted sector, operating under challenging labor circumstances. It is the legal obligation of the owner or employer to guarantee the health and safety of employees in the workplace. A secure and healthy work environment minimizes the risks of accidents, injuries, or harm to lives and property, as well as reduces occurrences of workforce impairment.
To safeguard the workers from accident risks and guarantee a hazard-free workplace in the brick sector, the following guidelines are proposed for implementation at the plant level:

- A first aid kit must be accessible on-site. Personal Protective Equipment (PPE) such as gloves, footwear, helmets, masks, and protective clothes must be provided for workers.
- Offer Health and Accident Insurance protection for brick kiln laborers. Measures should be implemented to observe the combustion process within the kiln from a secure distance to prevent fire-related incidents.
- Arrangements for a restroom on-site and drinking water at the kiln have to be made.
- An essential occupational training program must be implemented to familiarize personnel with the specific hazards associated with their respective job assignments.
- Measures must be implemented to ensure that no employee is subjected to noise levels exceeding 85 dB(A) for more than 8 hours per day without appropriate hearing protection.
- Implement preventive and control strategies for fire and explosion risks.
- Employers must use suitable measures to preserve air quality in the workplace.
- The employer must implement protocols and mechanisms for documenting and reporting workplace accidents, diseases, and hazardous events.

Conclusions

The Brick Making and Brick kiln Establishment (Control) Act, 2013 is in place that has banned the use of fuel wood and fixed chimney kilns and has reconsidered the location and height of brick kiln chimneys. However, the study represents a scenario that hardly matches the requirements of the act. While the law has been an on-paper tiger, its application has been facing multi-faceted challenges at the field level. The situation has been worsened due to the bureaucratic complexity, political influence, and administrative weaknesses of the allied departments. While the country has thousands of brick kilns –large and small- legal and illegal – clustered and sporadic, brick kilns with large production sizes might be approved in specific brick production zones. The government should adopt a mechanism for the phase-wise reduction in the total number of brick kilns by replacing small-scale brick kilns with large brick kilns with modern technology to produce a sufficient amount of quality bricks. High production capability and low energy consumption features of green brick technology should be utilized to attract the owner of the kilns. This would expectedly save agricultural land and soil as specified in the Act 2013. As a number of studies have already suggested, the Act 2013 is impracticable in its present form by many of its Sections. Comparing the Act with those of the neighboring countries portrays that the law has been relatively too tough for the kiln owners to be fully compliant with its sections. While forcing the kilns to use gas and coal only, the Bangladesh Government should ensure an adequate supply of quality coal and natural gas to stop fuel wood usage. At present situation, the publicly imported coal cannot meet the quality requirement as specified in the Act 2013. The recurrent shift in chimney types within short intervals discourages brick kiln owners from shifting chimneys into cleaner ones. During the fieldwork, the kiln owners explicitly expressed their concern and dissatisfaction over the recurrent shift of chimney types and chimney heights. Financial support through long-term loans might help smoothen the shift of legally required kilns and chimneys. All the studied brick kilns were producing traditional bricks with soil. They have no idea about hollow bricks, which the law requires to be produced at least by 50% of the total. After more than three years in application, the law enforcing authority was not aware of the kiln owners what and why hollow bricks are for. Albeit, the use of hollow bricks is important for saving agricultural topsoil from being used as brick raw materials. So, extensive awareness programs are needed to motivate kiln owners to produce hollow bricks. Another issue with hollow bricks is their market demand. Since the concept of producing hollow brick is relatively new in the country, brick users also need motivation on why and how to use it. Unless market demand is created, the kiln owners would hardly show any interest in producing hollow brick. Thus creating markets for hollow bricks is of prime importance. While it is praiseworthy that Act 2013 has put excessive importance on saving rural roads from heavily loaded brick-transporting vehicles, it is also the government’s responsibility to arrange for alternative transportation tracks for the brick industry to haul the bricks. Rather than building new roads, the existing rural roads can be upgraded to withstand heavy loads. It would benefit both the rural folks and the kilns with a better rural lifestyle good communication and cost-effective brick transportation.

An overly rigid nature of the Act 2013 reduces its compatibility with society. Transformative development at the policy level through recurrent surveys and thus modification of the law into a more practicable one is necessary. During our present consultation with the DoE officials, the law is probably going to need an amendment. Responsible law-making authority should have deep insight into the problem to reform the law according to the current socioeconomic conditions of the country. Again, only an amendment might not work if the appropriate implementation agencies lack sufficient resources, especially human power, to implement the provisions of the law. The DoE needs to be strengthened with skilled manpower and efficient technology to do so. In the end, there should be strong administrative support and dedication from law enforcement agencies and the willingness of the brick kiln owners to comply with the law for the proper implementation of the legal tools.

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RESEARCH ARTICLE

Towards Carbon Neutrality: The Impact of Private AI Investment and Financial Development in the United States – An Empirical Study Using the STIRPAT Model

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Abstract
This investigation analyses the influence of private AI investment and financial development (FD) on CO2 emissions in the United States, using the STIRPAT framework to account for the functions of GDP, population, and foreign direct investment (FDI). The data's robustness was verified through the application of a variety of unit root tests, which confirmed that the variables are free of unit root issues and exhibit a varied order of integration. The ARDL bound test was used to investigate the cointegration among the variables and it found a long-run equilibrium relationship. The ARDL model results show that income, FDI, FD, and population significantly increase CO2 emissions in both the short and long term. In contrast, we found that private investment in AI led to a significant reduction in CO2 emissions over these time frames. Additional estimations were conducted using FMOLS, DOLS, and CCR methods to verify the ARDL results, all of which attested to the initial findings' robustness. In addition, the study implemented a pairwise Granger causality test to illustrate the directional relationships between the variables. There is a unidirectional causal link between GDP, private AI investment, FDI, population, and CO2 emissions, according to the findings. Most notably, we observed bidirectional causality between CO2 emissions and FD. Diagnostic tests further corroborated the validity of the study's conclusions, confirming that the model is free from specification errors, serial correlation, and heteroscedasticity.

Keywords: Private AI Investment; Financial Development; FDI; Carbon Neutrality; United States

Introduction

Researchers from all around the world have been discussing and analyzing environmental economics and global warming for a few decades (Abid et al., 2022). Growing urbanization and industrialization have brought about significant environmental changes in recent decades (Mehmood and Tariq 2020). People widely recognize CO2 emissions as the primary proxy of ecosystem damage (Voumik et al., 2024). UN research predicts that the 2015 Paris Agreement's aims for limiting global disasters may not be achieved if emissions of CO2 aren't drastically cut below 2°C and 1.5°C. Serious social and economic repercussions will follow the failure to meet the carbon mitigation target (Ridwan et al., 2024). With 6677 million metric tons of CO2, CO2 accounted for 81.3% of all GHG pollution in 2018 (EPA, 2020). Of the GHGs released in 2018, 22% came from industrial activity alone or predominantly (EIA, 2020). In 2021, the US possessed the largest economy and ranked second in terms of CO2 emissions among developed nations (British Petroleum 2022; World Bank 2022). In this sense, AI approaches can predict CO2 emissions, and contemporary technology can guarantee environmental sustainability. Moreover, Wang et al. (2019) demonstrated that there is no longer an association within CO2 pollution and economic growth, as the US GDP increased by 19% between 2007 and 2016. Given the United States' large scale and high CO2 emissions, further investigation is necessary to explore the correlation between CO2 emissions and GDP (Ulussever et al., 2023). Therefore, it is required to demonstrate the relationship across private investment in AI (PAI), financial development (FD), and CO2 emissions within the framework of the US, since this can potentially provide guidance for other countries. Therefore, we give special consideration to FD, FDI, and PAI due to their potential to increase CO2 emissions in this country. Scholars have conducted a thorough analysis of the United States' ecological state of circumstances (Acheampong, 2018). Since it draws attention to the harmful effects that our behavior has on the ecosystem, we applied it as a demand-side measure of environmental degradation. The United States has set a goal to achieve carbon neutrality, which means reaching a state where the level of GHGs generated is equivalent to the amount eliminated by the atmosphere by no later than 2050. US President Biden announced the US's return to the Paris Agreement in 2021 with the Clean Energy Revolution and Environmental Justice Plan, which seek for a green energy economy and a net zero CO2 emission by goal by 2050 (Harris, 2020). The state governments are eager to take some concrete steps against global warming to meet this objective (Dehdar et al., 2023). To achieve the SDGs, an economy must employ an effective policy to minimize CO2 emissions in addition to controlling finances (Yu et al., 2024). Although the US boasts the eighth-highest GDP per capita among 189 countries, its financial system face significant challenges due to the overuse of natural assets and CO2 emissions (Zafar et al., 2019). The expansion of GDP correlates with an upsurge in CO2 pollutions (Raihan et al., 2024b). Moreover, industrial revolution led to a substantial rise in the use of AI, and its implication on energy usage and CO2 releases could aid in the attainment of carbon neutrality. Furthermore, AI algorithms that decrease CO2 emissions contribute to the emergence of the sustainable financial system. By implementing strategies such as optimizing industrial structure, updating networks, and supporting creativity in sustainable technologies can effectively cut CO2 emissions. However, by enabling technology transfer to recipient nations, FDI promotes the formation of human resources and the spread of innovation (Shahbaz et al., 2019). Furthermore, it promotes the use of manufacturing goods that pollute the natural environment and spread industrial activity while also aiding in the GDP development of the host region (Balli et al., 2023). Furthermore, FD can encourage the purchase of expensive items like automobiles, houses, and other objects, leading to higher power use, manufacturing, and CO2 emissions (Dogan and Turkekul, 2016). Conversely, when individuals rapidly depend on fossil fuels to enhance their quality of life, the planet suffers. Consequently, countries experiencing a surge in population will exhibit higher levels of CO2 emissions (Esquivias et al., 2022). Our paper significantly contributes to the corpus of expertise currently available on ecosystem degradation in several important areas. First, it introduces a new method for analyzing short- and long-term implications on the US zone by breaking down the

STIRPAT model and combining it with the ARDL framework. We particularly scrutinize the possible determinants of CO2 emissions, namely PAI, FDI, and FD. Furthermore, by employing a relatively new dataset that encompasses a thorough investigation from 1996 to 2022 in the United States, our work contributes to the abundance of research already available on the environmental effects of PAI, FDI, and FD. Second, we use traditional unit root tests like ADF, P-P, and DF-GLS to assess the factors' stationarity. Third, we implement the ARDL bounds technique to cointegration to determine if there exists a cointegrating connection between CO2 emissions and their driving factors. We then use Granger causality tests to look at the causal connection among the selected factors. Lastly, we applied various approaches such as FMOLS, DOLS, and CCR, along with additional diagnostic instruments, to evaluate the validity of our results and address any potential issues with the dataset. This research shows that while GDP, FDI, and population all influence emission levels in the USA, FDI and PAI enhance environmental level by cutting CO2 emissions. This document arranges the remaining sections in the following order: Part 2 briefly represents the prior literature, while the next subsection illustrates the empirical model and information. The 4th portion provides the methodology. The 5th part displays the findings and critiques, the 6th chapter provides the conclusion, and Section 7 finally discusses the policy implications.

Literature Review

Several current studies focus on the complex links between CO2 emissions, GDP progress, FDI, AI investment, FDI, and population expansion in different locations globally. We review the current state of academic research in that area to identify any gaps in the existing body of knowledge. Moreover, we are trying to ascertain the novel and significant sides of our research that add to this continuously expanding field of study. Given the magnitude of global warming, it is essential to evaluate CO2 emissions by employing a diverse array of mathematical models and theories (Ridwan et al., 2023). The consumption of non-renewable energy and the loss of forests are rising, which leads to climate change, there has been an enormous rise in the number of studies focusing on CO2 emissions in recent years (Jaafar et al., 2020). Raihan et al. (2024c) conducted an experiment in Vietnam to look at the correlation between economic development and CO2 release. They concluded that there is a direct connection between GDP growth and CO2 emissions, using the DOLS technique. Raihan et al. (2022b) have established a clear correlation, indicating that in the United States, a 1% expansion in GDP causes a corresponding surge of 0.59% in CO2 pollutions in the short term and 0.29% in the long run. Ahmad et al. (2024) utilized the ARDL bound test for cointegration to explore the impact of GDP on China's ecological degradation. They demonstrated that a 1% boost in GDP corresponds to a 0.51% increase in CO2 emissions. In addition, Pattak et al. (2023) provide evidence that corroborates the findings of previous studies. They observe that a 1% expansion in Italian GDP over an extended time can leads to an 8.08% spike in CO2 emissions. Raihan et al. (2023a) investigate the ecological impacts of China's nuclear energy usage from 1993 and 2022, focusing on the EKC and PHH. They demonstrated that the expectation is that reducing CO2 emissions will improve environmental quality and accelerate GDP growth. Similarly, Mehmood et al. (2021) determined that the autonomous influence of GDP significantly reduces the CO2 emissions of Bangladesh and Pakistan. Contrarily, Acheampong et al. (2022) employed the NARDL approach and found that there is a minimal distinction between the increase and decrease in GDP in relation with CO2 pollutions. Numerous papers discussed the deployment of AI and ML to lessen CO2 emissions in construction sectors (Peng, 2019). A sizable number of studies have employed patent filings as a stand-in for invention (Balsalobre-Lorente et al., 2018; Herrerias et al., 2016). AI models, such as ML models, use data to create strategies for reducing pollution of CO2 from human activities (Delanoe et al., 2023). Similarly, Dong et al. (2023) adopted the dynamic panel data from China to create econometric models in order to look at the consequence of AI on CO2 production. Their outcome demonstrates that AI greatly lowers CO2 emissions. Conversely, empirical studies have demonstrated that robotic shocks significantly reduce CO2 emissions in

China's manufacturing industry (Chen et al., 2022; Jiang et al., 2022). From 2005 to 2016, Liu et al. (2022) looked into how artificial intelligence affected China's carbon intensity. They illustrated that AI significantly lowers carbon intensity by applying the STIRPAT framework. Zhao et al. (2023) used a fixed effects model to investigate the mechanisms and consequences of AI on China's CO2 pollutions between 2006 and 2019. The results indicate that there is a substantial drop of 6.63% in emissions for every 10% rise in the use of AI, suggesting that AI has the potential to considerably lower the intensity of pollutant emissions.

The hyperlink between FD and the quality of ecosystems has drawn the focus of a greater variety of scholars in recent years (Acheampong, 2019). The theory of FD emphasizes the impact of the monetary system on GDP growth and the potential of financial assets to contribute to sustainable development (Aghion et al., 2005). Mehmood (2024) uses the CS-ARDL methodology to evaluate the consequences of FD on CO2 emissions in Pakistan, India, Bangladesh, and Sri Lanka over the period 1984–2017. They assert that FD is essential for South Asian countries' development in order to achieve carbon neutrality. Tamazian and Rao (2010) found that FD has a major role in determining environmental performance, based on their analysis of 24 transition economies. Zafar et al. (2019) conducted a study where they examined the factors affecting the state of the earth in OECD zones. They identified a negative association between FD (which stands for a specific variable) and CO2 emissions. This means that as FD increases, the ecological health of the environment would deteriorate due to increased pollution. Nevertheless, Rjoub et al. (2021) noted that FD made more environmental pollution of Turkey. Suhrab et al. (2023) analyze the impact of FD on CO2 emissions in Pakistan using annual time series data from 1985 to 2018. The conclusion demonstrated a positive correlation between heightened FD and elevated levels of CO2 pollutions. At the same way, Shahbaz et al. (2023) examine the effects of FD and GDP growth on ecological health in 10 economies with the greatest natural impacts. The findings suggest that FD has a harmful effect on an ecosystem. Several studies, such as Shoaib et al. (2020) in D8 and G8 and Kihombo et al. (2021) in West Asia and the Middle East, have identified a direct correlation between financial progress and environmental harm. FDI is acknowledged as an essential environmental variable that boosts efficiency and GDP by progressing innovation and capital creation (Alvarado et al. 2017).The influence of FDI on ecological health varies across countries and regions, leading to conflicting findings from different research. FDI inflow, in particular, has been associated with increased ecological sustainability, primarily through technological knowledge and spillover channels (Duan and Jiang, 2021). It reduces ecosystem damage by supporting creative uses of green technologies, according to data from numerous studies (Zhu et al., 2018; Udema et al., 2020; Lahiani, 2020). Using the ARDL method, Saadaoui et al. (2024) evaluate how FDI affected Turkey's CO2 emissions from 1985 to 2021. In the nong run, the conclusions indicate that FDI mitigates emission level of CO2. Comparably, Zhang and Zhou (2016) demonstrated that FDI helps China reduce its CO2 pollutions. Wei et al. (2019) assert that FDI has the potential to enhance the natural environment by reducing pollution, but the use of green total productivity factors cannot achieve this boost. Nonetheless, increases in financial investment might encourage industrialization, which could worsen the environment and increase pollution (Baloch et al. 2019). Salahuddin et al. (2018), on the other hand, studied the empirical effects of FDI on CO2 emissions in Kuwait covering 1980 and 2013. Using the ARDL bounds testing methodology, they discovered that FDI increases CO2 emissions in both short and long terms. In a similar vein, Sapkota and Bastola (2017) discovered proof of FDI's detrimental effects on the ecosystem and indicated that a 1% spike in FDI is responsible for a 0.04% increase in ecosystem damage in Latin America. Population expansion (POP) has become a serious issue for environmental pollution, and several academicians are focusing on the nexus between boost in population and the release of CO2. It is one of the key elements causing pollution (Grigg, 1991). By deploying the sophisticated ARDL and the STIRPAT model, Voumik et al. (2023a) calculated the effects of rise in POP on CO2 pollution. The empirical data show that growing populations can raise the nation's emissions of CO2 in Kenya. According to Pachiyappan et al. (2021), there will be a 1.4%

rise in CO_2 emissions in India. Furthermore, Voumik and Ridwan (2023) conducted an investigation in Argentina from 1972 to 2021 using the ARDL methodology, and the empirical conclusions revealed that population development degrades ecosystem level in the long run. In a similar way, several studies, such as Ali et al. (2020) in Malaysia and Zhang et al. (2023) in the top 10 nuclear-generating economies, found the same outcomes. But Alam et al. (2016) investigated how growth in populations in China, Brazil, India, Indonesia, and China affected CO_2 emissions between 1970 and 2012. They demonstrated a statistically significant correlation between CO_2 emissions and POP increase for Brazil and India, but a statistically insignificant one for China and Indonesia. Conversely, Begum et al. (2015) surprisingly showed that the pace of population growth in Malaysia had no apparent consequences on the country's per capita emissions of CO_2. In contrast, Sulaiman et al. (2018) employed the ARDL model and found that population growth could only have an immediate implication on CO_2 emissions in Nigeria. With its focus on the U.S. setting and its distinct socioeconomic and ecological features, this study seeks to close a large knowledge gap. Despite growing global attention to equitable development, few thorough studies in USA to look at the combined influences of population rise, FD, FDI, PAI, and GDP development on CO_2 emissions. In-depth assessments of the intricate interactions between these factors tend to be absent in the literature that is currently available, especially when it comes to the STIRPAT model. The outcomes of the connection among FD, PAI, and CO_2 emissions are still contradictory, even though earlier research acknowledged the necessity for more thorough investigations on these associations. But it's crucial to consider that financial innovation and private investment in AI can encourage the uptake of cutting-edge, environmentally friendly technologies, which could assist in a decline in CO_2 pollutions. Therefore, the objective of this study is to fill these gaps and provide policymakers with useful information so they can establish long-term plans to cut emissions.

Methodology

Data and Variables

Table 1 displays a full description of the data sources and relevant information. This research uses a balanced time series dataset for the United States, spanning the years 1996–2021. The Global Footprint Network (GFN) provides statistics for assessing ecological viability through CO_2 emissions, which act as the dependent variable. Our World in Data provides one important parameter in this analysis: private investment in AI. The IMF provides statistics for the FD which is another important factor. The World Development Indicators (WDI) also provides population, GDP, and foreign direct investment data. We select the information sources based on their accessibility.

Theoretical Framework

The research utilizes modified IPAT and STIRPAT models for analyzing data.Ehrlich and Holdren (1971) first suggested the IPAT model as a framework for examining how growing population harms the environment. They adopted the following set of model instances:

$$I \equiv P.A.T \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

Here, "P" stands for population size, "A" for affluence, "T" for technological level, and "I" for the impact on the environment. There are several issues with the original IPAT identification. Dietz and Rosa (1994, 1997) suggested a modified format regarded as STIRPAT to address these issues. It includes a stochastic equation to account for unintentional errors in parameter estimations. The model not only incorporates factors beyond the original IPAT framework, but also enables the estimation of these factors' elasticities (Shu et al., 2024). These researchers examine the following formulation:

$$I_{it} = CP_{it}^{\gamma_1} A_{it}^{\gamma_2} T_{it}^{\gamma_3} \varepsilon_{it} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ (2)$$

At time t, P represents the country's population, A represents its wealth, and T represents its technology. The constant term in the STIRPAT model is C, while the random error component is represented by ε. Conversely, the symbols γ_1,γ_2, and γ_3 denote the coefficients of P, A, and T, respectively.We can express the logarithmic transformation of the model as follows:

$$LnI_{it} = C + \gamma_1 LnP_{it} + \gamma_2 LnA_{it} + \gamma_3 LnT_{it} + \varepsilon_{it} \ldots\ldots\ldots\ldots\ldots\ldots\ (3)$$

The variables used in our research were waste recycling as an expression of impact (I), population growth as an indicator of population (P), affluence (estimated by GDP, FD, and FDI), and technological level (as private investment in AI). The equation can be written as:

$$CO_2 = f(GDP_{it}, PAI_{it}, FD_{it}, FDI_{it}, POP_{it}) \ldots\ldots\ldots\ldots\ldots\ldots.... (4)$$

Table 1. Source and Description of Variables

Variables	Description	Logarithmic Form	Unit of Measurement	Source
CO_2	CO_2 Emission	LCO_2	CO_2 Emission (kt)	GFN
GDP	Gross Domestic Product	LGDP	GDP per capita (current US$)	WDI
PAI	Private Investment in Artificial Intelligence	LPAI	Estimated Investment in AI (US$)	Our World in Data
FD	Financial Development	LFD	Financial Development Index	IMF
FDI	Foreign Direct Investment	LFDI	Net Inflows (Current US$)	WDI
POP	Population	LPOP	Population, total	WDI

The explanatory variables in this instance are GDP, PAI, FD, FDI, and POP, whereas the dependent variable is CO_2. An alternate way to describe the empirical model in logarithmic form is as follows:

$$LnCO_{2it} = \beta_0 + \beta_1 LnGDP_{it} + \beta_1 LnPAI_{it} + \beta_2 LnFD_{it} + \beta_3 LnFDI_{it} + \beta_4 LnPOP_{it} + \varepsilon_{it} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ (5)$$

Where, $\beta_0$is the intercept term and $\beta_1, \beta_2, \beta_3, and\ \beta_4$are the coefficients of selected independent variables accordingly. The letter ε and L, stand for the natural log and the model's error term.

Empirical Methods

In this research, the DF-GLS, PP, and ADF assessments are among the most frequently used tests for unit root. Secondly, the statistical technique will employ robustness evaluations (FMOLS, DOLS, and CCR) to ensure the accuracy of the results, as well as the ARDL method to analyze cointegration across short and long periods. We then implemented the Granger causality test to explore the connection among the components, followed by a multitude of diagnostic tests.

Unit Root Test

Panel unit root testing is one approach to determining the integrational pattern for each variable, as the order incorporates all factors (Ozturk and Al-Mulali, 2015). It guarantees that the series is stationary and delivers an approximation of the regression equation employing stationary approaches (Raihan et al., 2023b). The standard unit root assessments that determine the sequence of variable integration include the P-P (Phillips and Perron 1988), the ADF (Dicky and Fuller 1979), and the DF-GLS test developed by Dickey-Fuller (Elliott et al., 1992). In comparison to the Dickey-Fuller (DF), the ADF technique is more robust and suited to more complicated procedures (Fuller, 2009).

ARDL Methodology

We use the cointegration and bounds testing approaches to determine whether there is a long-term link among CO2 emissions and their determinants, following the findings of the unit root analyses. Pesaran et al. (2001) recommended that the ARDL bounds test be deployed in this investigation to document the sequence's cointegration. Its main advantage is the ability to evaluate both short and long-term factors simultaneously. This allows it to analyze a wide range of time series data without requiring extensive previous testing (Raihan et al., 2022a). Furthermore, this framework (Raihan et al., 2024a) allows for the application of I (0) or I (1), or any frictionally integrated time series variable these variables typically represent. We represent the ARDL bound test in Eq. (6) as follows:

$$\begin{aligned}\Delta LCO_{2t} = \alpha_0 &+ \beta_1 LCO_{2t-1} + \beta_2 LGDP_{t-1} + \beta_3 LPAI_{t-1} + \beta_4 LFD_{t-1} + \beta_5 LFDI_{t-1} + \beta_6 LPOP_{t-1} \\ &+ \sum_{i=1}^{q} \delta_1 \Delta LCO_{2t-i} + \sum_{i=1}^{q} \delta_2 \Delta LGDP_{t-i} + \sum_{i=1}^{q} \delta_3 \Delta LPAI_{t-i} + \sum_{i=1}^{q} \delta_4 \Delta LFD_{t-i} + \sum_{i=1}^{q} \delta_5 \Delta LFDI_{t-i} \\ &+ \sum_{i=1}^{q} \delta_6 \Delta LPOP_{t-i} + \varepsilon_t \end{aligned} \quad (6)$$

In the ARDL limit analysis, the F-distribution and critical values proposed by Pesaran and Timmermann (2005) are used within the framework of the equation denoted by (6), where q represents the optimal lag length and Δ denotes the first difference operator. Equation (6) serves as the first step in the estimating process. Pesaran et al. (2001) suggest that long-term correlations with F-statistics that fall between the threshold values are inconclusive, but those that fall below the threshold should receive acceptance.

Robustness Check

Phillips and Hansen (1990) recommended the FMOLS examination, Park (1992) reported the CCR test, and Stock and Watson (1993) calculated the DOLS test to assess the robustness of the ARDL outcomes. Before implementing FMOLS and DOLS, the CCR (Canonical Cointegrating Regression) method serves as an excellent tool for verifying their accuracy (Sultana et al., 2023). The development of these methodologies addressed two primary concerns. Before implementing FMOLS, DOLS, or CCR, it is necessary to meet the cointegration criteria among the I(1) parameters (Raihan et al., 2023b). A second benefit of these methods is that they address issues such as serial correlation, bias from absent variables, heterogeneity, and measurement errors (Raihan and Tuspekova 2023).

Granger Causality Test

The Granger causality test is paired and evaluates the sum of the past and current values of the independent variable (X) and dependent variable (Y) (Voumik et al., 2023b). The same is true for Y and X's causal link; if the outcomes deviate from zero, then both parties are causally involved (Rahman and Majumder, 2022). The analysis used the paired Granger causality test introduced by Granger (1969), and the causal connection between Xt and Yt is depicted in the following equation.

$$E\left(Y_{t+h}\middle|J_{t,}X_t\right) = E(Y_{t+h}|J_t) \quad (9)$$

Here, Jt notation is used for the sets of information gathered from all of the outcomes up to a certain point of time (t).

Diagnostic Test

The Lagrange Multiplier (LM), Jarque-Bera (Jarque and Bera, 1987), and BPG (Breusch and Pagan, 1979) tests are important in time series analysis for making sure that model assumptions are correct and that results are stable. Since many statistical models require normally distributed errors for proper inference so the Jarque-Bera investigation can be performed. By looking for serial correlation in residuals, the LM examination ensures that errors do not converge over time and produce skewed and misleading estimations. Finally, we utilized the BPG test to confirm the heteroscedasticity, or nonconstant variance, of the residuals.

Results and Discussion

Table 2 summarizes information on a variety of factors. The average LCO2 is 15.46, with a range from 15.27 to 15.56. The mean LGDP is 10.64, with a minimum of 10.08 and a maximum of 11.15. Notably, LFDI has the highest mean (25.89), while LFD has the lowest. The standard deviations of LCO2 (0.08), LGDP (0.31), LPAI (1.66), LFD (0.13), LFDI (0.76), and POP (0.08) demonstrate the variability around the mean. LPAI is positively skewed, while LCO2, LGDP, LFD, LFDI, and POP are inversely skewed. All variables have a normal distribution with low Jarque-Bera probability values. The dataset includes 32 observations for each variable from 1990 to 2022 in the United States.

Table 2. Descriptive statistics of Variables

Variable	LCO2	LGDP	LPAI	LFD	LFDI	LPOP
Mean	15.46444	10.64393	22.0143	-0.167379	25.89841	19.4995
Median	15.45192	10.71885	21.2377	-0.096679	26.09007	19.50906
Maximum	15.56919	11.15938	25.66873	-0.081949	26.96048	19.62079
Minimum	15.27889	10.08116	20.55212	-0.520773	24.13474	19.33546
Std. Dev.	0.080244	0.318778	1.665446	0.137067	0.768762	0.086797
Skewness	-0.466593	-0.255693	0.989543	-1.662635	-0.716141	-0.311024
Kurtosis	2.635357	1.888894	2.466317	4.273768	2.616801	1.894884
Jarque-Bera	1.338404	1.994763	5.602132	16.90654	2.931032	2.144299
Probability	0.512117	0.368844	0.060745	0.000213	0.230959	0.342272
Sum	494.8622	340.6058	704.4575	-5.356143	828.749	623.9841
Sum Sq. Dev.	0.199614	3.150205	85.98507	0.582405	18.32085	0.233545
Observations	32	32	32	32	32	32

Three stationarity tests for log-transformed variables at the level and first difference form are shown in Table 3. It seems that only the population factor is stationary at level I(0) at the 1% significance thresholds in each of the three unit root evaluations. Before we took into account their initial differences, the CO2, GDP, foreign direct investment, private investment in AI, and FD were non-stationary and significant at 1% significance thresholds. Thus, the ARDL methodology should be used to conduct the evaluation today because of the heterogeneous sequence of integration.

Table 3. Results of Unit root test

Variables	ADF		P-P		DF-GLS		Decision
	I(0)	I(1)	I(0)	I(1)	I(0)	I(1)	
LCO_2	-0.155	-4.954***	-0.371	-4.959***	-0.521	-3.980***	I(1)
LGDP	-0.878	-4.841***	-0.953	-4.829***	-0.881	-4.085***	I(1)
LPAI	-0.806	-7.505***	-1.897	-7.403***	-0.673	-6.194***	I(1)
LFD	-2.731	-4.381***	-2.087	-4.551***	-1.889	-4.650***	I(1)
LFDI	-1.793	-6.508***	-1.565	-6.615***	-0.715	-4.882***	I(1)
LPOP	-4.896***	-7.881***	-6.881***	-8.605***	-3.831***	-5.750***	I(0)

Table 4 presents the bound analysis outcomes and reports the F-statistic as 4.2150, serving as a test statistic. We categorize the critical values using the integration order of the variables (I (0) and I (1)). The critical values for I (0) and I (1) are 2.08 and 3, accordingly, at the 10% significance level. Similarly, we provide critical values for both integration orders at the 5%, 2.5%, and 1% significance levels. These demonstrate the existence of a long-term correlation across the selected indicators.

Table 4. Results of ARDL bound test

Test Statistic	Value	Signif.	I(0)	I(1)
F-statistic	4.2150	10%	2.08	3
k	5	5%	2.39	3.38
		2.50%	2.7	3.73
		1%	3.06	4.15

We can evaluate their long-term relationship once the bound testing procedure reveals their cointegration. Table 5 adopts the novel ARDL method to outline the effects of different variables on LCO2 in the US, both in the short and long run. We can see from the given information that, a 1% spike in economic growth, the ecological condition drops by 0.057% over the long and by 0.044% over the short term. Beside the LGDP coefficient is both positive and statistically significant, we can infer that environmental pressure rises as US economic expansion accelerates. Azam et al. (2022), Cheng et al. (2021), Zafar et al. (2022), and Chien et al. (2023) have corroborated the findings and validated the beneficial association between GDP growth and carbon pollution. Furthermore, Pradhan et al. (2024) noted that as the economy expands, so does the consumption for goods and services, which raises output and, consequently increases emissions. According to the estimated coefficient for LPAI, there is an upward trend between LCO2 and private investment in AI, which promotes ecological condition in the US. In particular, an increase of 1% in LPAI delivers a long-lasting cut in CO2 emissions of 0.056% and an immediate decrease of 0.027%. This is because inventions are critical for improving energy efficiency and lowering CO2 emissions. Khalid et al. (2023) and Shahbaz et al. (2020) supported our conclusions. Additionally, higher amounts spent on eco-friendly procedures and greener technologies lessen their destructive implications on ecosystem and improve the health of our planet (Yao et al., 2021).

Table 5. ARDL short-run and Long-run Estimation

Variable	Coefficient	Std. Error	t-Statistic	Prob.
Long-run Estimation				
LGDP	0.057	0.6525	0.0882	0.012
LPAI	-0.056	0.0220	-2.5419	0.023
LFD	-0.357	0.2288	-1.5627	0.003
LFDI	0.027	0.0364	2.7630	0.025
LPOP	0.310	0.6517	2.1170	0.031
C	10.477	5.1367	3.2321	0.000
Short-run Estimation				
D(LCO2(-1))	0.127	0.1120	1.1368	0.071
D(LGDP)	0.044	0.2061	5.0596	0.001
D(LPAI)	-0.027	0.0086	-3.1973	0.015
D(LFD)	0.214	0.1352	2.5888	0.034
D(LFDI)	0.007	0.0106	-4.6978	0.000
D(LPOP)	0.2983	1.4912	2.5412	0.012
CointEq(-1)*	-0.475	0.1038	-4.5801	0.003

The calculated coefficients for LFD show an obvious inverse correlation with LCO2. This demonstrates that a 1% rise in FD generated a 0.214% short-term spike and a 0.357% long-term reduction. For this, the financial success plays a significant role in maintaining environmental sustainability in US. Numerous studies have revealed that the growth of the financial industry enhances the natural health (Saud et al., 2018; Latif and Faridi, 2023; Kartal et al., 2023). However, Pata et al. (2023) found the opposite result, holding that FD in the US had no bearing on the quality of the ecosystem. In addition, the destructive and statistically significant indications of the FDI coefficients suggest that an expansion in LFDI in both the long and short-run has a detrimental effect on environmental quality. Specifically, a 1% expansion in LFDI will result in a 0.027% and 0.007% increase in LCO2. It concludes that the present foreign direct investment of the United States is not conducive to reducing pollution; moreover, FDI can uplift the pollution level through energy consumption (Yang et al. 2020). Our findings align with Boubacar et al. (2024) in Africa, Zhang et al. (2023) in China, and Kouassi et al. (2024) across 43 African nations; they also concluded that greater FDI causes more release of CO2. Similarly, the results presented in Table 5 reveal that increased population degrades environmental quality in the US. An additional 1% expansion of LPOP will cause a 0.310% long and 0.298% short-run rise in CO2 pollutions. Our result aligns with Rehman et al. (2022) in Pakistan, Anser et al. (2020) in SAARC countries, and, Rehman et al. (2023) from a global perspective.
The inferences from the ARDL investigation are backed by the robustness findings shown in Table 6. At 1% significance threshold, the LGDP coefficients in the FMOLS, DOLS, and CCR models are statistically significant. According to FMOLS and CCR estimations, a 1% development in GDP results in a 0.196% and 0.117% boost in carbon pollutions, respectively, while DOLS reports a 0.016% cut in carbon emissions. A 1% rise in LPAI generates a corresponding drop in LCO2 of 0.045%, 0.030%, and 0.047% in FMOLS, DOLS, and CCR. In contrast, this result is significant in DOLS at the 10% level, as well as in FMOLS and CCR at the 1% level. Furthermore, in the FMOLS model, a 1% increase in LFD resulted in a 0.490% drop in LCO2. Conversely, there prevails a positive correlation, with a rise in CCR of 0.484% and a spike in DOLS of 0.352%. Furthermore, using the three estimation approaches, a 1% increase in LFDI yields an upsurge in LCO2 of 0.012%, 0.013%, and 0.010%. On the other hand, in FMOLS, a 1% rise in LPOP implies a 0.976% plunge in LCO2, which is notable at the 5% level. By comparison, DOLS and CCR predict a noteworthy 10% level of growth in emissions of 0.023% and 0.644%, respectively. The ARDL findings are in line with these contradictory responses.

Table 6. Robustness Check

Variables	FMOLS	DOLS	CCR
LGDP	0.196***	-0.016***	0.117***
LPAI	-0.045***	-0.030*	-0.047***
LFD	-0.490***	0.353**	0.484***
LFDI	0.012***	0.013**	0.010***
LPOP	-0.976**	0.023**	0.644*
C	10.678***	8.679***	10.561***

Table 7 outlines the causal relationships between various variables. This analysis reveals that LGDP does not cause LCO2, as observed by an F-statistic of 4.9537 and a p-value of 0.0154. This result suggests that, at the 5% significance level, we can reject the null hypothesis of no causal link between LGDP and LCO2. Additionally, there is evidence of one-way causation from LPAI, LFD, and LPOP to LCO2, supported by p-values below the conventional significance level. Similarly, there is a one-way causality between LCO2 and LFD, indicating that changes in LCO2 can influence LFD. Consequently, we can reject the null hypothesis of no causal relationship in these cases. On the other hand, p-values higher than the conventional limit of significance suggest that neither LLCO2 nor LGDP significantly contribute to LPAI, LFD, or LPOP, nor does LFDI contribute to LCO2. This implies that changes in LCO2 have no impact on LFD, population expansion, AI investment by the private sector, or economic growth. Furthermore, since LFFDI has no effect on LCO2, we cannot rule out the null hypothesis that these interactions lack a causal relationship.

Table 7. Granger Causality Test

Null Hypothesis	Obs	F-Statistic	Prob.
LGDP $\neq$ LCO2	30	4.9537	0.0154
LCO2 $\neq$ LGDP		0.8454	0.4413
LPAI $\neq$ LCO2	30	4.7929	0.0173
LCO2 $\neq$ LPAI		0.0127	0.9873
LFD $\neq$ LCO2	30	5.5694	0.0123
LCO2 $\neq$ LFD		0.2487	0.7817
LFDI $\neq$ LCO2	30	2.9103	0.0731
LCO2 $\neq$ LFDI		0.2741	0.0125
LPOP $\neq$ LCO2	30	4.6044	0.0198
LCO2 $\neq$ LPOP		0.6101	0.5512

Table 8 displays the results of three different diagnostic evaluations. Because the data are all conflicting, it is evident that no diagnostic method can completely rule out the null hypothesis. According to the Jarque-Bera test, the residuals exhibit a normal distribution with a p-value of 0.1074. Then, the Lagrange multiplier assessment shows that there is no serial correlation in the residuals, with a p-value of 0.4031 being higher than the usual level of significance. In the end, the BPG test confirms that there is no heteroscedasticity issue with the residuals, producing a p-value of 0.7459.

Table 8. The results of diagnostic tests

Diagnostic tests	Coefficient	p-value	Decision
Jarque-Bera test	2.3015	0.1074	Residuals are normally distributed
Lagrange Multiplier test	1.0361	0.4031	No serial correlation exits
Breusch-Pagan-Godfrey test	0.7459	0.3214	No heteroscedasticity exists

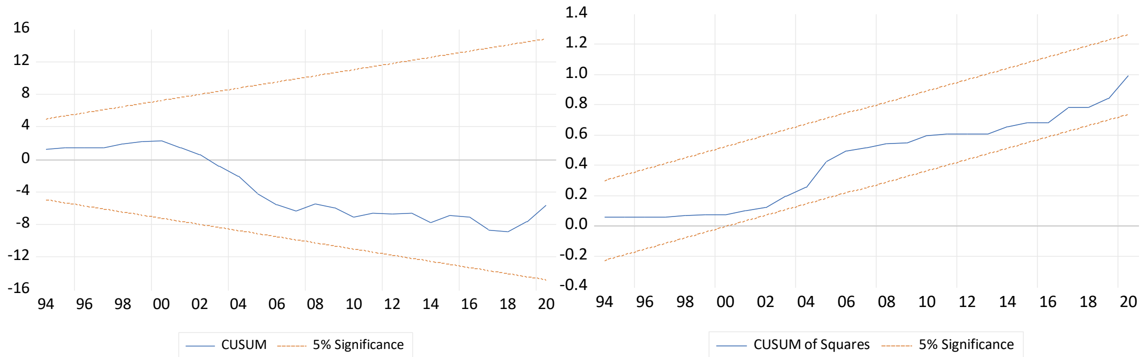

Figure 1. CUSUM and CUSUMSQ test

We performed the CUSUM and CUSUM-SQ tests to identify residuals of functions that reflect structural stability in both the short and long run. The statistical result in this case stays between the upper and lower bounds. The parameters are stable and well-defined at the 5% significant level, as evidenced by the CUSUMsq test plot's presence within the critical line (Figure 1).

Conclusion and Policy Recommendation

In the context of reaching carbon neutrality in the US, this study examines the connection among GDP growth, financial development, foreign direct investment, population growth, and private investment in AI. The analysis employs the ARDL bounds testing methodology within the STIRPAT framework using time series data spanning from 1996 to 2022. The unit root examinations confirm the stationarity of the variables and their lack of unit roots. Additionally, ARDL-bound experiments show that the factors do not cointegrate, confirming the lack of long-term equilibrium linkages. Nonetheless, the conclusions of the ARDL estimation indicate a strong and positive long-term correlation between GDP, FDI, POP, and CO2 emissions. The association between PAI and FD, on the other hand, is favorable and significant, suggesting a move toward more environmentally friendly financial practices and cutting-edge clean technology that lowers carbon emissions. According to the investigation, rising CO2 emissions in the United States are linked to economic development. However, technological and FD may be able to reduce these emissions, promoting healthy ecosystem. Robustness checks using FMOLS, DOLS, and CCR estimators validate the results, highlighting the complex relationships between these variables. Diagnostic tests confirm the regression model's reliability, and the residuals show no signs of serial correlation, heteroskedasticity, or deviations from normalcy. We also performed a Pairwise Granger causality test to investigate causal links between the variables. All things considered, this extensive investigation offers relevant details about the dynamics of development in finances, FDI, GDP expansion, AI investment, and CO2 emissions in the USA, providing a strong basis for responsible policy choices and environmental preservation plans. The findings have important policy ramifications for the United States as it strives to reconcile economic expansion with environmental sustainability. The relationship among wealth, FDI, FD, population, and CO2 emissions highlights the necessity for policies to tackle the environmental consequences of these economic activities. Law makers have to contemplate enforcing more stringent environmental restrictions on sectors that significantly contribute to CO2 emissions, particularly those that derive advantages from FDI and financial development. Moreover, the favorable influence of private investment in AI on decreasing CO2 emissions implies that advocating for AI-driven innovation might serve as a strategic means to alleviate environmental deterioration. One such approach is to provide incentives, such as tax exemptions, grants, or subsidies, to firms that invest in

AI technology with the goal of improving energy efficiency and decreasing carbon emissions. As a result, incorporating environmental risk assessments into financial decision-making processes and promoting green finance projects are critical measures to ensure that financial development is in line with sustainable environmental outcomes. Furthermore, given the one-way relationship in which GDP, FDI, and population influence CO2 emissions, it is critical to develop economic strategies that separate economic expansion from environmental damage. This may entail advocating for the adoption of the circular economy, allocating resources towards renewable energy, and raising public consciousness regarding sustainable purchasing habits. Furthermore, it is critical to ensure that urban planning and population control strategies are in line with environmental sustainability objectives, especially in densely populated regions where the population increase is more likely to worsen CO2.

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REVIEW ARTICLE

Sustainable development in Algeria: Investigating challenges and potential pathways

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Abstract
Sustainable development has emerged as a global priority, with the aim of balancing economic growth, environmental preservation, and social equity to meet present and future needs. Algeria's reliance on fossil fuels has led to environmental degradation and economic instability exacerbated by the recent financial crisis. This study aims to investigate the constraints and strategies of sustainable development in Algeria as well as the efforts of the Algerian government to achieve sustainable development. Through an in-depth analysis of scientific publications and official texts, this research examines the country's environmental state, economic growth in the non-oil sector, and individual living environments. All of which are crucial for sustainable development. This study employs descriptive and analytical methods to asses several action plans and policies, providing a comprehensive understanding of the complexities surrounding sustainable development in Algeria. The findings of this study will shed a light on the strategies for a more diversified and environmentally conscious economy, ultimately contributing to a more stable and prosperous future for the country.

Keywords: Challenges; Potential pathways; Sustainable development; Action plan; Algeria

Introduction

Over the last two decades, the concept of sustainable development has been established by public authorities, capturing the attention of the whole world since it was mentioned at the 1972 United Nations Conference on the Environment. After years of study at the Stockholm Conference, the International Committee on Environment and Development finalized a report entitled “Our Common Future”, which saw the need to follow alternative models, causing a qualitative leap in the concept of the relationship between development on the one hand and environmental considerations. Sustainable development expresses the desire to resolve difficulties. Its objective is to maintain a certain quality of the environment and living conditions favourable to the survival of the human species for future generations without compromising that of present generations. It is an alternative to the economist's vision of development based on a belief in the unlimited availability of resources and faith in science and technology to solve all problems. By 2030, the world population will increase by three billion people, 95% of whom will be in developing countries. Food production will have to double, and waste and effluent production will increase in cities. Without sustainable practices, economic growth can lead to excessive degradation of natural and social resources. Therefore, public authorities are challenged to reconcile the contradictory pressures on natural and social resources without sacrificing economic progress.

Algeria follows a development model based on the use of fossil fuels that are limited and highly polluting. In recent years, Algeria has suffered a financial crisis due to its dependence on a single resource, whose income has dropped. This has had serious consequences for the national economy and daily lives of citizens, thus putting the future of the country in an uncertain situation. It should be noted that the number of people in the world's population will grow to 3 billion over the next 50 years by the year 2030, 95% of those in developing countries. The world will have to double its food production rate, and food, waste, and effluent generation will increase even further in cities, which is disturbing. However, when economic development is not accompanied by sustainable measures, living standards can be overexploited along with natural and social capital. Thus, public authorities are faced with the task of meeting the conflicting demands of natural and social staff without negating development (Farinet and Niang 2004).

Using the case of Algeria, research has identified that the country has adopted a development model that heavily relies on the use of fossil fuels, which are finite and environmentally unfriendly. In the recent past, Algeria has been facing certain financial problems because the country has been exploiting only one resource and the returns derived from it have reduced. This has led to a soaring national economy, coupled with a total change in the daily lives of citizens, putting the future of the country at stake. This research is part of a relatively long process of research and analysis; it relies on several academic journals that dis-cuss sustainable development in Algeria, in addition to the official papers that were read. This paper is comprised of three main sections. The first part presents the precedent principles and basic concepts of sustainable development based on a scientific literature analysis. The second part of the study considers the environmental crises and sustainable development challenges faced by Algeria. Finally, we focus on an attempt by the Algerian government to achieve sustainable development.

Key issues Algeria facing

Environmental Challenges: Algeria's dependence on fossil fuels has led to widespread pollution, resource depletion, and a vulnerability to climate change. "Without sustainable practices, economic growth can lead to excessive degradation of natural and social resources." The consequences of industrial and household waste mismanagement, soil contamination, and water scarcity have created a precarious situation for both ecosystems and human health.

Economic Instability: The overreliance on fossil fuel exports has exposed Algeria to economic shocks, particularly when global oil prices decline. This has restricted fiscal capacity to invest in non-oil sectors, resulting in unemployment and reduced purchasing power for families.

Social Inequities: The combination of poverty, illiteracy, and uneven access to resources has heightened disparities between urban and rural areas, creating barriers to equitable development.

Government's response and strategic objectives

Recognizing these interlinked challenges, the Algerian government has undertaken a series of initiatives aimed at transforming its development model. Key actions include:

Promoting Renewable Energy: Through the National Renewable Energy and Energy Efficiency Program, Algeria seeks to reduce dependency on fossil fuels and expand its renewable energy portfolio. Between 2014 and 2017, the government constructed several photovoltaic solar plants to boost clean energy capacity.

Enhancing Water Resource Management: The government has adopted a Water Sector Development Strategy for 2030, focusing on desalination, infrastructure development, and equitable water access to combat scarcity.

Fostering Sustainable Urbanization: Urban planning reforms prioritize energy efficient housing, sustainable transportation, and green building codes to address the rapid pace of urbanization.

Biodiversity and Ecosystem Conservation: Algeria has expanded its network of protected areas and launched reforestation programs to mitigate deforestation and land degradation while safeguarding biodiversity.

What Is Sustainable Development (SD)?

In 1987, the World Commission on Environment and Development adopted a definition of sustainable development that remains an international reference. Sustainable development meets the needs of the present without compromising possibilities for future generations. To meet their needs. However, the birth of this notion is linked to an awareness of planetary limits and definiteness of natural resources. In other words, it is a long-term vision that integrates ecological and environmental dimensions as well as economic, social, and human dimensions. The objective is to meet human needs without harming future generations by preserving natural resources, social equity, and economic equity (L 2021).

The Pillars of Sustainable Development

Social, economic, and environmental are the three systems of sustainable development known and acknowledged by the 1992 Rio Earth Summit. Ideally, these three (3) main pillars should be integrated. The idea is to reconcile the economic, social, and environmental dimensions to ensure sustainable viability (Godard 2015). An action could be part of sustainable development when it manages to reconcile three (3) E's: economy, equity, and the environment (Mulder 2017, SD 2019). In this spirit, sustainable development means achieving a balance between humanity and nature, the poor and rich, the present generation, and the future generations Fig. 1.

Figure 1. The three (03) pillars of sustainable development (Author)

Various environmental risks in Algeria

Environmental threats in Algeria

Algeria's geographic size is 2,381,741 km^2, ranking second to Sudan among African countries. Algeria is in north-western Africa and has a Mediterranean Sea border with a 1200 km coastline. The Saharan Atlas divides the country into two distinct zones: a population of almost the entire population of the northern Mediterranean region; the remainder is in the south, including the Sahara, which occupies 85% of Libya. The Algerian population is estimated at 44.7 million inhabitants (2020). The capital city, Algiers, has more than 2.5 million inhabitants. The climatic areas are diverse and the climate varies from Mediterranean to Saharan. Along the Mediterranean coast, there is a hot summer that is dry and has a mild and humid winter. In the north, winter is characterized by rain, whereas summer is characterized by heat. In the south, summer is characterized by rain, whereas winter is characterized by dryness, and the climate along the coast is softened by the sea. Eastern Algeria is a rainier region than the west, and its river network is strongly subject to a seasonal regime (wadis). During the rainy period, numerous depressions (chotts) form shallow lakes (BAD) (Attalah 2018). Algeria today faces enormous environmental problems of a global nature, concerning the globe in general, the issue of the country's natural resources remains a major concern and is far from what one might expect from such an area, since they are limited and weakened by climatic conditions increasingly accelerated by anthropological actions.

Pollution caused by household waste

Waste refers to any residue from a production process, transformation, or use, any substance, any material, any product, or, more generally, any movable property abandoned, or that its holder intends to abandon (vivant 2019, BDC 2023). Algerian regulations define household and similar waste as all waste, the elimination of which is handled by local authorities directly or through approved companies (Martinez 1998, Gueye 2010). Thus, the management of household waste in Algeria is highly efficient. The quantity of waste generated annually is estimated to be 5.2 million tonnes,1.2 daily. It is of the order of 0.5 kg per inhabitant of solid waste. In large cities such as Algiers, citizens generate approximately 1.2 kg of waste per day. More than two-thirds of the urban waste generated per inhabitant per day comprises of organic elements. Fig. 2 shows the percentage distribution of household waste in trashcans. Waste is deposited in illegal landfills that do not comply with the regulations. It is often incinerated in open air. In addition, these landfills provide a suitable biotope for the proliferation of stray animals (dogs, cats, rats, flies, and mosquitoes) that are vectors of diseases.

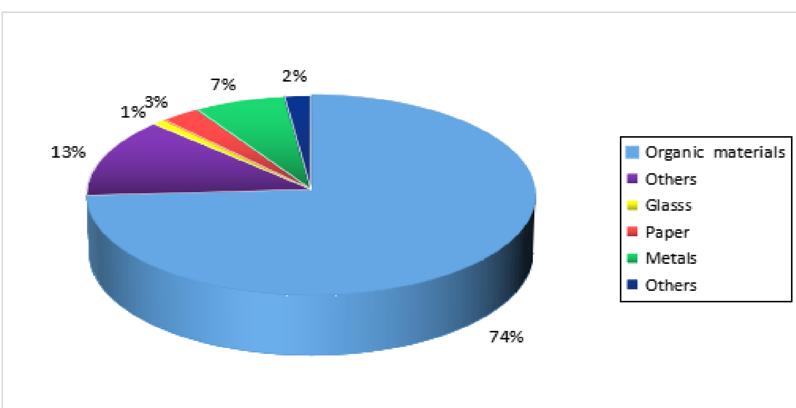

Figure 2. The average composition of household waste (PAC 2004, Medjitna 2021).

Industrial pollution

Algeria's industry has experienced sustained development in terms of its diversity and capacity Fig. 3. Steel and metallurgical industries account for half of the industrial activities. However, these issues have not been addressed in industrial processes. Before the promulgation of Law 83-18 of 1983 relating to environmental protection, industrial projects were conducted without environmental impact studies. Close to labour pools, communication routes, and amenities (Benadda 2004, Emmanuel 2004). This situation is harmful to the environment and public health.

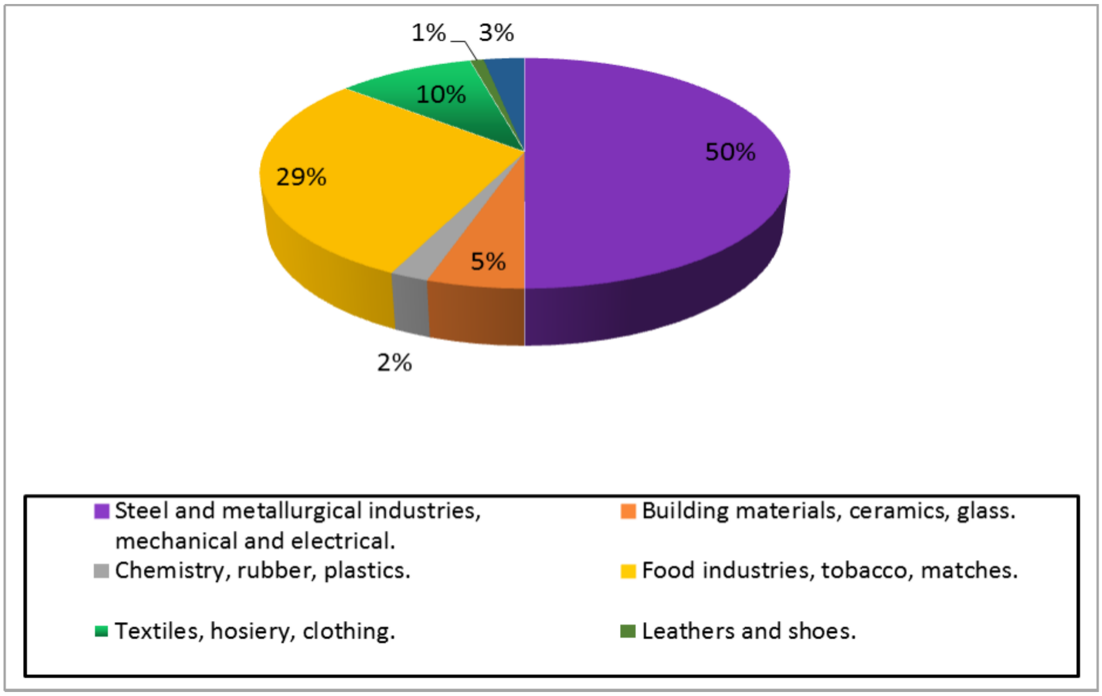

Figure 3. Waste production by major sectors of industrial activity (Mouhouche 2002, Medjitna 2021).

In addition, industrial activities produce toxic waste that can be recovered and stored with inefficiencies. They were evaluated in 1994 at approximately 185,000 tons per year, and the same study evaluated 344,000 tons of hazardous and toxic waste, including 90% in the Wilayas of Annaba and Tlemcen. In addition, all the hazardous waste produced is often stored in makeshift dumps under deplorable conditions. A large portion of this waste is found in nature, with all the risks of soil and water resource pollution. The Ghazaouet zinc electrolysis complex is expected to produce 40,000 tons of zinc, 90,000 tons of Sulfuric Acid (H_2SO_4), and 150 tons of cadmium per year. This is the origin of the significant release of heavy metals into the environment (Kehila 2006, Medjitna 2021) The analysis carried out in the region of Ghazaouet by the world organization "Greenpeace" on September 9, 1991, showed that lead, cadmium, mercury, zinc, and copper are found in more or less high concentrations, causing pollution of the soil and significant marine pollution.

Contamination of water resources

Water, an increasingly rare natural resource, is a part of the heritage of a nation in a specific way and the heritage of humanity in general. In Algeria, the issue of water resources remains a major concern because 95 % of the territory has an arid climate, aggravated by the risk of pollution, which renders the few resources available to the country unusable (Mouhouche 2002, Kehila 2006). Indeed, if water management is well controlled in the coming years, the water problem will be seen from the perspective of its quality and not just its quantity (Guouas 2002, Abdelaguerfi 2003). Cases of severe surface and groundwater pollution have been recorded throughout national territory. A study conducted by ANRH showed that industrial solid waste is generally disposed of along with household waste, making a significant contribution to the pollution of mobilization works, groundwater, and soil.

Soil contamination

It may also be regarded as a decline in the quality of soil due to anthropogenic utilization of the territory (Guassart 2001, RAC 2006). In Algeria, the issue of soil degradation is reported, which shows that it impacts a considerable portion of the agricultural lands as well as the steppe rangelands. It includes chemical, physical, and biological degradation, such as reduction in fertility, decline in aggregate stability, and salinity. Land degradation is widely used as an indicator of sustainability, as visual evidence of environmental degradation, and diminishing biological diversity (Kehila 2006, RAC 2006). For a long time, soil has played an important role in major biogeochemical cycles and the fate of polluting substances. It accumulates and provides plants and animals with most elements essential to life (air, water, natural elements, nutrients, etc.). In addition to its food function, soil can also constitute an effective environmental filter by purifying the water passing through it with various pollutants that can contaminate the food chain and groundwater. This complex environment raises important questions regarding its ability to retain elements, such as heavy metals.

There was, in fact, no beneficial legal regime for soil protection, but it was considered that the earth absorbed and “digested” everything (Catherine 1997, CNES 2000).

a. Either the critical load is exceeded or the soil no longer plays a buffering role so that pollutants penetrate the water table and rivers.

b. Pollutants accumulate in the soil to the point where a change in physical, chemical, and/or biological conditions results in their transfer.

Algeria’s journey toward sustainable development

Algeria’s approach to sustainable development has evolved significantly over the decades owing to its unique socioeconomic and environmental challenges. Below is the detailed historical context.

Post-independence industrialization (1960s–1980s)

Since its independence in 1962, Algeria has undergone many significant sociological, political and economic structural transformations. A development model based on socialism was immediately put in place with a desire to quickly achieve industrialization and an economic model close to that of Eastern European countries. This was able to see the light of the day and at one time gave the illusion that the country was on the right track only thanks to the hydrocarbon sector, the growth of which was conceived as a means of achieving rapid development through a heavy industrialization strategy. The oil counter-shock of 1986 and the debt crisis of the 1980s showed the limits of such a strategy as well as the fragility of the economy and its dependence on hydrocarbons.

Environmental Awareness and Legislative Foundations (1990s)

In June 1992, the government passed the Environmental Protection Act (1993) in Rio de Janeiro, Brazil. The United Nations Conference on Environment and Development (known as the Earth Summit) adopted a declaration that advanced the concept of the rights and responsibilities of countries in the environmental field. The Rio

Declaration on Environment and Development reflects two major concerns that emerged during the 20-year interval between the two conferences: the deterioration of the environment, including its capacity to sustain life, and the increasingly evident interdependence between long-term economic progress and the need for environmental protection. This era was marked by increasing efforts to align policies with international environmental standards.

National Strategies and Integration of Sustainability (2000s)

Since the 2000s, the state has decided to react and invest in sustainable development in order to end the process of environmental degradation. This desire is also a consequence of the commitments made by Algeria to the international community, which requires, in particular, the translation of the binding provisions of the international conventions and protocols to which the country has adhered into its national legislation. The realization of this intention was initially achieved by the adoption of the National Environmental Strategy (SNE 2001-2011). The two main tools of this strategy are the law on the protection of the environment and sustainable development promulgated in 2001 and the national action plan for the environment and sustainable development, PNAE-DD (MATE, 2002).

Accelerating Environmental Reforms (2010s–Present)

Renewable Energies Development

While the share of RE in Algeria's energy mix is negligible today, policies and support mechanisms (with/without feed-in tariffs) have been increasingly established to develop RE. In 2020, Algeria created the Ministry of Energy Transition and Renewable Energy (RE) to set out an ambitious roadmap. The "National Program for the Development of Renewable Energies" aims to achieve a 30% RE contribution in the energy mix by 2035. The ministry aims to develop 1000 MW of electricity from solar power plants spread across 11 sites in the first phase, focusing primarily on solar projects. The target for the long run is placing 15,000 MW by using 2035. Algeria released its first renewable energy plan in 2011, targeting the installation of 22 gigawatts (40 percent of its generation capacity) of renewable energy sources by 2030. Rather, today, Algeria produces a mere 411 MW of renewables. However, officials said the new strategy described here should help revive efforts to get more than 1 gigawatt of solar power up and running by the end of year-end and a further 13 gigawatts in line by 2030.

The hydrogen development in Algeria

Transporting 20 years-old notion of solar north Africa to Europe, the DESERTEC project1 envisaged transmitting solar electricity from the MENA region to Europe using high-voltage direct current transmission in its original conception (EcoMENA 2023). Nevertheless, this ambitious project has suffered from partial abandonment because of difficulties in establishing electricity infrastructure for intercontinental links. On the contrary, increasing interest in the alternative pathway of solar-to-hydrogen energy conversion for its export has arisen (Cherigui, Mahmah et al. 2009).

Sustainable development constraints in Algeria

Algeria is currently led by a development model based essentially on limited natural wealth, ecologically very polluting, and an unfair sharing of wealth as well as the financial crisis that the entire country is facing generated by this dependence on a single resource whose income has fallen in recent years. This has had drastic consequences for the national economy and impacted the daily lives of citizens, thus putting the country's future in an uncertain situation (CI Faurie 2003). In light of this, Algeria attempted to overcome some of these obstacles (Ramade 2000).

1) Lack of integration in productive sectors.
2) The increase in unemployment and the deterioration of income and purchasing power for families.
3) The weakness of the agricultural and industrial base and the absence of a solid strategy.
4) Absence of material and moral incentives in the area of budgetary expenditure.
5) The problem of poverty and the increase in illiteracy.
6) Lack of effective economic institutions, competition, lack of efficiency, lack of specialization in vital areas, and lack of supportive policy (Kehila 2001, MATE 2002).
7) Money supply, which corresponds to the quantity of currency circulating in the Algerian economy, reached 19,918.39 billion dinars at the end of October, compared to 17,659.64 billion dinars at the end of December 2020. This growth is mainly due to the increase in the aggregate (coins and notes in current accounts, assets immediately usable as means of payment) by 16.41%, going from 11,901.82 billion dinars at the end of December 2020 to 13,854.50 billion dinars by the end of October 2021 (Khababa 2009, Benali 2017).
8) Term deposits increased by 5.32%, reaching 6,063.89 billion dinars at the end of October 2021, compared to 5,757.82 billion dinars at the end of December 2020 (BOA 2021, Mesbahi 2021). The evolution of demand deposits at the end of October 2021 was marked by a strong growth of approximately 23.54%, going from 4,210.00 billion dinars by the end of 2020 to 5,201.23 billion dinars by the end of October 2021. The increase in demand deposits is mainly due to the growth in demand deposits in Sonatrach (Nassim 2019).
9) A stronger than expected fall in energy prices could reduce authorities' ability to support the dinar, thereby posing an upside risk to inflation forecasts.
10) According to the World Bank, the Algerian multidimensional poverty rate has increased from 2.1% to 1.4% between 2013 and 2019. “Algeria's 1.4% MPR is better than its regional neighbours: Egypt (5.2%), Iraq (8.6%), Morocco (6.1%), but not Tunisia, with a comparably better low rate of 0.8%) (Bank 2021)”
11) The MPI has shown that the most disadvantaged areas of the country have been cut off, even though there are some differences. The Central Highlands, the Hauts Plateaux-Ouest, and the South Region, with recent poverty rates of 4.4%, 2.6%, and 2.3%, respectively, underwent a remarkable improvement in poverty, but still remained behind the other four Algerian regions. In light of this, if we distillate the differences between urban and rural areas, we see that the poverty rate in 2019 was four times higher in rural areas than urban ones. There were no significant differences between the two survey cycles for men and women (Mesikh 2014, Bank 2021).

National context and strategy

The effects of climate change on natural and human systems are now clearly perceptible, and recurrently lead to climatic anomalies and extreme phenomena. These changes are inevitable in the scientific community. Algeria is located in an area that is particularly vulnerable to climate change. Estimates from the Intergovernmental Panel on Climate Change (IPCC) predicted a rise in temperature of approximately 2°C, drop in precipitation, and increase in the frequency of extreme events. While the country is already faced with a deficit in its water balance and sometimes a degradation of ecosystems, the analysis of vulnerability to climate change conducted on a national scale has highlighted the threats facing Algeria in the face of climate change. These include:

1) The reduction in agricultural production is leading to a risk of food insecurity given the strong dependence of Algerian agriculture on rainfall.
2) The limitation in quantity and quality of natural resources and the increase in water stress.
3) The degradation of coastal areas, with a potential rise in sea levels and destruction of fishing activities.

4) The resilience and adaptation capacity of forests, which have diminished and caused a major disruption of biodiversity.
5) Natural hazards such as earthquakes, floods, landslide phenomena, rising groundwater from desert palm groves, wind sand, etc.
6) Technological tools that threaten inhabited areas, in particular gas and hydrocarbon exploitation sites as well as energy product processing facilities (CDER 2015, RNVA 2019).

Faced with these challenges, which compromise sustainable development, Algeria decided in line with the 2030 Agenda to adopt a strategic policy aimed at:
1) The integration of climate change into policies and strategies at all levels.
2) Improving education and raising awareness about adaptation to climate change and mitigation of its impacts.
3) Strengthening resilience to climatic hazards and related natural disasters.

Adaptation of town planning

To prevent natural and technological hazards, urbanization programs in line with the spirit of urban planning instruments (the master plan for development, urban planning, and land use plans) are undertaken by considering the results of periodic geotechnical and vulnerability studies. These instruments set the fundamental orientations for the development of the territories concerned and determine the planning forecasts and rules. Specifically, they defined the conditions for development and construction to prevent natural and technological risks. Furthermore, more than three million buildings erected since 2000 have provided facade walls that are systematically made of double partitions of baked clay bricks (thermally efficient materials), and their terrace roofs are insulated with polystyrene. These measures aim to reduce energy consumption in homes to cope with climate change and limit atmospheric carbon dioxide emissions. The ministries in charge of housing and energy jointly initiated a project of 600 high energy performance housing units located in 11 wilayas representing all climatic zones in the country. Other actions are being undertaken and are expected to be generalized, such as the use of materials that allow for better energy efficiency, the use of low energy lamps in all new housing programs, the introduction of renewable energies in buildings, and the use of photovoltaics for public lighting.

Resilience to flood and forest fire risks

In 2016, the government adopted a national flood control strategy. It comprises of five main axes which are given below:
Improving knowledge of the risk of flooding and strengthening awareness of these risks.
1) Reducing vulnerability.
2) Review of Flood Protection Structure Planning.
3) Sustainable territorial development.
4) The water resource sector plays an essential role in promoting institutional cooperation and coordination.

This strategy is broken down into an interministerial plan aimed mainly at ensuring the safety of people in areas exposed to flooding, particularly through the construction of flood control dams to dissipate floods, the establishment of early warning systems for floods (Sidi Bel Abbes, Skikda, and El Harrach), the development of wadis, and the protection of towns and urban agglomerations. At the regional level, each hydrographic region has a water resource development master plan that defines strategic choices to ensure the prevention and management of risks linked to exceptional natural phenomena such as drought and floods. Furthermore, in the field of the protection of national forest heritage, a certain number of awareness raising actions and preventive work were

carried out by the forest administration and other organizations traditionally involved in the related system before the launch of each forest protection campaign against fires.
The Forest Sector Strategy for 2035 supports actions related to the mitigation and adaptation to climate change, particularly in terms of in situ and ex situ conservation. Algeria has made efforts to safeguard and extend the network of protected areas, in particular the National Parks, increasing from 165,361 ha to 194,932 ha in 2019. These ecosystems protect forest and plant cover in a manner that contributes to carbon sequestration. In addition, operational committees are set up at the level of each layout as well as at the level of daïras and communes. Their role is to coordinate intersect oral control operations in accordance with the forest fire plan approved by territorially competent "Wali". Local residents' committees have also been established to strengthen the organizational systems of local authorities (CDER 2015).

Encourage energy efficiency measures

The government has decided to integrate the energy efficiency component into the management of the activities of the Sonatrach oil group, following a diagnostic program for industrial units to bring installations up to standards in terms of energy efficiency. This decision is part of a series of measures, identified by the IPCC, to combat climate change. Furthermore, as electricity production is primarily based on natural gas, the Sonelgaz Group has contributed to GHG mitigation efforts for several decades. The development of the electricity production capacity of the group was based on the development of combined cycle, solar, and wind power plants. The Sonelgaz group determined actions aimed at further reducing the emissions from old power plants. These actions are in addition to the positive impacts of efforts to rejuvenate the production fleets. The conversion of diesel power plants into natural gas in localities covered by the national gasification program is also planned.

Reduce flares and greenhouse gas (GHG) emissions

The oil group Sonatrach continues to implement its program to eliminate flared gas. In addition to the government's introduction of a tax for flaring associated gases, several actions and projects have been implemented for this purpose, such as gas compression and reinjection facilities, 32 flared gas recovery projects, and one CO_2 sequestration project. These actions have enabled considerable reduction in Greenhouse Gas (GHG) emissions. Thus, since 1973, the flaring rate decreased from 78.6% in 1970 to 8% in 2016. This reduction effort will continue and be supported through the registration and implementation of new gas recovery projects in oil installations. And gas industries to reduce the rate of gas flaring to less than 1%, as provided for in Algeria's Nationally Determined Contribution (CDER 2015).

Achievements and level of achievement of the objective

Rehabilitate and safeguard terrestrial ecosystems and enhance their services

In 2016, Algeria established a forest sector development strategy for 2035, which is structured around three main axes, in this case sustainable management of forest heritage, defence, and conservation. Land restoration, conservation of floristic and faunal genetic resources with a view to their sustainable use and development, and the development and promotion of ecosystem goods and services within the framework of sustainable socioeconomic development. In this context, a forest heritage rehabilitation program, covering 39 wilayas, was implemented. It consists of the implementation of actions intended mainly for the restoration (renovation and reconstitution) and protection of forest stands.
As part of the sustainable use of freshwater ecosystems, the fishing sector implements actions linked to:

1) Raising awareness of the benefits of integrating fish farming into agriculture in terms of job creation, diversification of production and income, and soil fertilization through the use of water from fish farming.
2) Launch of pilot projects in aquaponics and above ground aquaculture associated with plant production on an experimental basis.
3) Increasing production through the exploitation of other underground water potentials (drilling), particularly in arid and semi-arid zones, and significant potential of operating dam sites.

As part of ecosystem protection, Algeria has made sustained efforts to classify spaces as protected areas that extend over a total area of 219,332 ha. The national network of protected areas thus includes ten national parks (Taza, Gouraya, Djurdjura, Belezma, Djebel Aissa, Tlemcen, Theniet El Had, Chréa, El Kala, BaborTababort, classified in 2019), five cultural parks (Tassili n'Ajjer, Ahaggar, Saharan Atlas, Touat Gourara, and Tindouf), one nature reserve (Cap Lindles), and four hunting reserves (Djelfa, Mascara, Tlemcen, and Zéralda), whose missions are the rehabilitation, multiplication, and development of native wildlife. Internationally, eight protected areas are classified as biosphere reserves within the framework of the Man and Biosphere Program (MAB/UNESCO), covering a total area of 14,191,883 ha, and 50 wetlands are classified on the Ramsar list (Ramsar 2022). International importance over an area of 2,981,421 ha and 21 Important Plant Areas in the Southern and Eastern Mediterranean: Priority Sites for Conservation (Concept of the International Union for Conservation of Nature (IUCN)) over an area of 2,611 ha (2016). Since the launch of the PNR in 2000, 809,877 ha of plantations have been planted, of which 485,225 ha are forest. These plantations account for 64% of the PNR objective, which aims to reach 1,245,900 ha by 2020. However, these plantations have enabled the reconstitution of heritage sites degraded by various factors, including repeated fires, grazing, and land clearing (IUCN).
Thus, it is not a question of plantations extending the wooded cover but of the densification and rehabilitation of existing woodlands. Thus, the forest area can be considered unchanged until the commitment of the new National Forest Inventory (CDER 2015). The achievements recorded by Algeria has also affected the level of safeguarding sites that are important for terrestrial biodiversity. Hence, with reference to international indicators, the proportion of sites that are important for terrestrial biodiversity and are located in protected areas increased from 24.6% in 2000 to 38.8% in 2018. The same is true for sites that are important for freshwater biodiversity, the proportion of which increased from 15% in 2000 to 49.0% in 2018 (CDER 2015).

Ensuring sustainable forest management

To ensure sustainable forest management, Algeria has identified and implemented the following actions:
1) Nearly 173,000 ha of forests have benefited from development studies with a target of 1,540,000 ha by 2030, which largely include restoration aspects sustainable.
2) A palliative measure was put in place in the absence of forest management studies through the adoption of simple management plans. This process resulted in the validation of five simple management plans covering an area of 7,269 ha, and eight simple management plans covering 10,619 ha are being validated.
3) Capacity building for forest administration field managers in the development of simple management plans in a ‘training through action’ mode.

However, establishing a consensus indicator for sustainable forest management is difficult. The United Nations recommends the use of four sub-indicators, each of which refers to a particular dimension of National Forestry Strategy. The international database reveals a non-decrease in these sub-indicators over the last decade, which would be a sign of forest management with a view toward sustainable development, although progress is slow and sometimes insignificant. It should be noted, however, that these indicators seem insufficient because they do not take into account, in particular, forest fires, which affect the increase in the area of forests. However, since

2000, Algeria has recorded 491,000 ha of land covered by fires (CDER 2015). Furthermore, these indicators do not consider the obsolescence of forest management.

Combat land degradation and desertification

A vast treatment program for 107 watersheds upstream of hydraulic structures is underway as a part of a policy to combat water erosion and soil conservation. This intervention plans to cover a territory of nearly 5.6 million hectares across 30 wilayas and 747 municipalities. Currently, 66 watersheds are being treated by essentially carrying out a volume of 1,300,000 m^3 of soil defence and restoration work (torrential correction, fixing of banks, stone lines, and low walls) and planting 89,000 ha, with a rate of progress of 84% in 2018. Another result to be achieved is the reduction of desertification and restoration of soils and degraded lands in pastoral regions (CDER 2015). To this end, the action plan was implemented and concerned 30 Wilayas and 723 municipalities, which has enabled the following achievements:

1) **Development and protection of ecosystems**: Nearly 31,900 ha of forest plants and 22,800 ha of fruit plants have been planted to maintain wooded spaces. Protection of economic infrastructure and agricultural land against silting. Therefore, 4,100 ha of threatened dunes were fixed at the level of the green dam area. Likewise, more than 2,600 ha has been developed, supplemented by water and soil conservation work by carrying out approximately 1.2 million m^3 of torrential correction, as well as 1,200 ha of bank fixation (CDER 2015).
2) **Pastoral development:** To improve fodder potential and regenerate natural resources, intervention in alfa layers and rangelands combined pastoral plantations on nearly 14,900 ha and fencing on 72,000 ha (CDER 2015).
3) **Improving the living conditions of populations:** More than 7,300 km of rural access roads have been built and 5,000 renewable energy kits have been developed with the aim of reducing pressure on natural resources as a source of energy (firewood in particular).
4) **Treatment (fixing) of the dune cordon of the Green Dam:** Between 2016 and 2017, 87 ha was treated for a target of 56,000 ha at the level of the Green Dam area, that is, a progress rate of 3% (CDER 2015).

Preserving and enhancing biodiversity and protecting areas essential for biodiversity

An important aspect of the forest sector's strategy is the creation of new protected areas. The establishment of protected areas is an important mechanism for safeguarding certain remarkable sites, including mountains and mountain ecosystems. Stems from a decline in biodiversity. The objective of 2030 is to have 13 sites between national parks and nature reserves for a total area of 1,283,480 ha, including five new sites to be classified as protected areas containing floristic and faunal genetic resources in view of their rational use and development. In addition to the eight national parks with areas of 165,361 ha, an effort to classify two new sites was recorded in January 2019 (Babor-Tababort National Park and Cap Lindles), bringing the total PA surface area to 194,932 ha. It should also be noted that four protected areas (Mazafran, Réghaia, Zemmouri, and the Chenoua protected area) were classified in accordance with Law No. 02-02 of February 5, 2002, relating to the protection and development of the coastline (PCAA 2005). There is a direct correlation between the vegetation cover of mountains and their capacity to fully play a role in the ecosystem. Therefore, the vegetation cover index of mountainous areas can provide an adequate measure of the conservation status of mountain ecosystems. Both climate change and deforestation can increase habitat vulnerability to shelter biodiversity. The overexploitation of the seas further accentuates this risk. Assessment of the state of biodiversity in the country using the Red List index necessitates a checklist of flora and fauna where the state is of concern. Endangerment status based on the classification made by the IUCN (International Union for Conservation of Nature). Information on the availability and quantity of

wild fauna and flora is scarce, given the lack of a national census, which is an important step for updating the data and introducing relevant conservation measures (CDER 2015).
Concerning access and benefit sharing (APA), in an inter-sectoral approach, the forest administration conducted a project in 2016 concerning 'The establishment of a national, legal, and institutional framework on access and use of genetic resources as well as the fair and equitable sharing of benefits arising from the use and knowledge of genetic resources in compliance with the Convention of Biological Diversity (CBD) and the Nagoya Protocol in Algeria. Another aspect of wildlife protection is anti-poaching and the fight against illicit trade in live animals through, among others, enforcement of the Convention on International Trade in Endangered Species of Fauna and Flora (CITES), which Algeria ratified in 1982. In addition, within the context of the program of Integrated Monitoring and Assessment of the Mediterranean Sea and its coastal zone launched by the Barcelona Convention for the protection. In the Mediterranean region, there is a national monitoring program for non-indigenous marine species (ENI) in Algeria. This program led to the production of a list of non-native marine organisms and a plan to monitor them.

Sustainable development and energy issues

It is now imperative both for oil producing countries and for oil consumers, as well as for global companies, to turn to alternative energy sources, with the conviction that fossil fuels, and more especially oil, are exhaustible energies on the one hand, and that it is the main factor in the increase in greenhouse gas emissions, and more particularly carbon dioxide, which further accentuates global warming, which induces sudden climatic disturbances that harm humanity (Cherif 2021). Today, with the substantial growth in internal energy consumption (+14%/year for electricity and 7%/year for natural gas), this energy model, which is based on an energy mix of 98% fossil fuels (30% oil and 68% gas), cannot be sustainable, and risks become completely irreducible in the near future if we do not react (Hadjam 2020). To resolve this problem, the government launched the National Renewable Energy and Energy Efficiency Program in 2011, elevated to the rank of national priority in 2016, but has not been followed by any tangible progress on the ground. A total capacity of 343 MW is provided by approximately 20 photovoltaic solar power plants built between 2014 and 2017 in the South and Hauts-Plateaux (Bounab 2020). According to an activity report carried out by the Renewable Energy Commission, the installed capacity of this type of energy in Algeria since 2010 has been approximately 400 MW. "The achievements of installed capacities in renewable energies between 2010 and 2019 are estimated at 390, or 1.8% of the 22,000 MW of the total capacity to be deployed by 2030. A simple comparison between the installed capacities for the production of electricity from gas and those based on renewable resources over the last decade highlights, that between 2010 and 2019. These installed mainly in the form of gas turbines practically doubled going from almost 11,000 MW in 2011 to almost 21,000 MW in 2019. That shows that all the priorities have been granted to the development of power production from natural gas during the last decade", contrary to the ambitious discourse on the preponderant place to be given to renewable energy (Nichane 2015).

Sustainable development and water management

Algeria is among the countries classified in the category of countries poor in water resources, with a water endowment of 600 m^3 per inhabitant per year. This is explained by the extent of the Algerian territory, covering 2,381,741 km^2, the majority of which (87%) are deserts where precipitation is almost zero. Ninety% of the surface water is located in the Tell region, which covers approximately 4% of the territory and is home to 65% of the country's population, estimated at 40 million inhabitants in 2016 (Nichane 2015). Algeria is subject to unfavourable physical and hydroclimatic conditions owing to its geographical location in arid and semi-arid zones. For several decades, Algeria has suffered from climatic hazards, including chronic droughts, shortages, and devastating floods, in addition to demographic and economic growth, with an increasing need for drinking, industrial, and agricultural water. The contribution of runoff to the surface water systematically decreased. Flows that are too low have the impact of insufficient filling of the existing dams (Nichane 2015).

To address this situation, the state has adopted a water sector development strategy for 2030 with the following main objectives:
1) Satisfy, quantitatively and qualitatively, the water demand of the entire Algerian population.
2) Ensure the availability of water for productive activities.
3) Preserve the living environment of citizens, water resources, and the environment.

This strategy is structured around the National Water Plan (PNE), Regional Water Resources Development Master Plans (PDARE), and National Sanitation Development Plan (SNDA). These strategic planning instruments set objectives and programs in terms of water access for different uses, sanitation, and resource preservation. The principle of sustainable development is enshrined in the main legal texts and instructions concerning land use planning, environmental protection, and the management and mobilization of water resources. The new Algerian Constitution of 2016 devotes through Article 19 the rational use of natural resources as well as their preservation for the benefit of future generations (Law No. 05-12 of August 4, 2005, relating to water completely reviews Algerian legislation in this area, with a view to implementing strategic management tools for the integrated management of water resources within the framework of sustainable development) (Hamiti 2021). During the period 2000-16 to a budgetary envelope of more than 50 billion USD for the implementation of a very ambitious development program, which was translated by the improvement in national indicators in terms of water resources.
Algeria has been set to mobilize water resources through the implementation of:
1) 80 dams with a storage capacity of more than 8.3 billion m^3, to which must be added five (05) dams currently under construction with an additional capacity of 300 million m^3.
2) 2,800 boreholes managed by Algérien Des Eaux (ADE) to strengthen and secure the drinking water supply, particularly for secondary towns and scattered areas, with a production capacity of more than 3,200,000 m^3/j.
3) Eleven large seawater desalination units, managed by dedicated project companies, with a drinking water production capacity of 2.1 million m^3/day, and four (04) units in the production stage project: two of 300,000 m^3/d each, one of 70,000 m^3/d and another 50,000 m^3/d.
4) 27 demineralization stations, in order to guarantee that available and quality drinking water meets current standards, particularly for the benefit of the populations of the localities of the “Wilayas” in the south of the country.
5) 21 major transfer and supply systems between the geographical areas of the country, to consolidate the principles of equity and universality of access to water to a total length exceeding 4000 km and a daily capacity of 2.9 million m^3 intended for the drinking water supply of 15 million inhabitants.
6) 127,000 km of the length of its drinking water supply and distribution network, whereas it did not exceed 55,000 km in 2001, making it possible to densify the network of the national drinking water network and reach homes located particularly in scattered areas or far from urban centres.
7) 14,365 reservoirs and water towers make it possible to mobilize 9 million m^3, thus ensuring regular availability of drinking water to populations.

Sustainable development and urbanization

Algeria has been through the process of adopting urbanization at an accelerated rate in the last two decades. The results from the general population and housing censuses in 1998 and 2008 represent Chantiers, which urbanized 58.3%, then 65.7%, an urbanization rate that has been estimated to be around 70%, including 751 urban settlements in which there is a constellation of urban areas. Of these, 279 are cities with at least 20,000 inhabitants (RNVA 2019). This rapid and continuous expansion poses significant challenges. It contributes to infrastructure congestion, housing and transport tensions, increased fuel consumption, and atmospheric pollution. Thus, the evolution of the number of households and the rate of urbanization by 2030 will generate annual housing needs of between 230,000 and 260,000 housing units, without counting the necessary operations to renew existing assets, particularly those built before 1962 (RNVA 2019). The consequences of this urbanization can be even more damaging given that several regions of Algeria with a high urban concentration are vulnerable and particularly exposed to major risks (earthquakes, floods, landslides, etc.) Finally, climate change, whether driven by natural or anthropogenic factors, accelerates people's and cities' exposure to natural disasters.

The government is fully aware of the problems faced by the people and has committed to the implementation of an urbanization programme aimed at improving urban living spaces and cities. The goals of this study are as follows:

1) Increased availability of high-quality housing at a lower price and improved basic services, especially transportation services in urban places.
2) A national urban policy that promotes a quality living environment for citizens.
3) Organized and controlled urbanization, including rebalancing at the national level of the urban framework.
4) Strengthening the resilience of urban spaces to natural disaster risks.
5) Reduce the negative environmental impacts of cities.

The government's efforts are also aimed at raising awareness and supporting industrial companies in respecting the national legislative and regulatory framework relating to environmental protection and the abandonment of manufacturing processes that are polluting or dangerous for health and safety environments (RNVA 2019).

Conclusion

It is necessary to write a long book to deal with the subject as complex and fascinating as the Algerian approach to sustainable development. Many things have not been covered in this article, but the essentials will have been mentioned in the sense that it has been highlighted that sustainable development in Algeria has not yet set a precedent, but that sustainable development believes it is possible, provided a certain amount of knowledge, from which we note that Algeria faces several constraints and challenges such as environmental pollution, economic growth rate, inflation, unemployment, and poverty. In the presence of inappropriate incentives, the pressures exerted on natural heritage by economic activities risk compromising its capacity for regeneration, thereby causing irreversible effects. Algeria has adopted a sustainable development strategy centered on the integration of the principle of environmental sustainability into various economic and social development programs by improving sustainable growth and reducing poverty at the lowest levels. However, Algeria continues to achieve its desired sustainable development objective. Therefore, as much to be gained for the North as for the South by submitting sustainable development to other reading grids, to other types of cultures, visions of the world as by confining it to an ethnicity that is for the moment largely Western, in the modern sense of the term and not of its past origin. A nation like Algeria, precisely geographically and culturally more Western than one would like to believe, like all the countries of North Africa, which is at the geographical and cultural crossroads between the majorities of the cultures of the world, could prove to be a formidable laboratory to attempt such an experiment.

Things seem to evolve in a direction that is difficult to determine for the moment. This means that everything is still possible for the moment, the fact is that, whatever happens, sustainable development cannot be invited to Algeria without having taken up the challenge of reconciling Algerian society with a notion as modern as it is traditional, that of the common good, and public space. More than ever, Algerian sustainable development must be involved in a work of mediation and reconciliation that is both original and inventive between Algerians, their ancestral local cultures, as well as their national identity, and of course, the spirit of a century that will surely see ecology take an increasingly important place in national and international political squares. For sustainable development, Algeria will have to commit itself to the path of this new modernity, which is as much linked to the past and the present as to the future.

Policy recommendations for Algeria

This review discusses several strategies, policies, and actions implemented by Algeria to address the challenges of sustainable development. However, it lacks a consolidated section with clear evidence-based policy recommendations that can address the gaps in current approaches. The policy recommendations are as follows:

Diversification of economic models

- The transition from fossil-fuel dependency to a more diversified economy by promoting sectors such as renewable energy, technology, and sustainable tourism.
- Establish financial incentives, such as tax benefits or subsidies, for industries investing in sustainable practices.
- Improve business management (particularly in environmental terms); transform or close the most polluting and financially least viable public companies.

Therefore, investing in environmental pros is economically profitable and facilitates Algeria's integration into the market economy.

Renewable energy expansion

- Accelerate the implementation of the National Renewable Energy and Energy Efficiency Program by setting measurable targets, increasing funding, and fostering public-private partnerships.
- Invest decentralized renewable energy projects in rural and underdeveloped regions to ensure equitable access to clean energy.

Integrated waste management

- Develop and enforce stricter regulations on waste disposal and recycling.
- Introduce community-based waste segregation and composting programs to reduce the burden on urban landfills.

Water resource management

- Desalination and water reuse projects should be expanded to address water scarcity.
- A detailed water resource assessment should be carried out in the High-Plateaux regions, with a view to rebalancing land use.
- Strengthening the capacities of the Hydrographic Basin Agencies, and carrying out major training programs in the areas of water management and sanitation for the Algerian Water Authority, National Sanitation Organization, and municipalities. The tariff instrument also constitutes a powerful conservation tool affecting both demand (behavior) and supply (cost coverage), and the completion of the tariff study and its gradual implementation also constitute a decisive aspect of a new policy.

Sustainable urbanization

- Promote green building codes and sustainable urban planning practices, incorporating Renewable energy, and efficient water use in housing projects.
- Develop public transportation networks to reduce emissions and ease urban congestion.

Capacity building and awareness

- Introduce educational campaigns emphasizing the importance of sustainability at schools, Universities and workplaces.
- Train local authorities and community leaders in implementing and monitoring sustainability initiatives.
- Instead of using old paradigm of agri-food self-sufficiency and achieve food security objectives through high value-added agricultural production, a sustainable irrigation policy, trade, and improving the rate of import coverage by exports.

Biodiversity protection

- Increased funding for the conservation of protected areas, national parks, and biodiversity hotspots.
- Formulated a legal framework for the participation of the local and riverside populations and other partners in projects related to the conservation of natural capital.
- Reduce waste production and introduce integrated waste management, both at institutional and financial levels.
- Improve the legal, institutional and environmental management frameworks, strengthen anti-poaching laws and promote community-driven wildlife conservation programs.

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RESEARCH ARTICLE

The nexus between energy consumption, financial development and ICT: A panel data analysis

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Abstract

This study explores the relationship between financial development, energy consumption and information and communication technology (ICT) in a sample of 83 global countries for the period of 1990 to 2020. By employing generalized method of moments, the findings shows that there is a long run co integration financial development, ICT and renewable energy consumption. This study reveals that in standalone, emerging, and developed financial markets, the development of the financial market and its associated factors, encompassing market depth and accessibility, play an important role in promoting the usage of renewable energy. However, in frontier financial economies, a contrasting trend is observed, where financial market efficiency is associated with lower utilization of renewable energy. Furthermore, the non-linear and moderating impacts of financial market growth on renewable energy adoption vary across nations with different financial market development stages. this study further provide important policy suggestions for the sample economies in context of ICT, financial development and renewable energy consumption.

Keywords: Financial development; ICT; financial market development; renewable energy

Introduction

A growing population, industrialization, and rapid technological development contribute to the increased demand for energy in terms of consumption and production. On a global scale, the predominant sources of energy are fossil fuels, such as coal, natural gas, and oil. Since fossil fuels can be produced relatively readily and cheaply, they have been widely used over the last 200 years. The utilization of fossil fuels also upsurges the chances of pollution (YILMAZ, 2012). Nations are increasingly dedicating their endeavours to fostering renewable energy sources and diminishing their reliance on non-renewable energy resources. This shift is propelled by the detrimental environmental consequences and the finite accessibility of fossil fuel reserves. The sources of renewable energy encompass solar power, hydroelectric energy derived from waves and streams, wind power, geothermal energy, biomass energy, and the energy harnessed from ocean waves. These sources are often perceived as sustainable due to their ease of generation, cost-effectiveness, and rapid returns on investment (ÇAKIR, 2010).

In this context, researchers are actively investigating approaches to alleviate the potential economic repercussions linked to environmental pollution caused by the emission of greenhouse gases resulting from the utilization of energy sources derived from fossil fuels. The prevalence of adverse externalities and assorted macroeconomic expenses resulting from worldwide contamination of the environment has focused the focus of academics and policymakers on the effective utilization of renewable energy resources. Renewable energy, compared to non-renewable counterparts, may exhibit a greater dependence on the stability of a robust financial system due to the relatively higher investment requirements associated with renewable energy projects. Enhancements in a nation's financial infrastructure mitigate the investment costs related to renewable energy initiatives, consequently promoting the adoption of environmentally sustainable energy resources. By fostering an environment of reliable environmental investment through advancements in the financial system, projects centred on installing and utilizing renewable energy resources gain enhanced efficacy and efficiency. In the coming years, the continuous establishment of a resilient financial market is poised to significantly bolster the use of renewable energy sources in the long run. It warrants attention that numerous emerging economies predominantly hinge on energy resources, entailing substantial raw material imports, including oil and natural gas, resulting in substantial outflows of foreign exchange. The utilization of renewable energy sources, characteristically heightening both energy consumption and productivity, presents a viable alternative, and could yield considerable foreign exchange savings that could be redirected towards financial markets, fostering their diversification and deepening. Hence, the anticipated foreign exchange savings generated by the usage of renewable energy sources play a substantial role in improving the economic condition of these countries. Additionally, it's important to highlight that financial development supports economic growth, fosters competition, and encourages innovative initiatives, ultimately leading to dynamic improvements in productivity. Numerous investigations in the vast realm of academic literature have delved into the relationship between the utilization of non-renewable energy and financial growth. Yet, it is worth highlighting that within the domain of energy economics, there has been a distinct lack of comprehensive investigations addressing the ramifications of financial advancement on renewable energy use. The present research carries significant weight in addressing this gap within the existing literature by providing a discerning insight into how a nation's financial progress influences the usage of renewable energy. Our research, in particular, emphasizes the expansion of financial markets, acknowledging it as a significant indicator, as affirmed by (Sadorsky, 2010, 2011). It's worth highlighting that limited prior investigations have employed market-oriented financial development measures to examine their implications on adopting renewable energy. Furthermore, the majority of prior studies have relied upon one-dimensional measures to gauge financial market development, despite its inherently multi-faceted nature, as corroborated by (Svirydzenka, 2016). The earlier studies have ignored the effect of ICT and energy consumption in the presence of heterogenous financial market stages and non-linearity of financial market for 83 economies. To fill this gap, we argue that financial market structure is a framework that takes ICT, energy consumption, and environmental risks into account. If the financial market is strong, it can benefit the environment through different ways. The ICT sector can improve the environment by investing in green technologies, smart infrastructure, and advanced environmental monitoring. Collaboration with environmental organizations and responsible e-waste management practices, including recycling, can further contribute to environmental sustainability. The energy sector can improve the environment by using funds from the financial market to invest in renewable energy projects, support clean technology research, and promote energy efficiency initiatives. This helps reduce carbon emissions and advances environmental sustainability. This study adds to the existing body of knowledge in several distinct manners: (i) This research delves into the impact of financial development stages on renewable energy across 83 countries during the timespan from 1990 to 2020. Moreover, the study divides the growth of the financial market into sub-measures, which are; financial market depth, accessibility, and efficiency. These aspects are complicated and warrant a comprehensive examination of their individual effects on the utilization of renewable energy. (ii) Secondly, this research explores the intricate, non-linear impact manifested by the expansion of financial markets on the adoption of renewable energy sources. (iii) Thirdly, this paper delves into the intricate dynamics of how the stages of financial development within countries interact with ICT to shape the consumption of renewable energy. (iv) Fourthly, the study investigates whether the interaction between financial development and energy consumption amplifies or mitigates its influence on the utilization of renewable energy and (v) whether this influence exhibits significant regional variations. In this investigation, the Instrumental Variable Generalized Method of Moments (IV-GMM) is employed as a potent analytical instrument to tackle issues concerning variable bias and endogeneity. The paper's framework is unveiled as follows: Section 2 is the comprehensive review of the existing literature, whereas Section 3 immerses into the details of the methodology and the data utilized. Moving forward, Section 4 encompasses the empirical discoveries and discussion, ultimately culminating in the presentation of conclusions and policy directives.

Literature review

The dynamic relationship between the widespread usage of renewable energy and the growth of financial markets has ignited a passionate discussion, emphasizing the critical imperative to reconfigure our financial systems in alignment with the pursuit of sustainable development. As highlighted by (Eren et al., 2019), the complex landscape of investments in renewable energy initiatives, characterized by formidable obstacles encompassing substantial initial expenditures, ongoing responsibilities for repaying long-term debt, and sustaining investments in research and development. Substantiate the substantial contribution, totalling a remarkable 42.42%, to the critical trajectory of renewable energy development in China, as they clarify the critical importance of financial market expansion in accelerating the advancement of renewable energy integration (Ji & Zhang, 2019). Their analysis underscores the chief importance of the capital market in this framework. Besides, (Le et al., 2020) delved into this symbiotic association by using a comprehensive dataset spanning 55 countries from 2005 to 2014. Their findings parallel those of (Kim & Park, 2016), especially in emphasizing the fundamental role of financial growth in fostering the renewable energy industry within high-income nations. Conversely, its role appears less pronounced in nations with low and moderate-income levels. They explicitly demonstrated that the progress of financial development is crucial in promoting the sustainable expansion of the renewable energy sector in developed nations. In contrast, its significance appears less pronounced in economies with modest or lower incomes. Conversely, (Raza et al., 2020) utilized the panel smooth transition regression (PSTR) method to investigate the intricate relationship between financial progress and the adoption of renewable energy sources in the world's primary energy consumers during the period from 1997 to 2017. Their findings shed light on how various aspects of financial development contribute to adopting renewable energy. (Alsagr & van Hemmen, 2021) examined emerging economies during the period 1996 to 2015. Using the system Generalized Method of Moments (GMM), their investigation unveiled a compelling link between the growing adoption of renewable energy and financial progress. (Shahbaz et al., 2021) they delved into the impact of financial development on the transition to renewable energy in 34 developing countries between 1994 and 2015. Their empirical results show that financial growth serves as a stimulant, promoting the renewable energy demand. (Denisova, 2020) examined the electricity usage in Germany and financial growth. The practical findings of this study shed light on a scenario where both economic growth and the influence of urbanization exert significant consequences on energy usage. In contrast, the influence of the growth of the financial market remains insignificant. In African nations (Sare, 2019) delved into the complex relationship between energy consumption and financial progress was explored in depth. This study revealed the efficacy of financial development by employing threshold estimation and a sample-splitting technique. It was found that energy consumption is encouraged by financial development when the financial development index is below a certain threshold. Nevertheless, as this index surpasses the threshold, the stimulating effect experiences a gradual attenuation.

Research on the intersection of ICT and renewable energy can be classified into two main groupings. The first group addresses the environmental consequences of renewable energy and ICT, as evidenced by studies such as those by (Charfeddine & Kahia, 2021; Hussain & Lee, 2022). The second viewpoint focuses on how information and communication technology (ICT) has an impact on the uptake and production of renewable energy. (Awijen et al., 2022) unveiled that the surge in the proportion of Internet users and ICT adoption is accompanied by raising the use of renewable energy. According to (Yu et al., 2023), ICT is now recognised as a helpful component in facilitating renewable energy utilisation. The complex link between ICT and renewable energy adoption in India and China, using both generalised method of moments and conventional least squares approaches. Their studies revealed that ICT has a considerable favourable influence on the use of renewable energy (Chowdhury et al., 2022). Conversely, (Bano et al., 2022) conveyed findings of an adverse relationship between adopting renewable energy and ICT. In China's shift towards renewable energy, (Li et al., 2023) identified research and development (R&D) and financial advancement as the fundamental driving forces behind the nation's energy transition. As explored in a research (Tzeremes et al., 2023), a comprehensive investigation unfolds, scrutinizing the intricate connections among economic progress, Information and Communication Technology (ICT), the transition towards sustainable energy, and CO2 emissions within the BRICS nations, ICT emerges as a significant avenue for advancing the energy transition and mitigating environmental challenges. The Information and Communication Technology (ICT) sector is enhancing the adoption of renewable energy in the South Asian region. This observation holds even when the proportion of renewable energy in the overall final energy consumption continues to increase. The research conducted by (Murshed, 2020) delves into the complex non-linear effects of Information and Communication Technology (ICT) development on renewable energy-related trade. (Saidi et al., 2017) extensively analysed data from 67 countries to examine the connection between electricity consumption and Information and Communication Technology (ICT). Their investigation unveiled that ICT significantly contributes to enhancing electrical power usage. Another study (Longo & York, 2015) explored the influence of ICT on energy consumption, and their results shed light on the fact that the widespread prevalence of telephones and mobile phones exerts a considerable influence on power consumption. (Lange et al., 2020) investigate four hypothesised processes by which ICT influences energy use: direct impact, energy utilisation enhancement effect, rebounding impact, and reforming impact. They discover that the direct contributions impact and rebounding impact are presently dominating, and ICT promotes increased usage of energy. Chinese data were used to experimentally assess the presence of direct contributing impacts and rebounding impacts of ICT. They discovered that technical advancement, changes in financial development, industrial structure, and human capital are major avenues via which ICT influences energy use (Ren et al., 2021). The second academic viewpoint is that ICT decreases energy use. Scholars who agree with the thinking that ICT may be effectively incorporated into social and economic endeavours while also contributing to energy waste reduction (Bastida et al., 2019; Collard et al., 2005). Information and Communication Technology (ICT) significantly promotes the growth of internet-based endeavors like remote work, virtual meetings, digital commerce, and electronic transactions. This shift from tangible to virtual operations saves substantial time and transportation cost savings and enhances energy efficiency, as illuminated by the research of (Zhao et al., 2022). ICT growth also helps with the fast growth of environmentally friendly financing, which has become a key policy instrument recently in major countries throughout the globe to lessen greenhouse gas emissions and energy consumption (Lv et al., 2021). This is because environmentally friendly finance necessitates a greater amount of environmental info than conventional financing. ICT serves as a catalyst in disseminating and disclosing environmental information, thereby mitigating the detrimental consequences of information asymmetry on the advancement of eco-friendly finance. Consequently, this leads to decreased energy usage, as explicated by the investigation of (Akomea-Frimpong et al., 2021). The earlier studies have ignored the effect of ICT and energy consumption in the presence of heterogenous financial market stages and non-linearity of financial market for 83 economies. To fill this gap, we argue that financial market structure is a framework that takes ICT, energy consumption, and environmental risks into account. If the financial market is strong, it can benefit the environment through different ways. The ICT sector can improve the environment by investing in green technologies, smart infrastructure, and advanced environmental monitoring. Collaboration with environmental organizations and responsible e-waste management practices, including recycling, can further contribute to environmental sustainability. The energy sector can improve the environment by using funds from the financial market to invest in renewable energy projects, support clean technology research, and promote energy efficiency initiatives. This helps reduce carbon emissions and advances environmental sustainability. How financial development influences renewable energy is likewise unclear. Because the integration of financial development with other industries alters the mode of functioning of social and economic operations, the influence of financial development might extend beyond its direct effects on renewable energy, potentially affecting renewable energy through alternative pathways, which have yet to be investigated by scholars. Therefore, to thoroughly comprehend the complex relationship between renewable energy and financial development across various markets, this study employs models that consider moderating effects to investigate the indirect processes and nonlinear patterns of the association between renewable energy and financial development.

Methodology

Following the model introduced by (Shahbaz et al., 2021), this study is conducted to examine the influence of financial development on renewable energy usage across various financial economies, including standalone, developed, frontier, and emerging markets. For this purpose, data from 83 countries were collected between 1990 and 2020. The complete sample was classified into emerging, developed, standalone, and frontier markets using the stock market categorization of Morgan Stanley Capital International (MSCI). As a result, the study is divided into 23 emerging financial markets, 29 frontier financial markets, 22 established financial markets, and 9 standalone financial markets. Used variables are: renewable energy (RE) was represented by the proportion of renewable energy consumption within the final energy consumption. Gross Domestic Product (GDP) serves as a representation of the growth in GDP per capita, while energy consumption is approximated by kilograms of oil equivalent per capita. The total population was used to estimate population, whereas total urban population was used to represent urbanisation. The dataset utilized for this analysis is drawn from the World Development Indicators provided by the World Bank. Additionally, the International Monetary Fund's (IMF) financial development index is employed in this study. The IMF development of financial market measures ranges from 0 to 1. This dataset outperforms the WDI development of stock market measures in various ways. Firstly, it covers many factors and gives multiple perspectives on financial market development (Svirydzenka, 2016). It also provides sub-measures for the development of the financial market, such as accessibility of the financial market, depth, and efficiency. This research scrutinizes an array of financial market indicators, providing a comprehensive view of financial market development. These encompass the broad spectrum of financial market growth (FD) along with distinct sub-indicators, including financial market efficiency (FEF), accessibility (FAC), and depth (FDE). For analysis purpose, firstly the descriptive statistics is analysed, following by cross sectional dependence (CSD) and slope heterogeneity tests. Further, the CADF and CIPS unit root tests, Pedroni cointegration and Westerlund cointegration and in the last instrumental variable generalized method of moments (IV-GMM) applied to this research data. In this empirical research to examine the linkages between above considered variables, we checked for cross-sectional dependence of the data which is a crucial factor to be determined before carrying out further analysis. Without checking for cross-sectional dependence can lead to inaccurate results. Therefore, we took into account (Pesaran, 2015) CSD test. The CSD equation is given by:

$$\mathrm{CSD} = \sqrt{\left(\frac{2T}{N(N-1)}\right)}\left[\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\widehat{\rho_{ij}}\right]$$

Furthermore, we applied (Pesaran & Yamagata, 2008) slope heterogeneity technique for considering problems related to the CSD. The equation of slope heterogeneity is given by:

$$\Delta = (N)^{\frac{1}{2}}(2k)^{-\left(\frac{1}{2}\right)}\left(\frac{1}{N}S - k\right)$$

The equation adjusted for biasness for Δ is given by:

$$\Delta_{\mathrm{Adj}} = (N)^{\frac{1}{2}}\left(\frac{2k(T-k-1)}{T+1}\right)^{-\left(\frac{1}{2}\right)}\left(\frac{1}{N}S - k\right)$$

After confirming these results, we can effectively ascertain the suitability of unit root analysis for our research investigation. Within this investigation, we incorporated (Pesaran, 2004, 2007) unit root test methodology to ascertain the stationarity of the dataset. Among the available methodologies, the choice of Pesaran's unit root test stems from its comprehensive consideration of both slope homogeneity (SH) and cross-sectional dependence (CSD) variables. Furthermore, within this study, (Pedroni, 2004) and (Westerlund, 2005) cointegration analysis emerges as the preferred approach to unravel the intricate connections between energy consumption, information and communication technology, financial market, and renewable energy for 83 economies. This preference is rooted in the limitations of previous methods, such as random and fixed effects, which fail to account for CSD in error terms, potentially leading to misleading test outcomes. In this intricate model the core structure of the model mirrors the framework proposed by (Shahbaz et al., 2021), the adoption of renewable energy (RE) serves as the dependent variable, while the growth of financial markets (FD), energy consumption (EN), the influence of information and communication technology (ICT), and a range of control variables (μ) function as the independent variables. By including fixed broadband subscriptions, fixed telephone subscriptions, the extent of internet utilization by individuals, and mobile cellular subscriptions, we construct an index for ICT in alignment with the methodological approach detailed by (Shehzad et al., 2022); we adopted their prescribed methodology for our study. In addition, we use reduced-form modelling to explore the impact of financial market development on renewable energy use. Therefore, empirical estimations were derived from the logged model as presented in Equation (1).

$$\ln RE_{it} = \beta_0 + \beta_1 \ln EN_{it} + \beta_2 \ln ICT_{it} + \beta_3 \ln FD_{it} + \beta_4 \mu_{it} + \beta_5 i_i + \varepsilon_{it} \quad \ldots\ldots\ldots..(1)$$

As argued by (Shahbaz et al., 2018) and (Acheampong, 2019), financial development may exhibit an intricate, non-linear connection with renewable energy use. This indicates the possibility of a curved, possibly U-shaped, or inverted U-shaped connection between financial growth and the utilization of renewable energy. Therefore, this research extends the work of (Shahbaz et al., 2018) and (Acheampong, 2019) by introducing the financial market growth quadratic term (lnFD2) into Equation (1). This is done to investigate whether the relationship between financial market growth and the use of renewable energy aligns with a U-shaped or inverted U-shaped pattern. We define the renewable energy consumption equation in Equation (2). This equation incorporates the square term of financial growth, facilitating investigating this complex relationship.

$$\ln RE_{it} = \beta_0 + \beta_1 \ln EN_{it} + \beta_2 \ln ICT_{it} + \beta_3 \ln FD_{it} + \beta_4 FD^2 + \beta_5 \mu_{it} + \beta_6 i_i + \varepsilon_{it}$$

(2)

The connection between the growth of financial markets and the utilization of renewable energy sources might display fluctuations instead of consistently uniform. Therefore, if β3>0 and β4<0, the link between renewable energy utilization and financial growth takes on an inverted U-shaped pattern. Conversely, when examining the relationship between financial market development and the adoption of renewable energy, it follows a U-shaped course if β3<0 and β4>0. As per the inverted U-shaped linkage, the initial phases of financial market expansion stimulate the consumption of energy from renewable sources, but at a specific level of financial market growth, renewable energy begins to fall. On the contrary, In the event that the U-shaped connection identified between the advancement of financial markets and the incorporation of renewable energy implies that the initial expansion of financial markets results in a decrease in the usage of renewable energy. However, beyond a certain threshold of financial market development, a subsequent resurgence in renewable energy utilization emerges.

To delve into the moderating effects of ICT and financial market growth (lnFD×lnICT), and energy use and financial market growth (lnFD×lnEN) on the use of renewable energy, we adapt Eq. (2) into Equation (3) and Equation (4). In this manner, we employ Equation (3) to analyse how ICT and the growth of financial markets (lnFD×lnICT) moderate the use of renewable energy. Similarly, we utilize Eq. (4) to investigate the moderating impact of energy use and financial market growth (lnFD×lnEN) in relation to renewable energy.

$$\ln RE_{it} = \beta_0 + \beta_1 \ln EN_{it} + \beta_2 \ln ICT_{it} + \beta_3 \ln FD_{it} + \pi_1 (\ln FD \times \ln ICT) + \beta_4 \mu_{it} + \beta_5 i_i + \varepsilon_{it}$$

(3)

$$\ln RE_{it} = \beta_0 + \beta_1 \ln EN_{it} + \beta_2 \ln ICT_{it} + \beta_3 \ln FD_{it} + \pi_2 (\ln FD \times \ln EN) + \beta_4 \mu_{it} + \beta_5 i_i + \varepsilon_{it}$$

(4)

where i = 1 to N, t = time, β0 is the constant parameter; β1 to B5 is the coefficient to be estimated; π1and π2 symbolize the indirect influence of financial development; ii is the separate influence; error term is denoted by εit; μ show controls includes population (lnPOP) and urbanisation (lnURB) used by (Salim & Shafiei, 2014) which have potential impacts on the use of renewable energy. All these variables are in log form.

Given the potential endogeneity issues connected with the renewable energy usage and financial development relationship modelling Eqs. 1-4 using traditional estimators, for example, fixed effects or Ordinary Least Squares (OLS), may provide inefficient findings. Furthermore, there are several additional factors that may influence renewable energy use; hence, omitted variables bias occurs if failed to account for such variables, providing conflicting and inaccurate findings. It should also be highlighted that based on markets, indicators of financial development undergo evaluation with significant errors, which might lead to weakened bias, leading the fixed effects and OLS estimations to fall.

Hence, the research employs the instrumental variable generalized method of moments (IV-GMM) technique to assess the influence of financial growth on renewable energy utilization. This approach addresses potential issues like inconsistencies, reverse causality, variable omission bias, and endogeneity. Furthermore, IV-GMM, by ensuring the orthogonality prerequisite, offers robustness against concerns such as autocorrelation and unforeseen heteroscedasticity (Baum et al., 2003). These methodological choices align with the study's goal of examining the impact of financial market growth on renewable energy use, necessitating the inclusion of stock market indicators. According to (Stock et al., 2002), it can be hard to identify suitable exogenous instruments. In this study, a unique methodology was implemented involving the utilization of financial market metrics as lag instruments for the financial market expansion measures under investigation. To ensure the reliability of these instruments, the analysis employs statistical tests, including F-statistics based on the Cragg-Donald and Kleibergen-Paap tests, along with the Hansen J tests. This thorough examination aims to validate the instruments' effectiveness.

Results and discussions

Preliminary tests

The descriptive statistics, definitions of the variables, and correlation matrix has been provided in Table 1A, 1B, 1C in Appendix A accordingly. According to Table 1A, the average renewable energy use is higher in developed markets, and frontier financial economies and lower in standalone markets and then emerging markets. The data also shows that developed markets have high financial market development averages and sub-measures, whereas frontier countries have low averages. Regarding the ICT (information and communication technology) average, emerging markets have the most, then frontier financial countries, while standalone financial markets have the least. The frontier markets have the highest average consumption of energy, which is followed by the emerging market, and standalone markets, while the developed markets have the most minor average usage of energy. These summary statistics give a good picture of the features of emerging, developed, standalone, and frontier markets. At this point in Table 2 the Pesaran CSD and unit root results are given. The cross-sectional dependence status determines the econometric model that will be chosen for the sample used. The CSD test, according to (Pesaran, 2004, 2015), can reduce bias from empirical conclusions derived from econometric techniques. There is a cross-sectional dependence among the panel units, according to the CD test results, which demonstrate the statistical significance at the level of 1%. After checking the CSD results and the values are significant, which means panels are dependent on each other. Similarly in Table 2, the SH test of (Pesaran & Yamagata, 2008) results confirms that all the models are highly significant thus by confirming the heterogeneity in the panels, we applied (Pesaran, 2004, 2007) CADF and CIPS tests given in Table 1 to handle the CSD and SH problems. The SH results for model 1-4 are given in Table 2 The result suggest that the panels are stationary at I(0) and I(1). The results of CSD, CADF, and CIPS are presented in Table 1.

Table 1: Pesaran CSD, CADF, and CIPS tests

Variables	Pesran CSD	CADF		CIPS	
	CD-test(p-value)	Level	t-statistics	Level	t-statistics
lnRE	169.302***	I(1)	-15.070***	I(1)	-4.745***
lnEN	42.922***	I(0)	-16.666***	I(1)	-4.895***
lnGDPC	27.905***	I(0)	-6.708***	I(0)	-3.481***
lnPOPT	.454***	I(0)	-8.312***	I(1)	-2.490***
lnUPOP	165.266***	I(0)	-7.080***	I(1)	-2.193***
lnICT	183.737***	I(1)	-4.901***	I(1)	-3.324***
lnFD	164.798***	I(0)	-4.271***	I(0)	-2.491***
lnFMA	92.647***	I(1)	-15.205***	I(1)	-4.633***
lnFMD	144.976***	I(0)	-2.616**	I(1)	-4.737***
lnFME	30.619***	I(1)	-13.046***	I(1)	-4.509***

Note: ***, ** show 1% and 5% probability

Table 2: Slope heterogeneity results

	M-1	M-2	M-3	M-4
	lnRE lnEN lnGDP lnPOP lnURB ICT FD	lnRE lnEN lnGDP lnPOP lnURB ICT FD FD2	lnRE lnEN lnGDP lnPOP lnURB ICT FD FDICT	lnRE lnEN lnGDP lnPOP lnURB ICT FD FDlnEN
	Statistics	Statistics	Statistics	Statistics
Δ tilde	39.889***	35.613***	20.530***	32.097***
Δ tilde (Adj.)	46.309***	42.274***	28.227***	38.596***

Note: *** is 1% significance

Table 3 shows the outcomes of our cointegration analysis. Both (Pedroni, 2004) and (Westerlund, 2005) cointegration results of Model-1 confirms the long run relationship between lnEN, lnGDP, lnPOP, lnURB, ICT, FD, and lnRE. In Model-2, we have included the non-linear impact of FD on renewable energy which is also significant. In Model-3, we have augmented the impact of interaction term of FD and ICT on renewable energy and confirms the long-run relationship whereas in Model-4, we included the impact of interaction term of FD and lnEN on renewable energy which is highly significant. In all four models, there is a long run relationship between lnEN, lnGDP, lnPOP, lnURB, ICT, FD, FDICT, FDlnEN, and lnRE.

Table 3: Cointegration results

	M-1	M-2	M-3	M-4
Pedroni cointegration	lnRE lnEN lnGDP lnPOP lnURB ICT FD	lnRE lnEN lnGDP lnPOP lnURB ICT FD FD2	lnRE lnEN lnGDP lnPOP lnURB ICT FD FDICT	lnRE lnEN lnGDP lnPOP lnURB ICT FD FDlnEN
Modified Phillips-Perron t	8.927***	10.489***	10.736***	9.905***
Phillips-Perron t	-7.550***	-7.917***	-10.616***	-4.374***
Augmented Dicky-Fuller t	-7.161***	-7.338***	-9.071***	-3.551***
Westerlund cointegration				
Variance ratio	-3.626***	-2.526***	-4.113***	-2.170***

Note: *** is 1% significance

After confirming the long-run relationship between the dependent and independent variables, we employed IV-GMM which is robust to variable bias and endogeneity. The results are given below.

Results of Emerging Financial market

The estimations for the emerging financial markets are shown in Table 4. M1 to M4, M5 to M8, and M9 to M12 depict the outcomes from Eq. (1), Eq. (2) and Eq. (3) respectively. At the 1% significance level, the anticipated coefficient demonstrates statistical significance regarding financial market development. Thus, renewable energy consumption increases by 4.433%, a 1% upsurge in financial growth. Financial market accessibility and depth significantly positively affect renewable energy consumption at 10% and 1%, correspondingly. According to this empirical conclusion, increasing financial market access and depth by 1% boosts renewable energy use by 0.825% and 2.788%. These outcomes align with the conclusions drawn by the study of (Samour et al., 2022). Notably, the influence of financial markets displays an insignificant effect on the use of renewable energy sources. The substantial influence of financial markets on renewable energy consumption in emerging economies is unsurprising, given the recent growth of their financial systems. Thus, the financial market in developing economies, like the financial market in developed countries, more effectively uses renewable energy by improving the governance of companies (Claessens & Feijen, 2007) while providing corporations with ethical and financial incentives to participate in energy-saving plans.

The coefficients of financial market expansion, depth, and their corresponding squared components in non-linear models present predominantly positive and statistically significant effects on adopting renewable energy. In the case of market depth, the effect is non-significantly negative. These findings suggest that the relationship between financial development and metrics like depth and accessibility follows a pattern similar to an inverted U-shaped curve. When these indicators reach a specific threshold, it decreases renewable energy consumption. Access to the financial markets and its square has positive and insignificant impacts on renewable energy use, but after a particular time, this effect increases. Financial market efficiency demonstrates a statistically insignificant negative influence on renewable energy, while the non-linear effect is statistically positive but also non-significant. This implies that as financial market efficiency increases, it progressively fosters the utilization of renewable energy. The connection between financial market efficiency and renewable energy appears to exhibit a pattern similar to a U-shaped curve.

The combined impacts of financial market growth and ICT and financial market efficiency and ICT show adverse influences on renewable energy utilization. These effects are statistically significant at the 10% and 1% levels in the interaction models. Consequently, the growth of the financial market and efficiency moderate ICT in emerging markets to reduce renewable energy usage. However, the results convey that in the moderating models, the results show that there is no significant impact on the adoption of renewable energy when considering the moderating role of ICT in relation to both market depth and market accessibility. Consequently, when coupled with ICT, financial market depth and accessibility do not contribute to promoting of renewable energy utilization. Furthermore, the findings suggest that ICT exhibits a statistically significant negative effect at the 1% significance level, leading to a reduction in the utilization of renewable energy. Specifically, for each 1% increase in ICT, renewable energy usage experiences a decrease ranging from 1.125% to 2.069%. These results align with the conclusions drawn by (Bano et al., 2022). In contrast, (Lee et al., 2023) reported a positive relationship between renewable energy consumption and ICT. The computed coefficient for economic growth demonstrates a significant adverse connection with the utilization of renewable energy. As economic development increases, businesses and individuals tend to use non-renewable sources in the beginning of economic development and don’t care about the environment. These outcomes align with the discoveries of (Ocal & Aslan, 2013) and deviate from the conclusions of (Wang et al., 2022).

In each model, the predicted coefficient has a statistical significance at a 1% level of consumption of energy. The calculated consumption of energy coefficient falls between 0.705% to 0.852%. As a result, energy use in emerging markets is both effective and sustainable, consequently enhancing the utilization of renewable energy. The findings of (Khan et al., 2021) are contradictory to these findings. Urbanization has a substantial impact on renewable energy consumption at the 1% significance level in each model. These results contrast with the empirical findings of the studies conducted by (Wang & Dong, 2021) and (Ali & Khan, 2023), which suggest that urbanization has a negative effect on the utilization of renewable energy, thus increasing carbon emissions. The foreseen coefficient about the population demonstrates a significant and stark negative association at the 1% level. Hence, the ongoing growth of the population in emerging economies is driving their energy consumption toward non-renewable sources like fossil fuels, leading to environmental deterioration. These findings align with the research conducted by (Vo & Vo, 2021). The F-statistics of Cragg-Donald and Kleibergen-Paap suggest that the instruments aren't weak, and the probability value obtained from the Hansen test suggests that the instruments employed for analysis are not over-identified.

Table 4: ICT, financial development, and renewable energy in emerging economies

	M1	M2	M3	M4	M5	M6
lnEN	0.819***	0.782***	0.728***	0.794***	0.833***	0.786***
	(0.069)	(0.073)	(0.071)	(0.074)	(0.068)	(0.075)
lnGDP	-0.233*	-0.256**	-0.288**	-0.247*	-0.206*	-0.255*
	(0.121)	(0.130)	(0.127)	(0.131)	(0.123)	(0.130)
lnPOP	-1.289***	-1.274***	-1.254***	-1.295***	-1.283***	-1.277***
	(0.035)	(0.038)	(0.037)	(0.036)	(0.034)	(0.039)
lnURB	0.490***	0.513***	0.494***	0.517***	0.442***	0.511***
	(0.048)	(0.050)	(0.047)	(0.051)	(0.054)	(0.049)
ICT	-1.807***	-1.740***	-1.780***	-1.626***	-1.716***	-1.739***
	(0.219)	(0.214)	(0.221)	(0.208)	(0.225)	(0.214)
FD	4.433***				21.177***	
	(0.996)				(7.309)	
FAC		0.825*				0.131
		(0.484)				(1.730)
FDE			2.788***			
			(0.507)			
FEF				0.317		
				(0.303)		
FD2					-17.238**	
					(6.952)	
FAC2						0.838
						(1.767)
FDE2						
FEF2						
FDICT						
FACICT						
FDEICT						
FEFICT						
Constant	9.343***	10.656***	10.323***	10.823***	6.265***	10.810***
	(0.872)	(0.918)	(0.825)	(0.867)	(1.610)	(0.969)
Observations	280	280	280	280	280	280
R^2	0.965	0.962	0.965	0.962	0.966	0.962
j	2.422	1.152	1.389	1.871	3.089	1.137
jp	0.120	0.283	0.239	0.171	0.079	0.286
F-statistics	3353.249	857.072	1722.010	1708.148	37.549	79.704

Table 4: Continued

M7	M8	M9	M10	M11	M12
0.705***	0.791***	0.852***	0.791***	0.722***	0.819***
(0.071)	(0.074)	(0.070)	(0.073)	(0.071)	(0.073)
-0.314**	-0.236*	-0.246**	-0.257**	-0.298**	-0.244*
(0.125)	(0.132)	(0.118)	(0.129)	(0.126)	(0.128)
-1.250***	-1.298***	-1.286***	-1.278***	-1.245***	-1.304***
(0.036)	(0.036)	(0.035)	(0.039)	(0.039)	(0.036)
0.501***	0.525***	0.465***	0.528***	0.493***	0.478***
(0.048)	(0.057)	(0.049)	(0.052)	(0.047)	(0.050)
-1.701***	-1.581***	-1.276***	-2.069***	-1.654***	-1.125***
(0.236)	(0.242)	(0.301)	(0.273)	(0.216)	(0.212)
		5.866***			
		(1.174)			
			0.635		
			(0.516)		
7.151*				2.957***	
(3.987)				(0.518)	
	-1.378				0.251
	(3.299)				(0.292)
-5.168					
(4.621)					
	1.465				
	(2.756)				
		-1.492*			
		(0.786)			
			0.826		
			(0.517)		
				-0.450	
				(0.454)	
					-0.992***
					(0.277)
9.599***	11.037***	9.050***	10.472***	10.275***	11.484***
(1.014)	(0.854)	(0.882)	(0.910)	(0.826)	(0.855)
280	280	280	280	280	280
0.964	0.962	0.966	0.962	0.965	0.963
1.583	1.819	2.003	1.053	1.287	1.528
0.208	0.177	0.157	0.305	0.257	0.216
46.795	19.436	1519.444	718.336	1523.618	1609.470

Note: Standard errors robust to heteroscedasticity are in brackets. Hansen J-statistics (j) assesses the strength of instrument identity, as indicated by the p-value of Hansen J-statistics (jp). The F-statistics, particularly the Cragg-Donald and Kleibergen-Paap tests, corroborate these findings. Collectively, the results from the Hansen J-statistics, F-statistics, and p-value affirm that the instrumental variables employed in this analysis are not weak or over-identified, *** $p < 0.01$

Results of Standalone financial economies

The outcomes for the standalone financial markets are outlined in Table 5. M1 to M4, M5 to M8, and M9 to M12 correspond to the conclusions derived from Equation (1), Equation (2), and Equation (3). The calculated coefficient for financial market growth and indicators, accessibility to markets (insignificant positive), and market depth significantly contribute to the adoption of renewable energy. Additionally, the findings emphasize the substantial differences in financial sector development between developing and developed nations, as corroborated by the study conducted by (Svirydzenka, 2016). For example, although stock markets in developed nations are usually well-functioning, they are still in their early phases in emerging economies of development, with tiny sizes and defective functions. This phenomenon introduces the possibility of disparities in how financial development influences the utilization of renewable energy, with potential variations emerging between developing and developed nations. These outcomes are consistent with the research conducted by (Shahbaz et al., 2021), while in contrast, (Assi et al., 2021) did not observe a significant effect of financial market advancement on renewable energy utilization. Additionally, it's worth noting that financial market efficiency exhibits a noteworthy significant inverse relationship with renewable energy usage is observed at the 1% significance level. Therefore, it may be argued that the growth of the financial market growth in its entirety facilitates the adoption of renewable energy. The outcomes indicate that the financial development stage in standalone financial markets is notably advanced, thus fostering the utilization of renewable energy sources.

However, the expansion of financial markets and the indicators linked to them exhibit a nonlinear influence on the adoption of renewable energy. Within these intricate nonlinear models, it becomes apparent that within standalone financial markets, a combination of significant positive and negative impacts on renewable energy consumption arises from growth of financial market, market depth, and respective squared components. Though financial market accessibility and efficiency, as well as squared terms, the usage of renewable energy exhibits both negative and positive impacts. This discovery substantiates the presence of a curvilinear link, resembling an inverted U-shape, between the utilization of renewable energy and the growth of financial markets and depth in standalone markets. As a result, total financial market growth and depth boost renewable energy utilisation, however, usage falls after these financial market indicators reach a specific benchmark. In contrast, a distinct U-shaped relationship emerges when we delve into the connections among financial market accessibility, efficiency, and the adoption of renewable energy. These financial market policies initially reduce renewable energy use, but at a specific limit, they enhance the usage of renewable energy.

Moreover, the moderating influence of ICT in conjunction with financial market indicators exerts a notably on the adoption of renewable energy, there is a consequential significant and negative impact. As the impact of the interaction between ICT and financial development, along with its subsidiary indicators, intensifies, it results in a noticeable decrease in renewable energy consumption. This suggests that the progress of financial markets complements ICT in influencing the renewable energy utilization within standalone economies. ICT has significant negative effects in models M1, M3, M5, M7, and M9 whereas significant positive effects in models M9 and M11. Whereas non-significant negative and positive effects in models M2, M4, M8 and M6, M10, M12 respectively. The negative results align closely with the discoveries of (Bano et al., 2022) whereas the positive results are similar with (Yu et al., 2023) respectively. (Haldar & Sethi, 2022) reported that the combined effects of ICT and financial development on carbon emissions are insignificant. In models M1-M4, M7, M8, and M12, the energy consumption coefficient demonstrates non-significant negative sign whereas negatively significant in model M11 at 1%. Furthermore, it is positive and non-significant in M5, M9, and M10 whereas significant positive in model 6 at 10%. (Khan et al., 2021) reported an inverse correlation between renewable energy and fossil energy. The coefficients related to economic growth exhibit non-significant results, both negative and positive, across all models except for model M5. Population estimated coefficient is negative and significant at

1% As a consequence, it results in a reduction in the utilization of renewable energy. Urbanization exerts a twofold effect, characterized by positive and negative consequences on incorporating renewable energy. These results align with the research outcomes of (Li & Shao, 2021), illustrating a similarity in their findings.

Table 5: Nexus ICT, financial market development, and renewable energy in standalone economies

	M1	M2	M3	M4	M5	M6
lnEN	-0.001	-0.094	-0.256	-0.247	0.201	0.910*
	(0.138)	(0.606)	(0.179)	(0.194)	(0.145)	(0.473)
lnGDP	-0.199	-0.091	-0.022	0.030	-0.403*	-0.196
	(0.178)	(0.284)	(0.268)	(0.292)	(0.212)	(0.141)
lnPOP	-0.829***	-0.921***	-0.749***	-0.893***	-0.836***	-1.383***
	(0.040)	(0.245)	(0.082)	(0.066)	(0.045)	(0.192)
lnURB	0.603***	0.728***	0.379	0.805***	0.416**	0.872***
	(0.160)	(0.251)	(0.313)	(0.210)	(0.169)	(0.165)
ICT	-1.610***	-0.249	-1.055**	-0.087	-2.888***	0.307
	(0.318)	(0.260)	(0.525)	(0.218)	(0.599)	(0.225)
FD	10.038***				99.895***	
	(1.525)				(27.571)	
FAC		1.331				-18.338***
		(4.141)				(4.925)
FDE			4.762**			
			(2.299)			
FEF				-5.901***		
				(2.270)		
FD2					-181.447***	
					(55.763)	
FAC2						44.408***
						(5.098)
FDE2						
FEF2						
FDICT						
FACICT						
FDEICT						
FEFICT						
Constant	5.008**	6.150	10.924**	5.714*	-1.728	4.141
	(2.267)	(4.821)	(4.554)	(3.374)	(2.832)	(3.624)
Observations	79	79	79	79	79	79
R^2	0.984	0.978	0.979	0.979	0.982	0.991
j	0.774	2.115	1.994	0.404	1.146	0.574
jp	0.379	0.146	0.158	0.525	0.284	0.449
F-statistics	992.124	27.957	140.545	37.274	11.450	7.864

Table 5: Continued

M7	M8	M9	M10	M11	M12
-0.166	-0.163	0.057	0.543	-0.431***	-0.252
(0.190)	(0.174)	(0.056)	(0.733)	(0.085)	(0.203)
-0.234	0.066	-0.018	-0.087	0.008	0.029
(0.280)	(0.226)	(0.112)	(0.248)	(0.165)	(0.292)
-0.766***	-0.934***	-0.984***	-1.191***	-0.716***	-0.893***
(0.082)	(0.071)	(0.039)	(0.303)	(0.056)	(0.067)
0.432	0.723***	0.339***	0.788***	-0.275	0.813***
(0.306)	(0.201)	(0.089)	(0.246)	(0.192)	(0.228)
-1.659**	-0.004	5.125***	0.654	3.803***	0.074
(0.787)	(0.226)	(0.952)	(0.416)	(0.883)	(1.679)
		0.012			
		(1.667)			
			0.630		
			(3.967)		
16.605*				-0.737	
(9.238)				(1.985)	
	-33.036**				-7.662
	(13.948)				(18.311)
-25.086					
(17.107)					
	39.467**				
	(18.852)				
		-18.269***			
		(2.086)			
			-7.306***		
			(2.389)		
				-20.227***	
				(2.598)	
					-2.803
					(28.992)
9.113**	8.446**	13.101***	4.432	23.839***	5.677*
(4.295)	(3.404)	(1.640)	(4.972)	(2.933)	(3.426)
79	79	79	79	79	79
0.979	0.979	0.993	0.980	0.989	0.979
1.488	0.750	0.000	0.678	1.012	0.392
0.223	0.387	0.994	0.410	0.314	0.531
11.004	8.135	262.942	28.774	91.547	3.228

Note: Standard errors robust to heteroscedasticity are in brackets. Hansen J-statistics (j) assesses the strength of instrument identity, as indicated by the p-value of Hansen J-statistics (jp). The F-statistics, particularly the Cragg-Donald and Kleibergen-Paap tests, corroborate these findings. Collectively, the results from the Hansen J-statistics, F-statistics, and p-value affirm that the instrumental variables employed in this analysis are not weak or over-identified, *** $p < 0.01$

Results of Developed Financial Economies

The estimations for the developed market economies are shown in Table 6. Eq. (1) is used for estimating M1-M4, Eq. (2) is used for estimating M5-M8, and Eq. (3) is used for estimating M9-M12. The findings indicate that the coefficient related to the growth of financial markets, as well as the depth and accessibility of these markets, holds statistical significance and demonstrates a positive impact at a notable 1% significance level.

Therefore, an escalation in financial market development and its associated indicators leads to an increase in renewable energy utilization by 3.863%, 1.538%, and 2.668%, respectively. These outcomes are consistent with the discoveries made by (Shahbaz et al., 2021). It is also noteworthy that the effectiveness of financial markets does not exert a significant effect on the acceptance of renewable energy. Conversely, the distinctly positive impact of financial market growth, depth, and accessibility underscores the propensity within developed markets for fostering the advancement of sustainable renewable energy technologies. These outcomes lend support to the supposition that well-established financial markets play a role in stimulating technological innovations in this domain that reduce the use of fossil fuels, thereby reducing environmental degradation (Zagorchev et al., 2011), as well as creating credibility for companies or business sectors to make investments in green-technological initiatives.

In the context of non-linear models, it's notable that financial market growth and depth demonstrate non-significant positive impact. On the other hand, there is a significant and positive impact on the adoption of renewable energy attributed to financial accessibility and efficiency. Additionally, it's worth highlighting that the squared term of financial accessibility reveals a noteworthy negative significance, in contrast, The coefficients for financial market growth, depth, and efficiency all yield non-significant negative results. The non-monotonic impacts demonstrate that financial market growth does not necessarily have a linear influence on renewable energy usage. This research is in accordance with the viewpoints put forth by(Shahbaz et al., 2018), emphasizing the curvilinear impact of financial development. As a result, within developed economies, a complex interconnection emerges, marked by a U-shaped relationship between the usage of renewable energy sources and the expansion of financial markets, their accessibility, depth, and efficiency. The ultimate results highlight that enhanced financial market accessibility and efficiency play a pivotal role in substantially increasing the utilization of renewable energy sources, whereas, in developed nations, the adoption of renewable energy exhibits a decline once particular financial market sub-indicators reach certain thresholds.

The moderating influence of advancement of financial market, accessibility of the market, and efficiency of the market demonstrates an adverse impact on ICT concerning its role in shaping the consumption of renewable energy. Additionally, the interaction variables involving financial market growth (lnFD×lnICT), access (lnFAC×lnICT), efficiency (lnFD×lnFEF) and ICT apply significantly negative influence on the usage of renewable energy at a 5%, 1%, and 1% level correspondingly. Hence, within developed financial economies, the progress of financial markets, their accessibility, and efficiency collaborates with ICT to restrict the utilization of renewable energy. This indicates that the allocation of financial resources to the ICT sector in these countries primarily hinges on significant amounts of fossil fuels, leading to detrimental environmental repercussions. Economic growth coefficient in all models is negative and non-significant. These non-significant findings are consistent with the observations made in earlier research conducted by (Bhuiyan et al., 2022; Chen et al., 2020). Furthermore, the outcomes reveal that the estimated energy consumption coefficient holds statistical significance in the models M1, M2, M4-M9, and M12 at 5% and 10% in all the models whereas non-significant positive in models M3, M10, and M11. These findings contradict those of (Khan et al., 2021). The estimated coefficient of ICT is negatively significant at 5% and 10% in models M1, M2, M3, M5, M6, and M7 whereas non-significant negative in models M4, M8, M10, and M11. The adverse impact of ICT on environmental harm corresponds with the findings of (Chang et al., 2022) whereas (Chowdhury et al., 2022) identified relationship between renewable energy and ICT. Furthermore, it is non-significant positive in models M9 and M12. Population estimated coefficient is significant negative at 1% in all the models. As a result, population growth combined with excessive usage of non-renewable energy sources may harm the environment in developed financial markets. In all models, the anticipated coefficient related to urbanization displays at the 1% level significance, except model M8, which is non-significantly positive. This study suggests that as urbanisation grows in developed nations, so will renewable energy usage. Both individuals and enterprises exhibit a predilection for adopting renewable energy resources as a means to protect and preserve their environmental surroundings.

Table 6: ICT, financial development, and renewable energy in developed economies

	M1	M2	M3	M4	M5	M6
lnEN	0.171**	0.145*	0.122	0.178**	0.220**	0.166*
	(0.085)	(0.086)	(0.084)	(0.088)	(0.089)	(0.087)
lnGDP	-0.129	-0.113	-0.186	-0.058	-0.239	-0.071
	(0.142)	(0.138)	(0.142)	(0.128)	(0.169)	(0.136)
lnPOP	-1.063***	-1.039***	-1.046***	-1.076***	-1.080***	-1.033***
	(0.047)	(0.046)	(0.046)	(0.050)	(0.048)	(0.047)
lnURB	0.246***	0.151**	0.240***	0.163**	0.253***	0.205***
	(0.073)	(0.070)	(0.071)	(0.070)	(0.072)	(0.073)
ICT	-0.415*	-0.544**	-0.384*	-0.339	-0.499**	-0.447*
	(0.235)	(0.273)	(0.231)	(0.252)	(0.209)	(0.271)
FD	3.863***				26.449	
	(0.857)				(17.567)	
FAC		1.538***				9.813*
		(0.396)				(5.083)
FDE			2.668***			
			(0.428)			
FEF				0.661		
				(0.413)		
FD2					-15.362	
					(11.765)	
FAC2						-6.866*
						(4.077)
FDE2						
FEF2						
FDICT						
FACICT						
FDEICT						
FEFICT						
Constant	12.232***	15.722***	13.462***	15.982***	4.106	12.573***
	(1.455)	(1.209)	(1.217)	(1.141)	(6.709)	(2.204)
Observations	285	285	285	285	285	285
R^2	0.942	0.940	0.944	0.938	0.944	0.939
j	0.067	0.416	0.079	0.001	0.169	0.447
jp	0.796	0.519	0.779	0.973	0.681	0.504
F-statistics	1793.013	1525.523	3053.757	455.957	27.010	24.339

Table 6: Continued

M7	M8	M9	M10	M11	M12
0.166*	0.168*	0.173**	0.131	0.121	0.209**
(0.097)	(0.086)	(0.085)	(0.086)	(0.084)	(0.091)
-0.282	-0.027	-0.170	-0.177	-0.202	-0.107
(0.185)	(0.128)	(0.142)	(0.141)	(0.143)	(0.127)
-1.063***	-1.065***	-1.067***	-1.030***	-1.047***	-1.082***
(0.050)	(0.048)	(0.048)	(0.046)	(0.047)	(0.051)
0.244***	0.109	0.252***	0.151**	0.242***	0.159**
(0.070)	(0.078)	(0.073)	(0.071)	(0.070)	(0.069)
-0.473*	-0.379	0.697	-0.056	-0.090	0.436
(0.251)	(0.254)	(0.592)	(0.317)	(0.353)	(0.311)
		3.671***			
		(0.818)			
			1.616***		
			(0.391)		
7.252				2.578***	
(5.690)				(0.401)	
	6.240*				0.245
	(3.656)				(0.378)
-3.505					
(4.262)					
	-4.598				
	(2.853)				
		-1.516**			
		(0.721)			
			-0.939***		
			(0.334)		
				-0.428	
				(0.417)	
					-1.288***
					(0.371)
12.148***	15.582***	12.326***	15.736***	13.527***	16.321***
(2.122)	(1.142)	(1.443)	(1.209)	(1.221)	(1.143)
285	285	285	285	285	285
0.944	0.940	0.942	0.940	0.944	0.940
0.091	0.028	0.022	0.566	0.076	0.158
0.763	0.867	0.883	0.452	0.783	0.691
28.355	10.764	1586.669	1440.689	2621.051	427.536

Note: Standard errors robust to heteroscedasticity are in brackets. Hansen J-statistics (j) assesses the strength of instrument identity, as indicated by the p-value of Hansen J-statistics (jp). The F-statistics, particularly the Cragg-Donald and Kleibergen-Paap tests, corroborate these findings. Collectively, the results from the Hansen J-statistics, F-statistics, and p-value affirm that the instrumental variables employed in this analysis are not weak or over-identified, *** $p < 0.01$.

Results of Frontier financial economies

The findings pertaining to financial markets in frontier economies are showcased in Table 7. M1 to M4, M5 to M8, and M9 to M12 represent the outcomes derived from Eq. (1), Eq. (2), and Eq. (3), correspondingly. The estimated coefficient for the growth, accessibility, depth, and efficiency of the financial market is 1%, which is negative and statistically significant. As the financial market growth and sub-measures increase by 1%, renewable energy usage reduces by 6.540%, 1.824%, 3.335%, and 5.632%, respectively. Our results are negative, which is in line with those of (Amin et al., 2022). On the other hand, research conducted by (Sadorsky, 2010) found that metrics tied to value traded and stock market capitalization, often referred to as market depth indicators, had no observable influence on energy consumption. This conspicuous negative impact of financial market expansion, depth, and efficiency pertaining to the reduction in the adoption of renewable energy resources within frontier markets alludes to the notion that the financial markets of these frontier countries exhibit fragility and inefficiency. In contrast to the established market, the immature financial market fails to foster good corporate governance, create inventiveness, or encourage businesses to adopt sustainable technological developments, and it lacks adequate legislation that ban enterprises from investing in non-renewable energy projects. As a result, the findings show that financial sectors might successfully assist the renewable energy industry, facilitating sustainable growth. As the results shows, the contribution of financial organizations in fostering the adoption of renewable energy can be depicted as a pivotal provider of enduring and significant financial backing. This monetary assistance empowers renewable energy firms to extend their activities and advance their technological proficiencies (Sun et al., 2023).

In compliance with the nonlinear models, it becomes apparent that the development of the financial markets, efficiency of financial markets, accessibility, depth along with their corresponding squared terms, noticeably have both positive and negative impacts on the usage of renewable energy within frontier markets. Hence, the advancement in the financial market and its associated measures leads to a decrease in the utilization of renewable energy, yet at a specific threshold of financial market expansion and measures, renewable energy consumption experiences an upsurge. The findings unveil a nuanced perspective on the impact of financial market advancement, indicating a non-monotonic trend. Furthermore, the results elucidate a connection that exhibits a U-shaped pattern when exploring the linkage between financial market advancement and its distinct components concerning renewable energy utilization. Initially, both the progress of the financial market and its component factors display a decrease in renewable energy consumption. However, once a certain threshold is surpassed, renewable energy starts upsurge remarkably.

Among the variables scrutinized, it's worth noting that only the moderating influences of market efficiency and ICT reveal a considerable adverse influence on renewable energy consumption, signifying statistical significance at the 10% level within the moderating models. Hence, the efficacy of financial markets, when acting as a moderating element in conjunction with ICT, collaboratively contributes to the reduction in the utilization of renewable energy. The interaction between the financial market, its accessibility, and depth serves as a catalyst, fostering the utilization of ICT to drive and improving the consumption of renewable energy. With each 1% increment in financial development, there is a positive relationship between renewable energy and ICT which is projected to increase, ranging approximately from 2.536% to 6.313%. Consequently, these findings robustly suggest that financial development acts as a moderator for ICT, enhancing the utilization of renewable energy. Improvements in financial development will encourage ICT's favourable influence on renewable energy usage. The outcome proposes an approach for boosting renewable energy usage using ICT and suggests that a collaborative effort between ICT and financial growth vital in the usage of renewable energy. The results also reveal the presence of both significant and non- significant negative relationship between renewable energy and economic growth. Findings suggests that, in frontier financial economies economic activities are mostly carried out by using fossil fuels. Hence, it is advisable to conduct economic activities reliant on energy sources from the renewable energy sources rather than depleting non-renewable energies.

In each model, the anticipated energy consumption coefficient is notably positive at a 1% significance level. Consequently, the consumption of renewable energy is positively influenced by the use of consumption of energy within frontier markets. The estimated coefficient for ICT, conversely, exerts significant adverse impacts on the usage of renewable energy. Therefore, it can be concluded that information and communication technology has a discouraging effect on the utilization of renewable energy. These results are the opposite with (Pasalic, 2023) and in line with (Amin et al., 2022). Simultaneously, the coefficient linked to energy consumption is significantly positive across each model, at the significance of 1%. Hence, energy consumption in frontier financial markets promotes the adoption of renewable energy, while the estimated coefficient indicates a substantial negative impact of ICT on the usage of renewable energy. Therefore, the information and communication technology hinder the deployment of renewable energy.

Table 7: ICT, financial development, and renewable energy in frontier economies

	M1	M2	M3	M4	M5	M6
lnEN	0.467***	0.504***	0.483***	0.501***	0.424***	0.487***
	(0.088)	(0.094)	(0.103)	(0.092)	(0.087)	(0.094)
lnGDP	-0.235	-0.290**	-0.220	-0.105	-0.288**	-0.288**
	(0.144)	(0.145)	(0.151)	(0.144)	(0.146)	(0.144)
lnPOP	-1.098***	-1.081***	-1.079***	-1.071***	-1.116***	-1.079***
	(0.051)	(0.054)	(0.052)	(0.049)	(0.054)	(0.054)
lnURB	0.581***	0.304***	0.445***	0.491***	0.542***	0.308***
	(0.108)	(0.093)	(0.108)	(0.102)	(0.106)	(0.093)
ICT	-1.474***	-1.906***	-1.782***	-1.862***	-1.214**	-1.882***
	(0.460)	(0.481)	(0.470)	(0.445)	(0.478)	(0.482)
FD	-6.540***				-16.443***	
	(1.128)				(5.077)	
FACC		-1.824***				-2.885*
		(0.456)				(1.620)
FDEP			-3.335***			
			(0.780)			
FEF				-5.632***		
				(0.956)		
FD2					18.464**	
					(8.629)	
FAC2						1.526
						(2.183)
FDE2						
FEF2						
FDICT						
FACICT						
FDEICT						
FEFICT						
Constant	10.697***	13.907***	11.602***	10.804***	12.656***	13.930***
	(1.674)	(1.573)	(1.805)	(1.722)	(1.878)	(1.584)
Observations	331	331	331	331	331	331
R^2	0.931	0.928	0.927	0.930	0.932	0.928
j	5.362	0.328	0.165	5.183	4.869	0.236
jp	0.021	0.567	0.685	0.023	0.027	0.627
F-statistics	2398.657	1315.444	983.166	126.539	77.306	102.950

Table 7: Continued

M7	M8	M9	M10	M11	M12
0.398***	0.411***	0.457***	0.428***	0.457***	0.490***
(0.107)	(0.089)	(0.083)	(0.089)	(0.102)	(0.092)
-0.211	-0.118	-0.160	-0.264*	-0.181	-0.094
(0.152)	(0.139)	(0.144)	(0.140)	(0.151)	(0.145)
-1.061***	-1.062***	-1.100***	-1.099***	-1.067***	-1.080***
(0.053)	(0.050)	(0.050)	(0.055)	(0.051)	(0.050)
0.464***	0.516***	0.675***	0.246***	0.426***	0.490***
(0.110)	(0.098)	(0.104)	(0.092)	(0.108)	(0.101)
-1.644***	-1.664***	-2.690***	-1.814***	-2.107***	-1.591***
(0.471)	(0.434)	(0.478)	(0.453)	(0.471)	(0.481)
		-5.917***			
		(0.978)			
			-1.253***		
			(0.383)		
-8.763***				0.474	
(3.248)				(1.189)	
	-17.288***				-6.795***
	(3.461)				(1.235)
9.279*					
(4.853)					
	18.846***				
	(5.208)				
		5.952***			
		(0.873)			
			2.536***		
			(0.432)		
				6.313***	
				(1.490)	
					-2.259*
					(1.200)
11.746***	11.157***	9.063***	15.249***	11.733***	10.936***
(1.780)	(1.663)	(1.602)	(1.607)	(1.800)	(1.716)
331	331	331	331	331	331
0.927	0.934	0.937	0.931	0.928	0.930
0.018	0.810	6.075	0.588	0.179	5.350
0.892	0.368	0.014	0.443	0.673	0.021
61.532	20.714	2239.285	1025.261	110.340	33.207

Note: Standard errors robust to heteroscedasticity are in brackets. Hansen J-statistics (j) assesses the strength of instrument identity, as indicated by the p-value of Hansen J-statistics (jp). The F-statistics, particularly the Cragg-Donald and Kleibergen-Paap tests, corroborate these findings. Collectively, the results from the Hansen J-statistics, F-statistics, and p-value affirm that the instrumental variables employed in this analysis are not weak or over-identified, *** $p < 0.01$

These findings contradict (Pasalic, 2023) but are consistent with (Amin et al., 2022). In all models, precisely at the 1% significance level, the population variable's coefficient reveals a statistically significant inverse relationship. Similarly, the calculated urbanization coefficient holds statistical significance at the 1% level in all models. The Kleibergen-Paap and Cragg-Donald F-statistics, along with the Hansen test probability value, indicate that the instruments employed are not excessively identified and display no signs of weakness.

Results on the interaction role of financial market and energy consumption on renewable energy consumption

Table 8 displays the results concerning how the interaction between energy consumption and financial market growth impacts the adoption of renewable energy for frontier, developed, standalone, and emerging financial markets using Eq. (4). In Table 8, specifically within models M1-M4, we can observe that the influence of financial market growth and its associated metrics (such as financial market efficiency and depth), in in moderating model with energy consumption, significantly affects the adoption of renewable energy in developed economies, significant both positive and negative outcomes. The inference drawn from this analysis is that within developed financial markets, the expansion of financial markets doesn't promote energy consumption, thereby failing to significantly impact the usage of renewable energy.

Table 8: Interaction terms models

Variables	M1	M2	M3	M4	M5	M6	M7	M8
	Developed Financial economics				Emerging Financial economics			
lnEN	0.115	0.276***	0.075	0.319**	0.987***	0.715***	0.774***	0.919***
	-0.192	-0.093	-0.116	-0.15	-0.159	-0.085	-0.08	-0.103
lnGDP	-0.12	-0.194	-0.175	-0.08	-0.233*	-0.264**	-0.294**	-0.250*
	-0.148	-0.139	-0.144	-0.132	-0.12	-0.129	-0.126	-0.128
lnPOP	-1.062***	-1.040***	-1.045***	-1.081***	-1.294***	-1.270***	-1.248***	-1.304***
	-0.048	-0.046	-0.046	-0.051	-0.034	-0.039	-0.038	-0.037
lnURB	0.244***	0.152**	0.239***	0.169**	0.471***	0.536***	0.493***	0.501***
	-0.074	-0.071	-0.07	-0.069	-0.051	-0.053	-0.047	-0.05
ICT	-0.409*	-0.399	-0.363	-0.437	-1.820***	-1.793***	-1.772***	-1.633***
	-0.236	-0.261	-0.238	-0.286	-0.216	-0.214	-0.213	-0.206
FD	3.617***				6.410***			
	-1.189				-1.928			
FDlnEN	0.074				-0.342			
	-0.209				-0.295			
FAC		2.708***				0.17		
		-0.616				-0.621		
FAClnEN		-0.315***				0.194*		
		-0.111				-0.117		
FDE			2.483***				3.407***	
			-0.586				-0.751	
FDElnEN			0.063				-0.163	
			-0.1				-0.144	
FEF				0.986*				0.910*
				-0.538				-0.47
FEFlnEN				-0.154				-0.190**
				-0.1				-0.088
Constant	12.442***	15.280***	13.613***	15.607***	8.770***	10.500***	10.151***	10.748***
	-1.642	-1.257	-1.26	-1.163	-0.986	-0.908	-0.85	-0.866
Observations	285	285	285	285	280	280	280	280
R^2	0.942	0.94	0.944	0.939	0.965	0.962	0.965	0.962
j	0.089	0.629	0.08	0.037	2.194	1.145	1.34	1.792
jp	0.765	0.428	0.777	0.848	0.139	0.285	0.247	0.181
F-statistics	676.224	515.014	1333.304	155.066	348.102	278.154	524.499	363.659

Table 8: Continued

M9	M10	M11	M12	M13	M14	M15	M16
Frontier Financial Economies				Standalone Financial Economies			
0.241***	0.412***	0.441***	0.517***	1.347***	1.874**	0.211***	-0.408**
-0.092	-0.091	-0.117	-0.092	-0.092	-0.746	-0.069	-0.179
-0.128	-0.271*	-0.209	-0.108	0.114	-0.061	0.165	0.012
-0.146	-0.141	-0.152	-0.142	-0.097	-0.19	-0.14	-0.296
-1.099***	-1.089***	-1.066***	-1.076***	-1.201***	-1.701***	-0.773***	-0.885***
-0.049	-0.054	-0.051	-0.049	-0.028	-0.305	-0.031	-0.063
0.659***	0.261***	0.432***	0.494***	0.347***	1.057***	-0.402***	0.775***
-0.107	-0.092	-0.11	-0.101	-0.091	-0.227	-0.14	-0.206
-1.649***	-1.765***	-1.810***	-1.799***	1.967***	0.798**	2.634***	-0.388
-0.441	-0.463	-0.46	-0.439	-0.236	-0.338	-0.413	-0.261
-10.174***				15.762***			
-1.358				-0.693			
1.301***				-4.564***			
-0.193				-0.267			
	-2.964***				10.948**		
	-0.566				-5.052		
	0.464***				-2.981***		
	-0.097				-0.454		
		-3.537***				19.557***	
		-0.785				-1.713	
		0.374				-6.397***	
		-0.335				-0.508	
			-5.210***				-9.058***
			-0.933				-3.503
			-0.352				4.102**
			-0.283				-1.748
10.049***	15.008***	11.842***	10.752***	9.547***	-2.071	24.154***	6.158*
-1.621	-1.607	-1.854	-1.717	-1.543	-4.996	-2.198	-3.324
331	331	331	331	79	79	79	79
0.936	0.93	0.927	0.931	0.994	0.985	0.993	0.98
5.754	0.479	0.149	5.358	0.298	0.102	0.746	0.77
0.016	0.489	0.7	0.021	0.585	0.75	0.388	0.38
1519.13	964.243	934.962	92.282	722.81	27.431	49.886	19.571

Note: Standard errors robust to heteroscedasticity are in brackets. Hansen J-statistics (j) assesses the strength of instrument identity, as indicated by the p-value of Hansen J-statistics (jp). The F-statistics, particularly the Cragg-Donald and Kleibergen-Paap tests, corroborate these findings. Collectively, the results from the Hansen J-statistics, F-statistics, and p-value affirm that the instrumental variables employed in this analysis are not weak or over-identified, *** $p < 0.0$

Within model M9-M12, the interaction of energy consumption and the progress of financial markets, and financial market accessibility results in a significant influence on renewable energy utilization in frontier financial economies. Conversely, the influence of financial market depth and efficiency, on the contrary, lacks statistical significance in the moderating models. As noted in the case of frontier markets, the advancement of financial markets in these regions is capable of increasing energy consumption, hence increasing energy from renewable energy. In models M13 to M16, in standalone economies, the moderating effect of energy consumption, financial market growth, accessibility, and depth is associated with a decrease in renewable energy utilization. However, it's important to note that financial market efficiency shows a statistically significant positive impact in this context. Conversely, the utilization of renewable energy experiences a decline due to the moderating influence of financial market accessibility and energy consumption. In emerging financial market in models M5-M8, the moderating influence of energy consumption, along with financial market access and efficiency yields a mixed impact on renewable energy utilization, with both positive and negative effects observed at the 10% and 5% significance levels. On the contrary, the interaction variables involving advancement of financial market and depth do exhibit a negative influence, but it is not statistically significant in their influence on usage of renewable energy. This finding implies that financial market accessibility and efficiency help enhance and minimize renewable energy use. Thus, financial market accessibility assures consumption of energy efficiency, which enhances renewable energy usage.

Conclusions and policy implications

In recent times, policymakers have been engaging in discussions concerning the impact of financial development on environmental sustainability, raising questions and deliberations on this matter. While the rising theoretical literature is incoherent, empirical proof is conflicting thus fails to account for disparities in financial growth stages. As a result, there are contradictions in the literature. Within the scope of this investigation, our objective is to assess the effects of the growth and development of financial markets on the adoption and utilization of renewable energy sources, utilizing an extensive panel dataset spanning from 1990 to 2020 for 83 countries by employing IV-GMM. We utilize a comparative approach to investigate how financial market expansion affects renewable energy adoption across emerging, developed, standalone, and frontier financial economies, while also considering factors such as ICT, population, economic growth, urbanization, and energy consumption. Below are the outcomes of this study:

To begin, the results disclose that the impact of financial markets on renewable energy varies based on the type of financial economy. According to the empirical findings, financial market expansion, accessibility, and depth in emerging financial economies improve environmental quality through encouraging the usage of renewable energy. Furthermore, despite the depth and expansion of the financial market in standalone markets, the usage of renewable energy is encouraged but diminished by market efficiency. The advancement of the financial market, coupled with increased accessibility and depth, contributes to the increased utilization of renewable energy within developed financial markets, however, in the context of frontier financial economies, the expansion of financial markets and the metrics associated with it have a pronounced and statistically significant negative impact on the adoption of renewable energy. These findings indicate that in emerging, standalone, and developed financial markets, eco-technological advances are facilitated, effective corporate governance is promoted, and credibility and economic benefits are created for businesses to make investments in eco-enhancing initiatives, thus boosting the use of renewable energy (Sun et al., 2023). Contrasting to these financial markets, the frontier economies' undeveloped and inadequate financial markets fail to promote effective corporate governance, improve innovation, encourage business sectors to adopt environmentally friendly technologies, and do not have adequate laws to encourage industries to make investments in green projects that promote sustainability. In addition, the insignificant influence of financial market efficiency in the emerging and developed markets, as well as financial market access in the standalone market, on renewable energy consumption may be related to their financial industry's immaturity. Moreover, empirical data underscores a relationship that is non-linear rather than linear one, regarding the adoption of renewable energy and the progress of financial markets. Financial market development policies have a somewhat non-linear influence on renewable energy adoption in certain economies, despite the fact that they have no linear impact. Consequently, within emerging markets, the growth and depth of financial markets exhibit intricate, inverted U-shaped associations with the usage of renewable energy.

Additionally, within these emerging markets, market efficiency exhibits a connection characterized by an inverted U-shaped pattern in terms of renewable energy utilization. Meanwhile, in isolated markets, the growth and depth of financial markets present a nuanced, inverted U-shaped relationship with the adoption of renewable energy. Moreover, the financial market and its components in developed financial markets exhibit a similar inverted U-shaped relationship with renewable energy consumption. The findings provide support for the existence of an inverted U-shaped relationship between the utilization of renewable energy and financial market components, indicating that these measures encourage the utilization of renewable energy up to a specific threshold, after which there is a decline in the consumption of renewable energy. In contrast, financial market growth and sub-measures in frontier markets show a U-shaped link with the usage of renewable energy. This illustrates that financial growth and sub-measures reduce renewable energy usage, but after a particular threshold, it increases.

Third, the research outcomes elucidated that the financial market exerts an influence on both energy consumption and ICT, which in turn influences renewable energy use. Financial market accessibility plays a moderating role in shaping consumption of energy patterns within advanced financial economies, effectively curbing the reliance on renewable energy sources. Furthermore, ICT is influenced by financial growth, accessibility, and efficiency in developed nations, in contrast, reduces the adoption of renewable energy. In emerging economies, access to financial markets and efficiency govern energy consumption to increase and decrease reliance on renewable energy. The results indicate that the financial market acts as a moderator for ICT and energy consumption, thereby impacting the utilization of renewable energy. Specifically, financial market accessibility moderates' energy usage within developed financial markets, limiting the usage of renewable energy. Moreover, within developed nations, financial expansion, the accessibility of financial markets, and their efficiency collectively act as moderators for ICT, subsequently in a decrease in the renewable energy utilization. Financial market access and efficiency in emerging financial markets moderate energy consumption to increase and decrease the use of renewable energy.

Though this article proves that an advanced financial market increases the usage of renewable energy directly, it indirectly increases ICT and energy usage, which degrades environmental quality. In conclusion, this research has shown that when evaluating the effect of financial markets on renewable energy use, the stages of financial development. The current research posits that the connection between the adoption of renewable energy and advancement of financial market isn't strictly to a linear shape but may, in fact, display a curvilinear character. Furthermore, the paper emphasizes the indirect relationship between utilization of renewable energy and financial market, but financial market also moderates use of energy and ICT to affect renewable energy consumption. Our work not only advances our understanding of the financial market's influence on renewable energy use, but it also has substantial policy implications, particularly for policymakers in standalone financial markets. While taking advantage of the financial market, policymakers from standalone financial markets should embrace and invest in sustainable and green technology. Furthermore, this research demonstrates that the financial market directly contributes to the improved usage of renewable energy in emerging and developed financial markets since business sectors or companies in these markets have benefit of making investments in sources of renewable energy as a due to stringent regulations and laws. As an outcome, financial markets should be used as a regulatory tool which is available to regulators in pursuit of environmental sustainability and long-term well-being and, to a large extent, combat the impact of climate change. Whereas the financial sector indirectly reduces renewable energy use in standalone markets by driving ICT and consumption of energy, in developed countries, the financial industry indirectly curtails the utilization of renewable energy by encouraging the information and communication technology (ICT) sector. These economies' policymakers should encourage investments in renewable energy resources and ICT industries that support renewable energy.

Appendix 1

Table 1A. Descriptive statistics

Developed financial economies	mean	SD	min	max
lnRE	14.869	7.154	-.061	23.629
lnEN	2.294	3.370	-3.050	9.042
lnGDPC	1.223	.848	-3.196	4.488
lnPOP	4.665	7.190	-3.749	17.453
lnUPOP	16.503	1.673	13.156	21.067
lnICT	-.136	.827	-.741	2.465
lnFD	.697	.146	.33	1.000
lnFAC	.527	.236	.01	1.000
lnFDE	.604	.270	.07	1.000
lnFEF	.669	.285	.06	1.000
Emerging financial economies				
lnRE	13.737	8.870	-2.995	23.660
lnEN	2.727	3.535	-3.028	8.872
lnGDPC	1.167	.901	-2.496	3.900
lnPOP	6.094	7.817	-5.490	18.668
lnUPOP	16.497	1.601	13.788	21.057
lnICT	.191	1.209	-.7413946	5.057
lnFD	.418	.142	0.11	.85
lnFAC	.354	.192	0.000	1.000
lnFDE	.331	.210	0.02	0.95
lnFEF	.516	.321	0.000	1.000
Frontier Financial economies				
lnRE	13.869	8.058	-1.660	24.381
lnEN	2.729	3.386	-2.969	8.905
lnGDPC	1.162	.846	-3.556	3.264
lnPOP	5.159	7.363	-6.078	17.673
lnUPOP	16.495	1.455	12.998	19.241
lnICT	-.000	.967	-.741	2.322
lnFD	.227	.130	0.0001	0.58
lnFAC	.198	.247	0.0001	0.99
lnFDE	.124	.161	0.0001	0.77
lnFEF	.113	.186	0.0001	1.000
Standalone financial economies				
lnRE	12.064	7.968	-.494	21.263
lnEN	2.595	3.199	-1.862	8.994
lnGDPC	1.250	.906	-3.091	2.908
lnPOP	4.910	7.983	-2.896	19.619
lnUPOP	16.904	1.592	14.051	19.428
lnICT	-.1481	.815	-.741	1.703
lnFD	.290	.103	0.0001	.52
lnFAC	.222	.205	0.0001	.83
lnFDE	.160	.136	0.0001	.74
lnFEF	.210	.300	0.0001	1.000

Table 1B. Symbols, definitions, and sources

Symbols	Variable	Unit	Literature source	Source
RE	Renewable energy	Renewable energy consumption % of total final energy consumption	(Shahbaz et al., 2021)	WDI
EN	Energy use	Energy use (kg of oil equivalent per capita)	(Khan et al., 2021)	WDI
GDPC	Gross domestic product	GDP per capita growth	(Wang et al., 2022)	WDI
POP	Total population	-	(Acheampong et al., 2020)	WDI
UPOP	Urban population	-		WDI
ICT	Information and communication technology	-	(Shehzad et al., 2022)	WDI
FD	Financial development	Ranges from 0 to 1	(Shahbaz et al., 2021)	IMF
FAC	Financial market access	Ranges from 0 to 1	-	-
FDE	Financial market depth	Ranges from 0 to 1	-	-
FEF	Financial market efficiency	Ranges from 0 to 1	-	-

Table 1C. Correlation matrix

	lnRE	lnEN	lnGDP	lnPOPT	lnUPOP	lnICT	lnFD	lnFMA	lnFMD	lnFME
lnRE	1									
lnEN	-0.863***	1								
lnGDPC	0.418***	-0.448***	1							
lnPOPT	-0.962***	0.917***	-0.445***	1						
lnUPOP	0.167***	-0.194***	0.132***	-0.115***	1					
lnICT	-0.880***	0.875***	-0.452***	0.890***	-0.172***	1				
lnFD	0.0754*	-0.104***	0.0723*	-0.0807*	0.127***	-0.0598	1			
lnFMA	0.188***	-0.203***	0.137***	-0.204***	0.0881**	-0.145***	0.687***	1		
lnFMD	0.115***	-0.106***	0.110***	-0.103**	0.128***	-0.0789*	0.912***	0.583***	1	
lnFME	0.0611	-0.0912**	0.108***	-0.0599	0.150***	-0.0714*	0.767***	0.366***	0.694***	1

Note: $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

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RESEARCH ARTICLE

Unveiling the Role of Artificial Intelligence and Stock Market Growth in Achieving Carbon Neutrality in the United States: An ARDL Model Analysis

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Abstract

Given the fact that climate change has become one of the most pressing problems in many countries in recent years, specialized researches on how to mitigate climate change has been adopted by many countries. Within this discussion, the influence of advanced technologies in achieving carbon neutrality has been discussed. While several studies investigated how AI and Digital innovations could be used to reduce the environmental footprint, the actual influence of AI in reducing CO2 emissions (a proxy measuring carbon footprint) has yet to be investigated. This paper studies the role of advanced technologies in general, and Artificial Intelligence (AI) and ICT use in particular, in advancing carbon neutrality in the United States, between 2021. Secondly, this paper examines how Stock Market Growth, ICT use, Gross Domestic Product (GDP) and Population affect CO2 emissions using the STIRPAT model. After examining stationarity among the variables using variety of unit root tests, this study concluded that there are no unit root problem across all the variables, with a mixed order of integration. The ARDL bounds test for cointegration revealed that variables in this study have a long-run relationship. Moreover, the estimates revealed from ARDL model in the short- and long-run indicated that economic growth, stock market capitalization and population significantly contributed to the carbon emissions in both the short-run and long-run. Conversely, AI and ICT use significantly reduced carbon emissions over both periods. Furthermore, findings were confirmed to be robust using FMOLS, DOLS, and CCR estimations. Furthermore, diagnostic tests indicated the absence of serial correlation, heteroscedasticity and specification errors and, thus, the model was robust.

Keywords: Artificial Intelligence; Stock Market Growth; ICT Use; Carbon Neutrality; United States

Introduction

Greenhouse gas (GHG) emissions resulting from fossil fuel usage, industrialization, production, forest loss, advances in technology, and growing populations are driving global warming, which is now one of the most serious ecological problems (Nunes,2023; Raihan et al.,2024g). The most advanced nations have prioritized the formulation of strategies to restrict and regulate carbon emissions within their energy and environmental policies (Finon,2019; Raihan et al.,2024e). The USA is acknowledged as a primary contributor to global carbon dioxide (CO2) emissions, significantly impacting the overall concentration of GHG's in the atmosphere (Dogan et al.,2024). Because of its reliance on fossil fuels for energy production, transportation, and industrial processes, the United States is one of the biggest contributors to global carbon emissions. The energy sector is the main source of carbon emissions in the United States, which are mostly caused by power plants, automobiles, and industrial operations (Pata et al.,2023). Notwithstanding this, recent years have seen a trend towards a decrease in emissions, which has been ascribed to a move towards renewable energy sources, energy-saving techniques, and more stringent environmental laws (Kartal, 2023). As of the end of 2021, the USA is the largest economy and the second highest carbon-emitting nation (British Petroleum 2022; World Bank 2022). In 2021, the USA consumed 92.97 exajoules of primary energy and released 4701.1 million tons of CO2 (Kartal, 2023). The selection of the United States as the subject of our research is warranted by its global economic significance and pivotal influence in defining the international landscape. The United States, as the world's largest economy with a GDP of $25.46 trillion in 2022, wields considerable influence (World Bank, 2023). Furthermore, the nation holds the second position in CO2 emissions owing to its rapid economic development and significant energy requirements resulting from its 338 million inhabitants. In 2020, the United States accounted for over 13% of global CO2 emissions, presenting considerable difficulties to its populace and the worldwide biosphere (Adebayo & Ozkan, 2024). In light of these issues, there is a rising consensus on the vital relevance of stock market capitalization, ICT utilization, and AI innovation as strategic remedies. Studies constantly show that progress in AI and ICT can significantly reduce CO2 emissions while promoting the transition to clean, renewable energy. It is expected that further advancements in AI, ICT, GDP, stock market development, and sustainable population growth will reduce environmental costs; therefore, it is imperative to explore the relationship between these factors and CO2 emissions in the United States. The motivation for this research lies in addressing the urgent need to achieve carbon neutrality in the United States amidst growing environmental concerns. Artificial Intelligence (AI) and stock market growth represent transformative forces that can influence sustainable development. AI offers innovative solutions for optimizing energy use, improving industrial efficiency, and promoting green technologies, while stock market growth reflects economic dynamism that can mobilize investments toward low-carbon initiatives.

Climate change has precipitated several catastrophic events, affecting both emerging economies and advanced countries (Shaari et al.,2022; Islam et al.,2023a). In 2023, U.S. energy-related CO2 emissions decreased by 7% compared to 2022, primarily due to a decrease in coal-fired electricity production and a shift towards natural gas and solar energy, primarily from the electric power sector (EIA, 2024). The United States leads the G-7 nations in CO2 emissions, followed by Japan, Germany, Canada, the United Kingdom, Italy, and France (Ayhan et al.,2023). ICT's explosive growth offers nations with new chances to improve their position in the global market, close the gap in economic and social progress, and counteract environmental damage (Asongo et al.,2018, Niebel 2018). The US has seen a significant increase in eco-innovation patents, from 646.32 in 1990 to 4,398 in recent decades, raising concerns about their potential environmental impact (Hossain et al.,2023). A cohort of scholars advocates for the use of ICT communication technology, positing that it contributes to societal education and ultimately plays a part in mitigating carbon dioxide emissions (Ozcan & Apergis 2018; Khan et al.,2020; Shaaban-Nejad & Shirazi, 2022). Moreover, environmental damage, coupled with global disaster, makes up a complex ecological issue (Raihan et al., 2022c) that requires innovative and sophisticated Artificial Intelligence (AI) solutions (Nishant et al., 2020). So, it is essential to emphasize the restricted application of AI in advancing sustainability across sectors such as energy, transportation, water, and biodiversity (Nishant et al., 2020). The public sector's investment in AI has increased significantly in recent decades, exemplified by the $3.2 billion allocated by the U.S. government in 2022 (JEC, 2023).

The United States is at essential intersections, when the need to tackle ecological issues aligns with the pursuit of significant economic progress (Adebayo et al., 2024). In addition, the nation possesses the largest GDP worldwide and allocates substantial funds to its energy infrastructure (Danish & Ulucak, 2021). The World Bank (2020) indicated that in 2018, the United States accounted for around 21.6% of the world GDP (constant 2010 USD).The swift increase of the economy and population, along with the increasing consumption of oil and gas, are the main factors driving the overall trend in developing nations to foster economic expansion (Rahman & Majumder, 2022; Voumik et al., 2023c). The density of individuals in metropolitan regions generates a more extensive labor pool, hence promoting economies of scale and fostering specialization (Raza et al., 2023). This leads to enhanced economic output and productivity (Ridwan,2023). Moreover, renewable energy is often viewed as an exceptionally effective way of advancing environmental sustainability (Onwe et al.,2024; Islam et al.,2024; Ridzuan et al.,2023; Raihan et al.,2024f). Investor perceptions of legal challenges pertaining to potential regulatory dangers and ecological obligations can impact stock market behavior (Topcu et al., 2020). This adverse effect would promote financial decisions that yield superior stock returns and reduced carbon emissions (Mushafiq & Prusak, 2023). Stock market advancements offer investors greater access to funding alternatives, including equity financing, potentially leading to heightened investment in sustainable energy initiatives (Paramati et al. 2016; Sadorsky, 2012).

The USA, despite its substantial contribution to global temperature rise, exhibits a notable study deficiency regarding the effects of multiple variables, rendering it the second-largest global emitter of CO_2 (Hassan et al., 2024). This study offers multiple insights into the existing body of work. It represents the inaugural inspection of the interplay between stock market capitalization and AI innovation concerning ecological effects in the United States. Unlike previous studies, this study's methodology allows for differentiation based on the carbon footprints of the USA, not its development levels. Therefore, we will tailor policy suggestions based on the pollution levels of the USA, not its level of advancement. Additionally, the consequence of factors like GDP growth, growing population, and ICT is also categorized based on the total emissions of the country in the evaluation. Incorporating these variables into the empirical model minimizes the risk of omitting key variables. This study is the inaugural complete investigation, within our expertise, of the influence of newly found variables on CO_2 emissions, addressing the following principal research questions: What is the impact of AI innovation and stock market capitalization on the environment in the USA? Also, how do ICT utilization, GDP, and growing populations affect carbon intensity in the USA? The study holds significance due to its emphasis on AI innovation and stock market development, areas that previous research has not sufficiently explored. The analysis employed ARDL techniques, utilizing data from 1990 to 2021, and the reliability of the results was further substantiated by FMOLS, DOLS, and CCR techniques. By recognizing these factors, policymakers and strategists can more effectively promote sustainable ethical actions. It provides significant insights for policymakers in the USA and around the world, enabling sustainable revenue growth and enhancing the condition of the planet, particularly through carbon neutrality.

The second part of the inquiry offers an in-depth review of current studies on the chosen determinants. The "Methodology" section fully delineates the data collection procedure, conceptual structure, experimental design of models, and the estimate techniques utilized. The fourth section, headed "Results and Discussion," gives an extensive review of the findings, clarifying the model's consequences. The final section combines the principal findings of the research and offers useful suggestions derived from them.

Literature Review

Numerous studies have assessed the state of the natural world using various indicators, including CO_2 emissions and ecological footprints. We undertake a comprehensive evaluation of the existing academic literature to detect differences. Consequently, we will look at prior research about the influence of CO_2 emissions on economic progress, population growth, artificial intelligence (AI), information and communication technology (ICT), and stock market capitalization, which will underpin the requirements of our investigation.

GDP and CO2 Emission

The correlation between economic progress and green growth has been the focus of numerous researches. For example, Ridwan et al. (2024a) examine the ecological impacts of GDP in six South Asian nations from 1972 to 2021. Utilizing the Driscoll Kraay Standard Error (DKSE) methodology and the CS-ARDL technique, they determined that GDP considerably reduces CO2 emissions in both the short and long term. Similarly, Using the EKC and Pollution Haven Hypothesis (PHH) as a framework, Raihan et al. (2023a) analyse the ecological effects of China's nuclear energy use between 1993 and 2022. The empirical evidence indicated that heightened economic growth could reduce emission levels in the future. Significant growth in economy and abundant resources coincide with heightened ecological degradation (Hunjra et al., 2024). On the other hand, Pattak et al. (2023) elucidate the implications of nuclear, green energy sources, with population and GDP on CO2 emissions in Italy, using the STIRPAT framework from 1972 to 2021. The ARDL paradigm indicates that an increase of 1% in Italian GDP over the long term can result in an 8.08% spike in CO2 emissions. Voumik et al. (2023b) estimate the influence of GDP, population, renewable energy consumption, fossil fuels, and foreign direct investment on Kenya's carbon emissions from 1972 to 2021. Utilizing the ARDL approach, they observed that a boost in Kenya's GDP can elevate the nation's CO2 emissions. Moreover, in their analysis of China's ecological harm, Ahmad et al. (2024a) examines the effects of technology, the economy, and renewable energy. The DOLS estimate indicates that a 1% rise in GDP leads to a 0.51% elevate in CO2 emissions. Multiple studies by Voumik et al.(2023a) in Indonesia, Ridwan et al.(2023) in France, Raihan et al.(2023c) in Malaysia, Raihan et al.(2023b) in Mexico, Rahman et al.(2022) within Bangladesh, Raihan et al.(2022b) in USA and Raihan et al.(2024c) in G-7 region also corroborated with the positive connection between GDP and CO2 emission.

AI Innovation and CO2 Emission

Artificial intelligence complemented by human skills, carefully assessing AI performance, and accurately defining business goals to ensure the effective alignment of AI technologies (Rahman et al., 2024). From 1990 to 2020, Shiam et al. (2024) look into how innovations in Artificial Intelligence (AI) have affected the Nordic region's ecological footprint. The study takes into account that there is a negative correlation between AI innovation and the ecological footprint, using the STIRPAT model. As per Rasheed et al. (2024), AI plays a proactive role in mitigating carbon emissions while sustaining the ecological balance of seven developing Asian countries. Akther et al. (2024) evaluate the influence of private investment in artificial intelligence (AI) on environmental sustainability in the United States from 1990 to 2019. The findings indicate that private investment in AI significantly correlates with the load capacity factor, hence improving ecological responsibility, as evidenced by the Autoregressive Distributed Lag (ARDL) bound test. The impact of AI innovation on environmental sustainability in the Nordic region is examined by Hossain et al. (2024) between 1990 and 2020. The study used the Panel Autoregressive Distributed Lag (ARDL) model to examine both short-run and long-run interactions, revealing that AI innovation strongly and positively impacts the environment in both time frames. In a similar spirit, Ridwan et al. (2024c) test the Load Capacity Curve (LCC) hypothesis to explore the function of Artificial Intelligence (AI) in fostering sustainability within the G-7 countries. They demonstrate that investing in AI has a major beneficial correlation with the LCF using the Moments Quantile Regression (MMQR) method, hence boosting ecological sustainability. Similar conclusion was also demonstrated by Ridwan et al.(2024b) in USA and Dong et al.(2023) in China. However, Al-Sharafi et al.

(2023) discovered that although AI solutions can save costs, conserve assets, and enhance disposal of waste, their effect on the planet is negligible, especially in developing countries.

SMC and CO2 Emission

Stock market capitalization (SMC) offers innovative, green technology to nations at all stages of growth, improving energy usage and fostering ethical production to lower CO2 emissions (Piñeiro Chousa et al.,2017; Tanchangya et al.,2024; Ahmad et al.,2024b). In Asian nations, Liang et al. (2023) investigate the impact of energy transition and stock market capitalization on ecological health between 1994 and 2020. The outcomes suggest that SMC can enhance the surrounding conditions. In a similar vein, Musah (2023) explored the relationship between EU environmental quality and the growth of stock markets between 1995 and 2014. According to their findings, the development of the stock market reduced ecological impact and thereby boosted sustainability. Furthermore, Paramati et al.(2017) performed a study in G-20 countries and found that SMC reduces carbon footprint only in emerged countries. Focusing on rapid revenue in the stock market may push companies to prioritize profits over ecological issues, possibly leading to increased harm to the planet (Taghizadeh-Hesary et al. 2022). Zhao et al. (2023) did studies in the BRICS-T countries to explore the link between SMC and emissions of CO2. Between 1990 and 2018, they demonstrated how the development of the stock market leads to a decline in ecological quality using second-generation approaches. Similarly, Zeqiraj et al. (2020) investigated the changing connection between the growth of stock markets and carbon emissions in low-carbon nations from 1980-2016. They established that SMC raises the intensity of carbon emissions over the short and long terms using the CS-ARDL approach. The destructive correlations between the SMC and CO2 emission was also observed by several studies like Shiam et al.(2024) in Nordic area, Zafar et al. (2019) in G-7 zone, Su (2023) in China, Nguyen et al.(2021) in G-6 countries. On the other hand, Azeem et al. (2023) analyzed the influence of stock market capitalization (SMC) on the release of carbon in 40 major carbon-emitting countries from 1996 to 2018. Utilizing the Driscoll-Kraay technique, they discovered an inverted U link between SMC and environmental damage.

ICT and CO2 Emission

Information and Communication Technology (ICT) significantly influences the environment and has profound implications for prosperity and social growth (Islam & Rahaman,2023).The manufacturing and processing of ICT gadgets is the reason for the degradation of the ecosystem (Danish et al., 2019). A lot of researches have been done regarding the effects of ICT on the surroundings. To determine the precise impact of ICT on harmful emissions, we examine relevant study articles. To determine the effect of ICT on CO2 emissions, You et al. (2024) analyzed panel data from 64 "Belt and Road Initiative economies between 2000 and 2021. Utilizing the Mean Group (MG) estimator, the Augmented Mean Group (AMG) estimator, and the Dumitrescu-Hurlin panel causality, they discovered a reverse connection between CO2 emissions and ICT use. Several examinations also illustrate similar outcomes such as Lu (2018) in 12 asian economies, Batool et al.(2019) in South Korea, Godil et al.(2020) in Pakistan, Appiah-Otoo et al.(2022) in 110 countries, Islam et al.(2023b) in GCC countries, and Tsimisaraka et al.(2023) in OBOR areas. Nevertheless, Uddin et al. (2024) looks into how ICT has affected G20 countries' CO2 emissions between 1980 and 2019. This study confirms the considerable and positive influence of ICT on CO2 emissions using the panel ARDL technique and the Generalized Method of Moments (GMM) calculation. Raihan (2024) examines the impact of ICT on CO2 emissions in Malaysia from 1990 to 2020 by employing the Dynamic Ordinary Least Squares (DOLS) approach. The result demonstrates that the rise in CO2 emissions is affected by ICT utilization. Moreover, Yahyaoui (2024) shows that ICT has a long-term positive effect on CO2 emissions in both Morocco and Tunisia. Additionally, Arshad et al. (2020) assessed the influence of ICT on CO_2 emissions across 14 South and Southeast Asian nations from 1990 to 2014. The researchers utilized the PMG, DOLS, and FMLOS techniques and determined that ICT adversely affected environmental quality in the region.

Population and CO_2 Emission

Over the past few decades, population expansion has been a major factor in the rise in worldwide CO_2 emissions (Rehman et al.,2022). Due to the increased demand for housing, healthcare, education, and transportation, increasing populations are considered to have a detrimental effect on the environment (Isik et al., 2019; Wu et al., 2021). Hassan et al. (2024) consider the link between nuclear energy, population, and CO_2 emissions for the United States. They discovered that population-induced pollution appears in both the short and long-term by using the ARDL simulations model. In five of Asia's most populous regions, Rehman and Rehman (2022) assess the underlying effects of population growth on CO_2 emissions between 2001 and 2014. They discovered that population expansion is the most intense component of the CO_2 emissions using a gray relational analysis (GRA). Similarly, Khan et al.(2021) checked the association between growth in population on ecosystem in USA from 1971 to 2016. They discovered an encouraging association between growing populations and CO_2 emissions and the ecological footprint using the GMM, robust least-squares, and generalized linear model (GLM). However, using rigorous econometric techniques, Pickson et al. (2024) explore population-related factors that affect CO_2 emissions from 1993Q1 to 2018Q4, covering a range of income levels in different nations. They revealed that in high and lower-middle-income countries, the density of people reduces CO_2 emissions, but in lower-income ones, it increases emissions. In a similar vein, Erdogan (2024) undertook an investigation in Germany from 1995 to 2020. They discovered that population density reduces environmental pollution in Germany by applying the ARDL technique. Moreover, Wu et al. (2021) observed that China's growing population could potentially yield both short and long-term advantages in mitigating biodiversity loss. By comparison, Begum et al. (2015) demonstrated that the population rise does not significantly impact environmental damage in Malaysia, based on the ARDL bounds testing approach.

Literature Gap

Even if the USA supports sustainable environmental quality, the methodologies for collecting information on ICT use, AI innovation, and the actual impact of stock market capitalization on CO_2 emissions are still not well defined. From the vantage point of the USA, domains such as AI innovation, ICT utilization, and stock market evolution remain comparatively underexplored research subjects. Furthermore, our research employs the ARDL limits testing methodology, a technique that has been infrequently utilized in prior investigations. This method facilitates a more efficient examination of data from panel models, which enhances conceptual comprehension in the discipline. By analyzing these characteristics, the chosen area can assess whether technical innovations, economic cooperation, and sustainable development can aid in addressing the planet's sustainability issues. This study addresses a deficiency in the literature by examining the evolving effects of GDP, population growth, ICT utilization, stock market capitalization, and AI on CO_2 emissions, employing sophisticated economic methods, with particular emphasis on the United Nations' objectives.

Methodology

Data and Variables

The current study examined data pertaining to the impact of specific factors on the environmental quality of the United States from 1990 to 2021. We obtained the Gross Domestic Product (GDP) and demographic data from the World Development Indicators (WDI). In addition, CO_2 emissions, utilized as an indicator of ecological sustainability, were likewise obtained from WDI as the endogenous variable. Information regarding AI innovation and ICT utilization was sourced from Our World in Data, whereas stock market capitalization (SMC) statistics were acquired from the Global Financial Development (GFD) database. In this analysis, stock market capitalization and AI innovation were regarded as essential policy variables. Consequently, enhancing the accessibility and trustworthiness of the study's approach ensures that the full documentation provides an explicit and integrated analysis.

Table 1. Source and Description of Variables

Variables	Description	Logarithmic Form	Unit of Measurement	Source
CO2	CO2 Emission	LCO2	CO2 Emission (kt)	WDI
GDP	Gross Domestic Product	LGDP	GDP per capita (current US$)	WDI
AI	AI Innovation	LAI	Patent Application in AI field	Our World in Data
SMC	Stock Market Capitalization	LSMC	Stock Market Capitalization (% of GDP)	Global Financial Development
ICT	Technological Innovation	LICT	ICT good imports (% of total goods imports)	Our World in Data
POP	Population	LPOP	Population, total	WDI

Theoretical Framework

The IPAT model is a highly focused framework utilized for analyzing the impact of economic activity on energy usage and ecological results (Borsha et al., 2024). This model has been extensively employed in previous studies to examine factors affecting ecological degradation across several contexts (Shaheen et al., 2022; Yu et al.,2023; Wu et al., 2024; Khan, 2024). The model asserts that the environmental impact, represented by the letter "I," is the product of three variables: population (P), affluence (A), and technical advancement (T) (Ehrlich & Holden, 1971).

$$I = \int PAT \qquad (1)$$

This research uses CO_2 emissions as a stand-in for environmental decline. In accordance with the STIRPAT model proposed by Dietz and Rosa (1997), we applied population growth as a metric for population (P), economic growth and stock market capitalization as indicators of affluence (A), and the adoption of AI and ICT as a gauge of technology (T). Equation (2) displays the revised form subsequent to the incorporation of the intercept component (C) and the standard error term (ε).

$$I_i = C.P_i^{\beta}.A_i^{\gamma}.T_i^{\delta}.\varepsilon_i \qquad (2)$$

The factual framework established in this paper results from an in-depth look of pertinent research, which has guided the ensuing interpretations.

$$Environmental\ Impact = f(Population, Affluance, Technology) \qquad (3)$$

Alongside independent variables, we incorporated CO2 emissions as a proxy indicator. In this context, GDP refers to gross domestic product, AI denotes artificial intelligence, SMC represents stock market capitalization, ICT means information and communication technology and POP pertains to population. In equation (4), we adjusted α_1 to α_5 for the coefficients of the independent variables, whereas α_0 represents the intercept term. The logarithmic forms of the variables are utilized in equation (5) to guarantee normal distribution. To derive Equation (4), execute the subsequent procedure:

$$CO_{2it} = \alpha_0 + \alpha_1 GDP_{it} + \alpha_2 AI_{it} + \alpha_3 SMC_{it} + \alpha_4 ICT_{it} + \alpha_5 POP_{it} \qquad (4)$$

The logarithmic forms of the variables are utilized in equation (5) to guarantee normal distribution.

$$LCO_{2it} = \alpha_0 + \alpha_1 LGDP_{it} + \alpha_2 LAI_{it} + \alpha_3 LSMC_{it} + \alpha_4 LICT_{it} + \alpha_5 LPOP_{it} \quad (5)$$

Estimation Strategies

This investigation implemented the ARDL approach to analyze the correlation between CO2 emissions and critical variables including GDP, AI innovation, SMC, ICT utilization, and population (POP) in the USA. Initially, we conducted unit root tests (ADF, P-P, and DF-GLS) to establish the stationarity of the variables. The ARDL limits test was used to investigate the cointegration among the variables, considering the peculiarities of the time series data. Additional estimating methods, such as FMOLS, DOLS, and CCR, were applied to guarantee robustness. After a comprehensive evaluation, the most effective and reliable econometric method was selected for the research.

Unit Root Test

The researchers conducted unit root analysis to validate the preference for the ARDL methodology over traditional cointegration methods. Utilizing a unit root test is crucial to avert erroneous regression analysis. This testing process determines the degree of integration (Polcyn et al.,2023; Ridwan et al.2024e). In this study, three stationarity tests were run: the DF-GLS test, recommended by Elliot et al. (1996), the Phillips and Perron (1988) test, and the Augmented Dickey-Fuller (ADF) test, which Dickey and Fuller (1981) proposed. In contrast to the Dickey-Fuller (DF) method, the ADF technique is more resilient and suitable for more complex procedures (Fuller, 2009).

ARDL Bound test

This study utilized ARDL bound testing (Pesaran et al., 2001) to determine the presence of cointegration among the variables. It is extensively utilized in econometric analyses to examine long-term cointegration among factors and to assess the impact of exogenous variables on the endogenous variable in both the long and short term (Ahmed et al., 2021; Raihan,2023; Atasoy et al.,2022b; Raihan & Bari, 2024).The ARDL limits test is superior to previous single-equation approaches in some respects when examining cointegration (Rahman & Islam, 2020; Ridwan & Hossain, 2024). The ARDL bounds testing methodology is reliable and efficient, even in limited information ranges, providing a thorough evaluation of the overarching structure in the long run. It can be used regardless of the integration order of the fundamental ARDL structure, which can be either of order 2 (I(2)) or order 0 (I(0)) or 1 (I(1)). Equation (6) mathematically displays the ARDL bounds test as follows:

$$\Delta LCO_{2t} = \beta_0 + \beta_1 LCO_{2t-1} + \beta_2 LGDP_{t-1} + \beta_3 LAI_{t-1} + \beta_4 LSMC_{t-1} + \beta_5 LICT_{t-1} + \beta_6 LPOP_{t-1} + \sum_{i=1}^{q} \alpha_1 \Delta LCO_{2t-i} + \sum_{i=1}^{q} \alpha_2 \Delta LGDP_{t-i} + \sum_{i=1}^{q} \alpha_3 \Delta LAI_{t-i} + \sum_{i=1}^{q} \alpha_4 \Delta LSMC_{t-i} + \sum_{i=1}^{q} \alpha_5 \Delta LICT_{t-i} + \sum_{i=1}^{q} \alpha_6 \Delta LPOP_{t-i} + \varepsilon_t$$

(6)
where q is the optimum lag length.

Pesaran et al. (2001) propose that F-statistics may be contrasted with critical values for both upper and lower bounds. If the F-statistics above the upper critical value, the null hypothesis (H0) is rejected, indicating a sustained connection. If the F-statistic falls below the lower critical value, the null hypothesis (H0) is upheld, however its validity remains ambiguous within the specified thresholds.

ARDL short and long run simulation

The investigation use the ARDL framework to examine the interaction of variables, taking into account both short-term and long-term dynamics. The long-run coefficient estimate is predicted by equation (7), which also confirms the cointegration of the parameters. It incorporates the ECT into the ARDL framework to compute short-term dynamic parameters derived from long-term estimates, employing an error correction term (ECT) approximation. The equation (7) represents the ARDL long run equation below.

$$\Delta LCO_{2t} = \beta_0 + \beta_1 LCO_{2t-1} + \beta_2 LGDP_{t-1} + \beta_3 LAI_{t-1} + \beta_4 LSMC_{t-1} + \beta_5 LICT_{t-1} + \beta_6 LPOP_{t-1} + \sum_{i=1}^{m} \alpha_1 \Delta LCO_{2t-i} + \sum_{i=1}^{m} \alpha_2 \Delta LGDP_{t-i} + \sum_{i=1}^{m} \alpha_3 \Delta LAI_{t-i} + \sum_{i=1}^{m} \alpha_4 \Delta LSMC_{t-i} + \sum_{i=1}^{m} \alpha_5 \Delta LICT_{t-i} + \sum_{i=1}^{m} \alpha_6 \Delta LPOP_{t-i} + \Omega ECT_{t-1} + \varepsilon_t$$

(7)
where Ω represents the coefficient of the ECT.

Robustness Check

This study employed the Fully Modified Ordinary Least Squares (FMOLS), Dynamic Ordinary Least Squares (DOLS), and Canonical Cointegrating Regression (CCR) methods to judge the reliability of the ARDL findings. These techniques have diverse benefits, as evidenced in the previous research (Merlin & Chen, 2021). Hansen and Phillips (1988) created the FMOLS analysis to integrate the most precise cointegration measures. To deal with the effects of cointegration on serial correlation and endogeneity in the explanatory variables (Zimon et al., 2023), this method changes the least squares method. Furthermore, it can clarify the causal relationships between the factors under study across a broad range of values (Pedroni, 2001). Stock and Watson (1993) derive an ongoing link in an illustration where the elements cointegrate but have a range of integration using parametric approaches in their DOLS framework. The proposed DOLS technique addresses the issues of simultaneity aversion and small sample bias through the use of leads and lags. The primary advantage of this assessment lies in its capacity to illustrate varying degrees of integration among discrete pieces inside the cointegrated framework (Raihan & Tuspekova, 2022). Park (1992) introduced the CCR approach, applicable for identifying cointegrating vectors in a system characterized by an integrated process of order one, denoted as I(1). Furthermore, it is applicable for both single equation regression and multivariate regression without modifications, demonstrating its continued utility.

Results and Discussion

Table 2 presents a comprehensive analysis of the variables. It encompasses statistical markers from normality evaluations, such as skewness, probability, kurtosis, and the Jarque-Bera test. The mean and median values for all variables exhibit similarity, indicating a normal distribution. Everything shows an inverse skewness, according to the results, with the exception of AI innovation. The skewness values, approximating 0, signify that all variables conform to a normal distribution. All the series exhibit platykurtic characteristics, with kurtosis values fewer than 3. The Jarque-Bera probability indicates that all variables have a normal distribution.

Table 2. Summary Statistics

Statistic	LCO2	LGDP	LAI	LSMC	LICT	LPOP
Mean	15.4644	10.6439	7.5055	4.7704	2.6251	19.4995
Median	15.4519	10.7189	7.1577	4.8772	2.6312	19.5091
Maximum	15.5692	11.1594	9.7244	5.2724	2.8711	19.6207
Minimum	15.2789	10.0812	6.3208	3.9489	2.2675	19.3355
Std. Dev.	0.08024	0.31878	1.0359	0.32158	0.13253	0.08679
Skewness	-0.4666	-0.2557	1.1557	-0.7628	-0.2705	-0.3112
Kurtosis	2.6354	1.8889	2.9923	2.9142	3.7837	1.8948
Jarque-Bera	1.3384	1.9948	7.1232	3.1131	1.2092	2.145
Probability	0.5121	0.3688	0.0284	0.2109	0.5463	0.3422

Table 3 illustrates the results of the unit root analysis using the ADF, DF-GLS, and P-P tests. The findings reveal that LICT and LPOP had stationary behavior at both the level and initial difference, as evidenced by the ADF, P-P, and DF-GLS tests. However, these tests identified the other variables (LCO2, LGDP, LAI, and LSMC) as non-stationary at I(0) and attained stationarity at I(1). The results of these tests necessitate the implementation of the study using the ARDL approach.

Table 3. Results of Unit root test

Variables	ADF		P-P		DF-GLS		Decision
	I(0)	I(1)	I(0)	I(1)	I(0)	I(1)	
LCO_2	-0.155	-4.954***	-0.231	-4.356***	-0.221	-3.889***	I(1)
LGDP	-0.878	-4.672***	-0.762	-4.032***	-0.760	-4.140***	I(1)
LAI	-0.258	-3.981***	-0.316	-4.002***	-0.289	-4.081***	I(1)
LSMC	-0.416	-4.990***	-0.336	-4.821***	-0.435	-4.779***	I(1)
LICT	-3.061**	-4.585***	-3.981***	-4.550***	-3.450**	-4.089***	I(0)
LPOP	-5.088***	-6.451***	-4.827***	-6.778***	-5.064***	-6.566***	I(0)

The ARDL bound test results, presented in Table 4, provide significant information about the cointegration of the components under study. The F-statistic value of 5.86, exceeding the upper limits for significance at the 10%, 5%, 2.5%, and 1% levels for both zero and first orders, suggests that H0 is false. This observation reveals a persistent link between the variables.

Table 4. Results of ARDL Bound test

	Test Statistics	Value	K	
	F statistics	5.8605	5	
	Significance level			
Critical Bounds	10%	5%	2.50%	1%
I(0)	2.08	2.39	2.70	3.06
I(1)	3	3.38	3.73	4.15

Table 5 presents the entire set of the ARDL simulation results. In the short term, CO2 emissions increase by 0.161% for each 1% rise in GDP. Over time, a 1% increase in GDP intensifies the correlation, resulting in a 0.354% rise in carbon emissions. The likely explanation for this phenomenon is that increased economic activity typically leads to increased energy consumption and industrial production, which often rely on fossil fuels, thereby causing environmental degradation. Several studies have corroborated with this findings such as Raihan et al.(2024d) in Indonesia, Sun et al.(2024) in 17 APEC countries, Raihan et al.(2024b) in Vietnam, Cao et al. (2022) in OECD economies, Abid et al. (2022) In G-8 countries, Pata et al.(2023) in USA, Raihan et al.(2024h) within Bangladesh, Mehmood (2024) in South Asian countries and Chen et al. (2022) in BRICS zone. On the other hand, Raihan et al.(2024a) in India and Saqib and Usaman (2023) in USA explained that economic growth is beneficial for the ecosystem level. Moreover, Salari et al. (2021) found an inverted-U shape relationship between CO_2 emissions and GDP in USA.

Conversely, a 1% increase in AI innovation correlates with a short-term reduction of 0.053% and a long-term decrease of 0.113% in CO2 emissions. AI innovation may enhance the natural environment by maximizing resource utilization, increasing energy efficiency, and advocating for sustainable behaviors across various industries. This result is aligns with Liu et al.(2022), Wang et al.(2023), Ding et al. (2023), Ahmad et al.(2021), Abir et al.(2024), and Bala et al.(2024). Conversely, Nahar (2024) indicated that AI-driven innovation did not have a beneficial impact on SDGs 10, 12, and 14–15 for the majority of nations among the 22 examined. On the other hand, a 1% increase in stock market value results in an immediate rise of 0.125% in carbon emissions and a long-term increase of 0.177%. The capitalization of the stock market elevates carbon emissions because heightened market activity frequently stimulates industrial growth and production, resulting in greater energy consumption and CO2 emissions. Similar outcome was also demonstrated by Alam et al.(2021); Ridwan et al.(2024d) causes more carbon emission.

Conversely, a 1% increase in ICT adoption results in a reduction of carbon emissions by 0.092% in the short term and 0.578% in the long term. We can assume that enhancing resource management efficiency, facilitating remote work, and promoting cleaner technology can make ICT consumption more environmentally friendly. Our findings is supported by (Danish,2019; Usman et al.,2021; Raihan et al.,2022a; Atasoy et al.,2022a; Qayyum et al.,2024) concluded that ICT might be utilized to lessen the detrimental effects of CO2 emissions and enhance the environmental quality. Conversely, Raheem et al.(2020), Huang et al.(2022) in E-7 economy claimed that the elevation in emissions causes by ICT use and hampers environment sustainability. A 1% increase in population growth leads to a 0.952% rise in CO2 emissions in the short term and a 0.810% increase in the long run. This may occur owing to heightened demand for energy, transportation, and resources, resulting in greater fossil fuel use and waste generation. In a similar vein, Voumik and Ridwan (2023) in Argentina, Voumik et al.(2023b) in Kenya and Appiah et al. (2023) in OECD economies expressed that population growth is harmful for the ecosystem. P-values below the established 5% significance level indicate that the coefficients demonstrate statistical significance in both time frames. These findings demonstrate that in the USA, there exists an inverse association of GDP, SMC, and population growth on carbon emissions. Conversely, studies have noted that the application of ICT and AI innovations reduces CO2 emissions in both the short and long term.

Table 5. Results of ARDL short-run and long-run Estimation

Variable	Coefficient	Std. Error	t-Statistic	Prob.
Long-run Estimation				
LGDP	0.354	1.503	1.897	0.020
LAI	-0.113	0.049	-2.303	0.027
LSMC	0.177	0.337	0.524	0.043
LICT	-0.578	0.464	-1.246	0.003
LPOP	0.810	0.034	0.756	0.034
C	75.201	13.863	0.907	0.015
Short-run Estimation				
D(LGDP)	0.161	0.177	2.153	0.000
D(LAI)	-0.053	0.031	-1.713	0.002
D(LSMC)	0.125	0.027	0.455	0.003
D(LICT)	-0.092	0.071	-1.196	0.051
D(LPOP)	0.952	1.424	3.476	0.013
CointEq(-1)*	-0.226	0.038	-5.891	0.000

Table 6 shows the results of the robustness investigation. It shows that the FMOLS, DOLS, and CCR simulations consistently showed good performance, producing results similar to those produced by the extended ARDL estimates over time. The GDP coefficients in all three models (FMOLS, DOLS, and CCR) are statistically significant at the 1% level and display positive values. A 1% increase in GDP results in a corresponding rise in LCO2 emissions of 0.977%, 0.872%, and 0.652% across the models, respectively. The FMOLS model suggests that a 1% increase in the LAI coefficient results in a 0.101% decrease in LCO2;

however, this finding is statistically insignificant. In the DOLS and CCR models, a 1% increase in LAI results in a considerable reduction of LCO2 by 0.192% and 0.017%, respectively. Furthermore, a 1% increase in stock market capitalization (LSMC) results in a 0.032% rise in LCO2 emissions in the FMOLS model, but a 1% increase in ICT usage (LICT) leads to a 0.250% decrease in emissions. These results align with the ARDL short-run and long-run estimations. A 1% increase in LPOP leads to a 0.342% increase in LCO2 emissions, as per FMOLS analysis. According to the DOLS model, a 1% rise in LSMC and LPOP results in an increase of LCO2 emissions by 0.081% and 0.256%, respectively. A 1% increase in ICT enhances environmental quality by decreasing LCO2 emissions by 0.186%, a finding that is statistically significant at the 1% level.In the CCR model, a 1% increase in LSMC and LPOP results in a 0.076% and 0.231% increase in LCO2 emissions, respectively, but a 1% increase in ICT leads to a 0.234% decrease in LCO2 emissions. The results align with the ARDL findings presented in Table 5, thereby strengthening the analysis's robustness.

Table 6. Results of Robustness Check

Variables	FMOLS	DOLS	CCR
LGDP	0.977***	0.872***	0.652***
LAI	-0.101	-0.192***	-0.017***
LSMC	0.032**	0.081**	0.076**
LICT	-0.250**	-0.186***	-0.234**
LPOP	0.342**	0.256***	0.231***
C	62.915***	59.566***	61.789***

Furthermore, this study included a number of diagnostic procedures to check how accurate the ARDL results were. Table 7 contains the calculations for the diagnostic assessment of the ARDL approach. The model functioned without any faults. The Jarque-Bera test, yielding a p-value of 0.57129, suggests that the residuals follow a normal distribution. The Lagrange multiplier analysis indicates the absence of serial correlation in the residuals, with a p-value of 0.06712. The Breusch-Pagan-Godfrey test indicates that the residuals do not display heteroscedasticity, as evidenced by a p-value of 0.3411. The diagnostic procedures applied to the ARDL model showed a high degree of agreement.

Table 7. Results of Diagnostic Test

Diagnostic tests	Coefficient	p-value	Decision
Jarque-Bera test	0.57129	0.4031	Residuals are normally distributed
Lagrange Multiplier test	0.06712	0.1023	No serial correlation exits
Breusch-Pagan-Godfrey test	1.76921	0.3412	No heteroscedasticity exists

Finally, the findings of causal linkages across several economic indicators are presented in Table 8. An F-statistic of 4.95374 and a p-value of 0.0154 indicate that LLGDP does not Granger-cause LCO2. This suggests that we reject the null hypothesis that there is no link between variables at the 5% significance level. Furthermore, the presence of one-way causation from LAI, LSMC, LICT and LPOP to LCO2 is confirmed by the p-values that are less than the conventional significance threshold. Thus, we rule out the null hypothesis that there is no causal relationship under these circumstances. On the other hand, p-values greater than the traditional significance criterion for each case show that there is no meaningful causal connection from LCO2 to LGDP, LAI, LSMC, LICT and LPOP. These results imply that changes in LCO2 do not influence ICT usage, economic growth, artificial intelligence, population growth and stock market capitalization. So, it is not possible to rule out the null hypothesis that there is no causality in these interactions.

Table 8. Results of Pairwise Granger Causality test

Null Hypothesis	Obs	F-Statistic	Prob.
LGDP ≠ LCO2		4.95374	0.0154
LCO2 ≠ LGDP	30	0.84545	0.4413
LAI ≠ LCO2		5.58219	0.0099
LCO2 ≠ LAI	30	1.83762	0.1801
LSMC ≠ LCO2		8.65988	0.0014
LCO2 ≠ LSMC	30	1.67744	0.2072
LICT ≠ LCO2		10.7905	0.0004
LCO2 ≠ LICT	30	0.0616	0.9404
LPOP ≠ LCO2		4.60632	0.0198
LCO2 ≠ LPOP	30	0.63614	0.5377

Conclusion and Policy Implications

This study seeks to analyze the long- and short-term effects of population increase, economic development, AI innovation, stock market capitalization, and ICT utilization on the carbon footprint in the United States, utilizing data from 1990 to 2021. The current research employed the ADF, DF-GLS, and P-P unit root tests to ascertain the integration order of the dataset. The variables exhibited long-term cointegration, as evidenced by the ARDL bounds test. Population growth, stock market development, and economic expansion would exacerbate environmental deterioration in the selected area, whereas advancements in artificial intelligence (AI) and the application of information and communication technology (ICT) would enhance the environment by reducing CO2 emissions. The anticipated results are solid and validated based on the CCR, FMOLS, and DOLS estimators. The Granger causality test suggests that LAI, LSMC, LICT, and LPOP may contribute to the carbon intensity of the USA in relation to LCO2. The diagnostic test confirms the appropriate distribution of the analysis residuals by revealing the absence of autocorrelation and heteroscedasticity. This article presents additional policy ideas for mitigating pollution while promoting sustainable development through the financing of green ICT, equitable advancement, sustainable stock market practices, and increased application of AI innovation. Finally, to avert resource depletion and promote sustainable development, the government ought to provide incentives for individuals to use green AI innovations and cutting-edge information technology. This study's findings yield various policy recommendations to improve carbon neutrality initiatives in the United States. The findings indicate that Artificial Intelligence (AI) and Information and Communication Technology (ICT) substantially decrease carbon emissions in both the short and long term, but economic development, population growth, and stock market expansion lead to increased emissions. Policymakers must prioritise the incorporation of AI and ICT in industries by offering incentives for enterprises to implement AI-driven solutions that enhance energy efficiency, minimise waste, and improve environmental performance. Advancing research and development in artificial intelligence for environmental sustainability is essential. Efforts must concurrently focus on dissociating economic growth from carbon emissions by advancing cleaner technologies, sustainable practices, and carbon-neutral regulations in industries such as manufacturing and energy generation. Urban planning and population management strategies must prioritise minimising the environmental impact of increasing populations via sustainable infrastructure and intelligent urban solutions. Ultimately, financial market regulations ought to promote environmentally sustainable investments, guaranteeing that stock market expansion bolsters green technologies and sustainable businesses. These steps can collectively guarantee that economic expansion and population growth do not impede efforts towards carbon neutrality.

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RESEARCH ARTICLE

Economic Indicators and Environmental Expenditure: A Re-evaluation of the Kuznets Curve in the EU-27

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Abstract

This study uses data from the European Union (EU-27) member states to examine the relationship between environmental expenditure and key socioeconomic indicators, including Gross Domestic Product (GDP) per capita, population size, urban population and unemployment rate. The analysis investigates if environmental expenditure follows the patterns suggested by the Environmental Kuznets Curve (EKC) hypothesis by applying linear and quadratic regression models. The results show a strong positive relationship between urbanization and environmental expenditure. However, rather than following the expected inverted U-shaped curve suggested by the EKC, the relationship between GDP per capita and environmental expenditure is more linear. The study finds a fairly significant negative relationship between unemployment and environmental expenditure but no significant relationship is observed between population size and environmental spending. These findings have significant policy implications as they highlight how urbanization affects environmental expenditure and the necessity of devising economic strategies that incorporate environmental protection at different stages of economic growth.

Keywords: Environmental Kuznets Curve; environmental expenditure; EU-27; GDP per capita; urbanization; unemployment rate

Introduction

Environmental expenditure is a crucial policy tool employed by governments to meet climate goals, mitigate environmental degradation and promote sustainable development. As countries around the world intensify their efforts to address issues associated with climate change, investments in environmental policies have become important for ensuring a sustainable future (Abbass et al., 2022). It is a pivotal factor for the EU-27 member states to meet their sustainability and carbon neutrality targets (Barrell et al., 2021) and a reflection of countries' commitment to environmental stewardship (Niu, 2024). There has been a surge in environmental spending in the recent past around the world. For instance, the EU environmental spending reached €130 billion in 2022 (Eurostat, 2024), indicating a steady increase in investment directed at achieving the region's sustainability targets. Previous research has examined the impact of environmental regulations on economic growth but the intricate relationship between environmental spending and socioeconomic factors remains an area of active research (Lenaerts, Tagliapietra, and Wolff, 2022). Socioeconomic factors like GDP per capita, unemployment rate, urbanization and population size may play a pivotal role in shaping countries' environmental policies because these variables determine the financial and social feasibility of sustainability measures implementation (Dalevska et al., 2019; Bhatti et al., 2024). Environmental expenditure is not only an indicator of a country's commitment to sustainability but also a crucial component of broader socioeconomic dynamics. However, such expenditure is dependent upon countries' economic condition. Countries with higher GDP per capita tend to spend more on environmental initiatives (Suhányi, Suhányiová, and Kočišová, 2023; Jayachandran, 2022). Moreover, countries with high GDP per capita generally have better environmental performance indices, suggesting that these countries tend to spend more on environmental infrastructure (Neagu, Ardelean and Lazăr, 2017). Furthermore, urbanization along with population growth have also been linked to environmental issues, necessitating governmental spending aimed at environmental initiatives (Jiang, Young and Hardee, 2008). Such relationships tend to be more common in developed regions, like the EU-27 (Suhányi, Suhányiová, and Kočišová, 2023; Romano et al., 2023).

The EU Green Deal (EGD) promotes the importance of resource allocation to sustainability initiatives, emphasizing the transformative effect of environmental spending in realizing ambitious targets aimed at climate change mitigation (Almeida et al., 2023). The EGD aims for a net-zero emissions by 2050 through investments in green technologies and infrastructure along with transitioning to a circular economy in the region (Kazak, 2020). Such initiatives could be funded through financial instruments like green taxation, which may not only promote sustainable practices but also foster economic growth (Phoomsavarth, 2023), leading to a rise in GDP per capita and job creation (Mulita, 2022). Environmental spending in light of the EGD may also result in sustainable urban development, leading to increased urbanization on account of cities adapting greener practices (Ruiz, Martin-Moreno, and Perez, 2023). The relationship between environmental expenditure and socioeconomic variables is complex and may not necessarily follow linear trends. Such non-linearities may emerge on account of different stages of economic development, demographic factors or policy priorities (Stern, 2004; Grossman and Krueger, 1995). The EKC suggests one of such non-linear relationships (Dinda, 2004; Halkos and Paizanos, 2013). It states that the initial stages of economic growth may result in a rise in environmental degradation but when economies reach higher income levels, the adverse impacts on the environment decline (Dinda, 2004). Developed countries, in particular, have shown similar trends at their various stages of development (Mohammed et al., 2024). The decline in environmental degradation is mainly due to technological advancements, countering the pollution effects of urbanization and income inequality (Ercan et al., 2024). Keeping in view the multifaceted nature of the relationship between environmental expenditure and key socioeconomic variables, this study uses both linear and quadratic models to provide nuanced analysis to better comprehend these dynamics and offer valuable insights for researchers and policymakers interested in interplay of economic growth and environmental sustainability. Quadratic models are particularly effective in capturing non-linearities like turning points in the relationship between environmental expenditure and GDP growth or urbanization rate. By focusing on the EU-27 member states, this study aims to analyse the relationships between environmental expenditure and socio-economic variables like GDP per capita, population size, Urbanization and unemployment rate. This analysis is important, because it highlights how a country's environmental policy and expenditure priorities are influenced by its economic and demographic conditions.

The rest of the paper is organized as follows. This section is followed by a comprehensive literature review, encompassing a detailed overview of the existing relevant literature. It is followed by data and methodology section. The subsequent section provides the analysis and results of the data, along with discussion of the results. The final part of this paper provides a concise conclusion of the study, including policy and future research recommendations.

Literature Review

The relationship between environmental expenditure and socioeconomic and demographic factors has been studied in literature in different contexts. For instance, GDP per capita is generally considered as a major driver of environmental expenditure (Upreti, 2015). However, this relationship is seldom uniform, as studies have highlighted the non-linear patterns (Cole and Elliott, 2003). Similarly, other variables like population size, urbanization and unemployment rates encompass layers of complexity, suggesting the multifaceted drivers of environmental spending and shaping policies.
This part of the paper provides an overview of the existing literature on the variables included in this study, focusing on theoretical and empirical underpinnings. It sets the foundation for the subsequent analysis, providing rationale for the models employed in this study.

GDP per capita

GDP per capita is often used to assess a country's economic development and financial condition (Upreti, 2015). A country's ability to invest in environmental protection is determined by the level of its economic development (Dasgupta et al., 2002). The EKC hypothesis has been extensively used in empirical studies concerning the relationship between environmental expenditure and GDP per capita. Countries with higher GDP per capita tend to allocate more resources to environmental protection. Same is the case in the EU (Eurostat, 2021). However, countries may experience diminishing returns on their environmental spending after reaching a certain threshold. Therefore, the relationship between GDP per capita and environmental expenditure may not follow a strict linear pattern (Grossman and Krueger, 1995; Dinda, 2004; Cole and Elliott, 2003; Halkos and Paizanos, 2013).

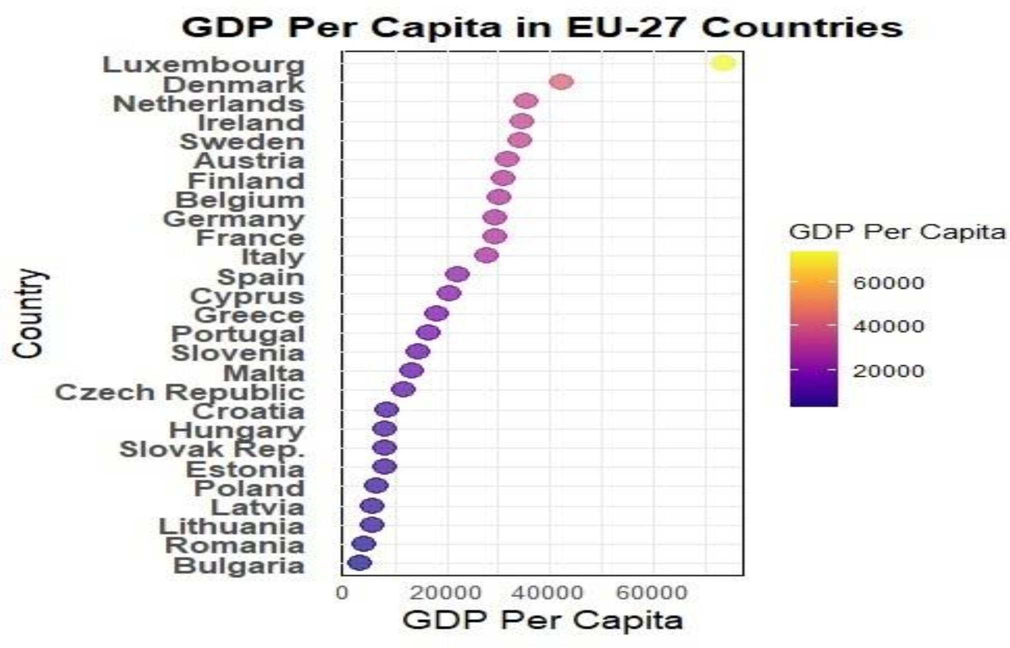

Figure 1. GDP per Capita in EU27

GDP per capita varies significantly among the EU member states, as depicted in Figure.1. It is mainly due to income inequalities (Ciurea and Cornelia, 2010), variations in labor utilization rates and different productivity levels (Mourre, 2009). That is why in Europe, the evidence supporting the EKC is mixed. Grossman and Krueger (1995) and Popsecu et al. (2023) provide evidence in favour of the EKC by observing inverted U-shaped curves between economic growth and environmental degradation. They argue that ecological footprints rise with income levels. However, when environmental awareness and new regulations become more prominent, it may eventually decline. Furthermore, Dritsaki et al. (2024) and Badulesco et al. (2019) find a positive relationship between environmental expenditure and GDP per capita. Some studies reveal that the relationship between environmental expenditure and GDP per capita is influenced by specific environmental variables. Leiter, Parolini and Winner (2011) argue that the outcomes of environmental investments can vary significantly across Europe based on institutional capacity, governance and the nature of environmental challenges. Similarly, Stern (2004) states that the effectiveness of environmental expenditure depends on how well environmental policies are integrated into the broader economic strategies. For instance, in Sweden and Denmark, the environmental regulations are in alignment with industrial strategies due to which environmental expenditure has resulted in positive economic and ecological outcomes. However, in Romania and Bulgaria, a more tenuous relationship between economic growth and environmental expenditure exists because governments prioritize economic growth over environmental protection (European Commission, 2018). Keeping in view the mixed empirical evidence and the potential non-linear relationship between GDP per capita and environmental expenditure, this study examines both linear and quadratic models to better understand the potential intricacies of this relationship.

Population Size

GDP per capita alone may not be sufficient to explain environmental expenditure as several other socioeconomic and demographic factors may also have an impact on a country's fiscal commitment to environmental protection. One of such variables is population size. The impact of population size on environmental expenditure is largely an unexplored area. Larger populations tend to put pressure on a countries' natural resources, necessitating robust environmental protection measures (Le Gallo and Ndiaye, 2021; Mohammed et al., 2024). This is relevant in the case of densely populated EU countries, such as Germany, France, and Italy (Eurostat, 2024). Figure. 2 shows that there has been a steady rise in population from 2001 to 2021 in the EU-27 member states. Larger populations may necessitate higher environmental expenditure to mitigate adverse environmental impacts. Similarly, Weber and Sciubba (2019) argue that regional population expansion in Western Europe has resulted in high levels of carbon emissions and Urbanization, validating the adverse impact of a larger population on the environment. Population structures vary greatly among the EU countries, resulting in different patterns in resource utilization, energy consumption and the level of Urbanization. Such a diversity in population structures may lead to varying levels of environmental degradation along with different environmental expenditure patterns (Mohammed et al., 2024). However, population size alone may not explain the environmental expenditure patterns. Environmental goals are more cost effective in more populous countries due to economies of scale. Fankhauser and Stern (2018) state that while larger population size may result in an increase in the absolute amount of environmental expenditure, the per capita expenditure may vary based on the countries' institutional frameworks, demographic factors and environmental priorities. While it is intuitive to presume that a large size population would result in environmental degradation leading to higher environmental expenditure. However, the relationship between the two variables is far more complex in the contemporary world. Moreover, the relationship between environmental expenditure and population size may not necessarily be linear. Countries with smaller populations like

Luxembourg may spend more on environmental protection on account of lifestyle choices and dietary patterns (Galli et al., 2023). This study explores whether larger EU countries allocate higher levels of environmental expenditure in comparison to the smaller states and whether this relationship remains consistent across different functional forms.

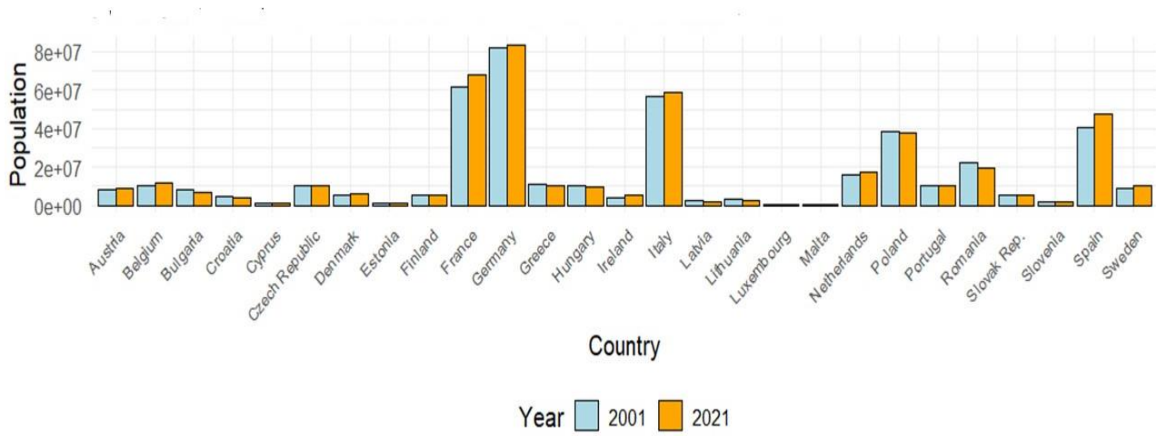

Figure 2. EU-27 Population Size 2001 vs. 2021

Urbanization Rate

Besides population size, urban population level may also impact the level of environmental expenditure (Singh, Shukla and Jain, 2024). Urbanization is a significant driver of environmental expenditure due to concentration of economic activities, population and infrastructure in cities (Hachaichi and Baouni 2020). Environmental challenges like air and water pollution, energy consumption and waste management are more prominent in urban areas, which necessitates higher environmental expenditure (Liang, Wang and Li, 2019; Di Clemente et al., 2021).

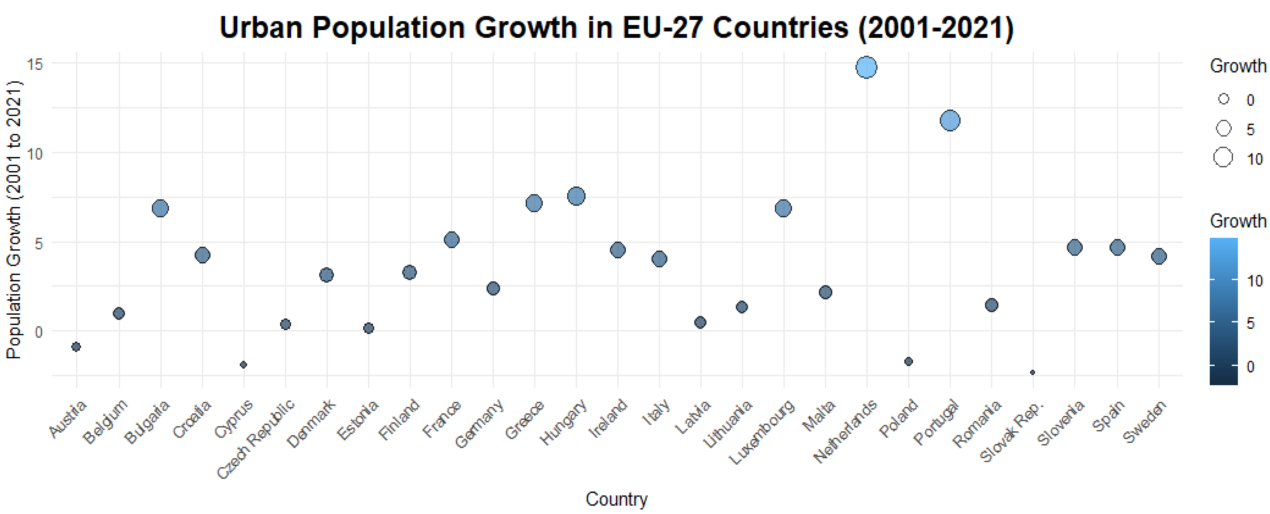

Figure 3. EU-27 Urbanization Rates

Urbanization has been a major contributor to environmental degradation and a driver of economic growth in the EU-27. The Netherlands has the highest urbanization rate as shown in Figure. 3 and may exhibit different environmental expenditure patterns in comparison to other EU member states (European Commission, 2020). Moreover, resource depletion and air pollution are more prevalent in Belgium and the Netherlands, two EU member states with high urban population densities. In response, governments have devised robust environmental policies, including increased investments in waste management, public transit and renewable energy (EEA, 2019).

Bowen and Hepburn (2014) suggest a direct correlation between Urbanization and environmental expenditure, drawing attention to the growing need for investment in environmental protection initiatives in the wake of urban expansion. Increased Urbanization correlates with higher energy consumption coupled with a rise in carbon emissions in most of the European countries, prompting governments to invest in environmental protection (Verbič, Satrovic and Muslija, 2021). Similarly, the European Environment Agency (EEA) notes that the EU-27 member states with high Urbanization rates tend to have higher levels of environmental expenditure (EEA, 2019). However, the complex relationship between Urbanization and environmental expenditure is influenced by several socioeconomic factors and may not be linear (Wang, Wang and Li, 2022; Liddle, 2017). For instance, Zhao et al. (2017) contend that variations in income levels and regional characteristics may cause shifts in the relationship between Urbanization and environmental expenditure. One of the objectives of this study is to explore whether there is a linear relationship or a diminishing return at higher levels of Urbanization between increased environmental expenditure and higher Urbanization rates.

Unemployment Rate

Besides the urban landscape, labour market conditions like unemployment rate may also have an impact on the level of environmental expenditure, particularly in countries that are under financial strain (Yip, 2018). A high unemployment rate can be interpreted as an indicator of economic distress (Collins, 2009) and may impact governments' spending priorities, resulting in lower environmental spending. In contrast, lower unemployment rates may allow for increased environmental spending (Meyer, 2016).

It is evident from Figure.4 that unemployment rates in the EU-27 member states fluctuate greatly in some countries, while in others these remain relatively stable. Such fluctuations in unemployment rates may affect environmental spending in these countries (Meyer, 2016). Similar to Urbanization, several variables may influence the relationship between unemployment and environmental spending. When unemployment rates are high, governments may put economic recovery ahead of environmental protection to create jobs. It may lead to a decline in environmental expenditure (Holum and Jakobsen, 2024). Same has happened in the EU over the years. Meyer (2016) reports that rising unemployment rates in some of the EU countries result in a decline in environmental spending because individuals prioritize economic survival over environmental protection. In contrast, Rosiek (2013) contends that insufficient environmental expenditure during economic downturns in the EU member states may lead to high unemployment due to stagnation of green industrial sectors.

Contemporary literature has explored sector-specific environmental spending. For instance, Kammen (2008) and Pollin, Heintz and Garrett-Peltier (2014) conclude that investments in renewable energy industry and sustainable infrastructure have significant potential for job creation. It implies that environmental spending can help lower the unemployment rate. Similarly, the European Green Deal emphasizes the potential of environmental expenditure in fostering economic resilience (European Commission, 2019). Fankhauser et al. (2013) also argue that investments in green technologies and infrastructure may not only address environmental challenges but also create new job opportunities. The EU's Just Transition Fund, which aims to assist member states that rely significantly on pollution-intensive industries, is an example of how environmental policies are used to promote economic development and reduce unemployment (European Commission, 2021).

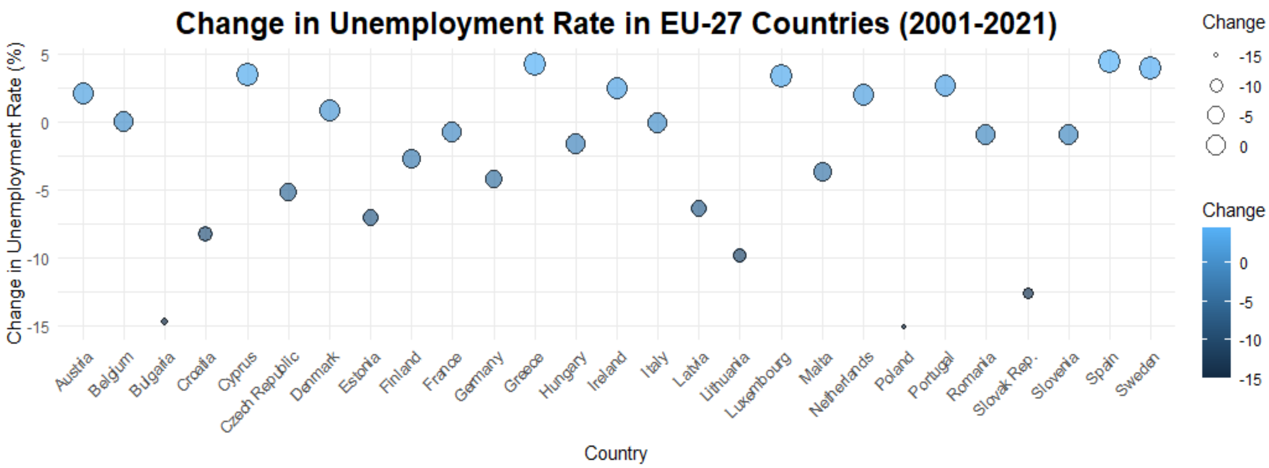

Figure 4. EU-27 Unemployment Rates

However, the relation between environmental spending and unemployment is more nuanced. While governments may hesitate to enhance environmental expenditure in the wake of high unemployment rate, initiatives resulting from environmental investment may serve as drivers of job creation, potentially contributing to economic recovery (Liu and Feng, 2022). As a result, depending on the regulatory frameworks and the nature of environmental initiatives implemented across the EU member states, the relationship between environmental expenditure and unemployment rate may differ (Fetting, 2020).
Although contemporary literature sheds light on these relationships, it reveals significant research gaps as the precise impacts of these variables on environmental expenditure are understudied. Therefore, the interplay of these variables in the context of the EU-27 necessitates a comprehensive examination. This study seeks to fill these gaps in literature by employing a variety of statistical tools to examine the relationship between environmental expenditure and key socio-economic variables.

Methodology

Data and Variables

The study uses panel data from the EU-27 countries from the period 2001 to 2021. Table. 1 provides details about the variables included in this study. Data for the dependent variable, Environmental Protection Expenditure (EPE), is sourced from the World Bank DataBank, providing records of environmental expenditure across the EU-27. The study involves four socioeconomic indicators serving as independent variables. Data for real GDP per capita (GDPPC) is extracted from the Eurostat. It is employed to examine its impact on environmental expenditure within the context of the EKC hypothesis. Data for Population Size (POP) is sourced from the Eurostat while the Urbanization (URB) data is collected from World Bank DataBank and serves to analyse the influence of urban growth on environmental expenditure. The Unemployment Rate (UNEM) data is also retrieved from the World Bank DataBank. The collected data ensures a comprehensive coverage of economic, environmental and demographic variables across the EU-27 region.

Table.1. Source and Description of Variables

Variables	Description	Unit of Measurement	Source
EPE	Environmental Protection Expenditure	Current US$	World Bank
GDPPC	Real GDP per Capita	Current US$	World Bank
POP	Population Size	Number of People	Eurostat
URB	Urbanization Rate	Percent of total population	World Bank
UNEM	Unemployment Rate	Percent of total labor force	World Bank

Empirical Methods

The study uses two regression models, i.e., linear and quadratic, to estimate the relationship between EPE and the four independent variables. Quadratic model is employed to determine whether the relationship of EPE and GDPPC reveals a U-shaped curve, as suggested by the EKC. The regression analysis is preceded by correlation analysis along with Granger Causality test.

Correlation Analysis

Correlation analysis is conducted initially to identify the strength and direction of the relationships between independent and dependent variables. The Pearson and Spearman coefficient matrices are calculated for each pair of variables to examine the extent of correlation and whether these are positively or negatively correlated.

Granger Causality Test

Correlation matrices are followed by Granger causality test to address the question of whether the one time series, i.e., GDPPC, POP, URB and UNEM can be used to predict another time series, i.e., EPE. Shahbaz et al. (2013) employed the Granger causality test to examine the causal relationship between economic growth, carbon emissions and energy consumption to determine the directionality between these variables over time. Fodha and Zaghdoud (2010) used it to analyse the causal relationship between economic growth and pollutant emissions in the context of the EKC hypothesis. In this study, it is crucial to use the Granger causality test as simple correlation may overlook directional causality.

Regression Analysis

Two regression models are employed to estimate the relationships between the above-mentioned variables.

Linear Model

A multiple linear regression model is used to examine the direct relationship between dependent variables like GDPPC, POP, URB, and UNEM and the dependent variable, i.e., EPE. Martınez-Zarzoso and Bengochea-Morancho (2004) used multiple linear regression to determine the relationship between economic growth and environmental degradation. Cagatay and Mihci (2006) also employed a linear regression model to determine the impact of environmental policies and economic growth on trade patterns.

The multiple linear regression model in this study can be written as follows.

$$EPE = \beta 0 + \beta 1.GDPPC + \beta 2.POP + \beta 3.URB + \beta 4.UNEM + \varepsilon$$

Where $\beta 0$ is the intercept, $\beta 1, \beta 2, \beta 3$ and $\beta 4$ are the coefficients for GDP per capita, Population, Urban Population and Unemployment, respectively. ε is the error term.

Quadratic Model

The non-linear relationships are determined through a quadratic regression model, in line with the EKC. Dinda (2004) and Stern (2004) employed quadratic regression models to examine the relationship between economic growth and environmental indicators in light of the EKC hypothesis. This study aims to capture the relationship between GDP per capita and environmental expenditure in the context of the EKC hypothesis.

The quadratic regression model in this study can be written as follows.

$$EPEvalue = \beta 0 + \beta 1.GDPPCvalue + \beta 2.GDPPCsquared + \beta 3.URBvalue + \beta 4.URBsquared + \beta 5.POPvalue + \beta 6.POPsquared + \beta 7.UNEMvalue + \beta 8.UNEMsquared + \varepsilon$$

Where EPEvalue is the environmental protection expenditure (dependent variable), GDPPCvalue is the gross domestic product per capita, GDPPCsquared is the squared term for GDP per capita to capture non-linear effects, URBvalue is the urbanization rate, URBsquared is the squared term for urbanization rate to model non-linear relationships, POPvalue is the population size, POPsquared is the squared term for population size, UNEMvalue is the unemployment rate, UNEMsquared is the squared term for unemployment rate, β0, β1,…, β8 are the coefficients to be estimated and ϵ is the error term. Data is analysed through R version 4.4.1.

Results and Discussion

This section encompasses results from the estimated methods discussed in the methodology part of this study. The preliminary analysis encompasses determining variable densities. Figure. 5 shows the distribution of variables included in this study, enhancing our understanding of these variables. Density plots in Figure. 5 show that the distribution of EPE and GDPPC are skewed to the right and have longer tails on the right side, indicating that a few higher values exist that pull the mean to the right. The distribution of POP is highly skewed to the right and has a longer tail on the right side. It suggests that there are some extremely large values that dominate the distribution. The UNEM distribution is almost symmetric, with a slight skew to the right. In contrast to the right-side skew of the other variables, the distribution of URB is skewed to the left, having a long tail on the left side. It indicates that there are a few lower values that are pulling the mean to the left. The skewness of the variables reflects differences in socioeconomic dynamics across the EU-27 member states.

Descriptive statistics

The descriptive statistics in Table. 2 reveal valuable insights into the variables. The mean value of EPE is 0.732, indicating a positive trend in environmental expenditure across the EU-27. However, the median value is lower than the mean, suggesting a right-skewed distribution. The range also shows significant disparities in environmental expenditure priorities among the EU-27 member states. Unlike EPE, the mean and media values of URB indicate a relatively symmetrical distribution, with a moderate variation among the countries as shown by the standard deviation.

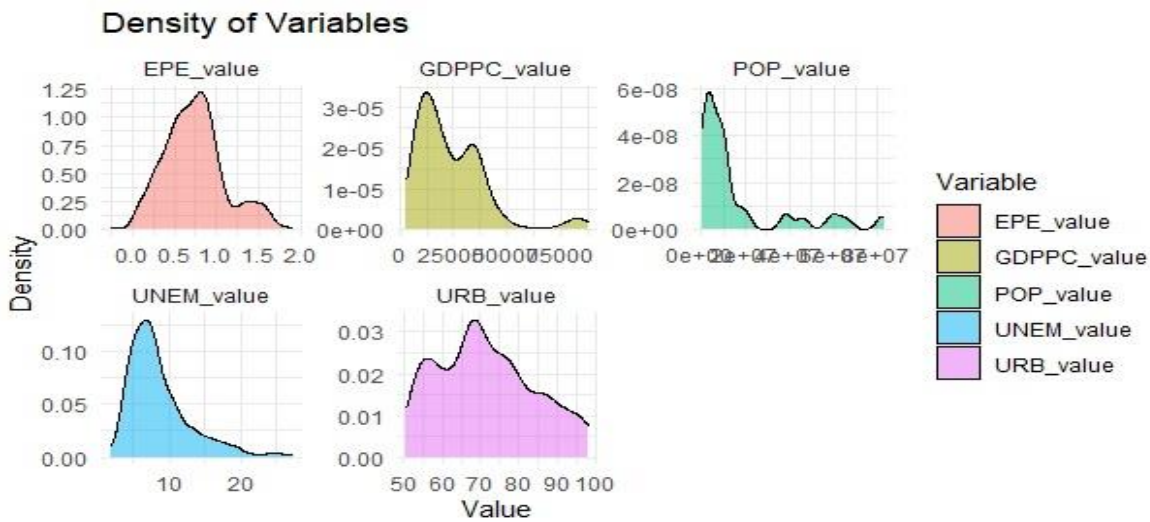

Figure 5. Density of Variables

GDPPC distribution is positively skewed as depicted by a comparison of the mean and median values. Standard deviation and range indicate a considerable economic disparity among the EU-27 countries. The UNEM mean value shows a moderately challenging employment landscape in the EU-27.

Table 2. Descriptive Statistics

Variables	Mean	Median	St. Deviation	Minimum	Maximum
EPE	0.732	0.707	0.359	-0.258	1.91
URB (%)	72.2	70.0	12.6	50.8	98.1
GDPPC ($)	24688	20670	16705	3210	88250
UNEM (%)	8.52	7.49	4.31	1.81	27.5
POP (‘000)	16322060	8391643	21465675	393028	83196078

Correlation Coefficient

Figure. 6 represents the Pearson correlation matrix, showing the relationship between EPE and the four socioeconomic indicators. The matrix shows a strong positive correlation between GDPPC and URB and a moderate positive correlation between EPE and URB. It shows that urbanization may have a moderate positive relationship on environmental expenditure. Moreover, a moderate positive correlation can be observed between POP and URB. Correlations between GDPPC and EPE, and POP and UNEM are weak.

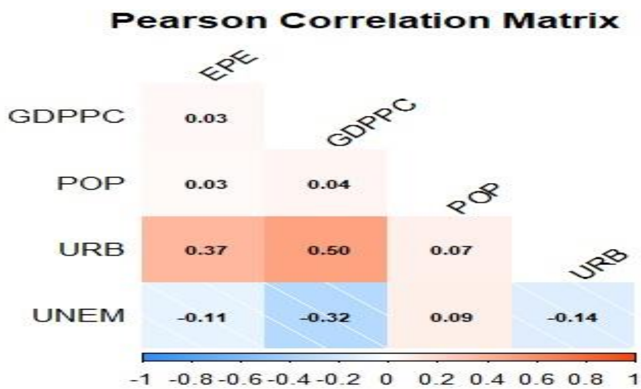

Figure 6. Pearson Correlation Matrix

Pearson correlation assumes that data points follow linear patterns (Myers et al., 2012). However, it may not accurately predict the strength of the relationship in case of non-linear relationships. Since the EKC suggests a non-linear relationship between economic growth and environmental spending, therefore, it is pertinent to examine the strength of the relationships through Spearman correlation. Moreover, the density plots show that the variables under study are not normally distributed and Spearman correlation is more appropriate in case of non-normal distribution (Schober, Boer and Schwarte, 2018).

Spearman Correlation

Spearman correlation matrix shows the relationships among five variables under study. The color scale in Figure. 7 represents the strength and direction of the correlations. The correlation matrix reveals that the most significant positive correlation is between GDPPC and URB, suggesting that as GDP per capita increases, EU-27 states experience higher levels of urbanization. Correlation between EPE and URB, and between POP and URB are moderately positive. It means that higher urbanization rates and population sizes may lead to higher environmental expenditure. Interestingly, the correlation between GDPPC and EPE, and POP and UNEM is weak, suggesting that GDP per capita may not have a direct impact on environmental expenditure. It also indicates that population growth may not have a strong impact on unemployment.

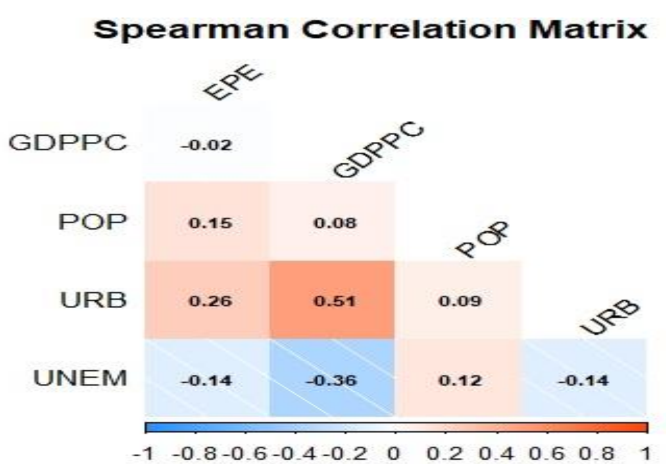

Figure 7. Spearman Correlation Matrix

A comparison of the two correlation matrices shows similar patterns. The strong positive correlation between GDPPC and URB and moderate positive correlation between EPE and URB are consistent in both Pearson and Spearman matrices.
Similarly, the correlation between GDPPC and EPE is weak in the matrices. Although the correlation between POP and URB is moderate in both matrices, it is slightly stronger in the Spearman matrix. It may show a non-linear relationship between the two variables.

Granger Causality Test

The correlation matrices provide insights into the strength and direction of the relationships between EPE and independent variables. However, correlation does not imply causality. If two variables are correlated, it does not mean that one causes the other. Therefore, it is pertinent to determine the causality through Granger causality testing, which is designed to determine whether one time series can be employed to predict another. This is crucial in cases where correlation analysis might overlook directional causality (Engle and Granger, 1987). Granger causality test is performed before regression analysis to determine the predictive relationship between EPE and the four socioeconomic variables. The rationale for employing this test lies in its ability to determine whether changes in one variable help predict changes in another variable over time (Engle and Granger, 1987). This test is relevant in economic research because understanding causal relationships can lead to informed policy and strategic decisions. Studies have used Granger causality tests to determine causal relation between export and economic growth (Jordaan and Eita, 2007), renewable energy consumption and economic growth (Aimer, 2020), CO2 emission, energy consumption and economic growth (Akadiri and Akadiri, 2020; Gorus and Aydin, 2019). Figure. 8 reveals that GDPPC, POP and UNEM do not Granger-cause EPE with a P-value of 0.586, 0.526 and 0.809, respectively. It shows that past values of these variables may not provide ample information for predicting future values of EPE. In contrast, URB shows a statistically significant Granger-causal effect on EPE with a P-value of 0.035, implying that past urbanization levels may help predict future environmental expenditure. Moreover, it suggests that increasing urbanization may result in higher environmental expenditure.

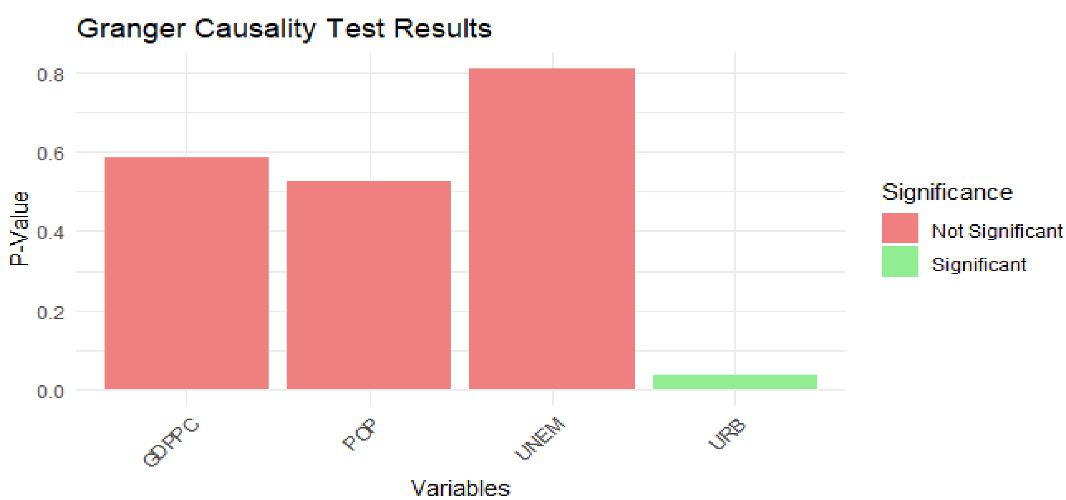

Figure 8. Granger Causality Test

After the Granger causality test, we will proceed to regression analysis, which will provide more detailed examination of how GDPPC, POP, URB and UNEM impacts environmental expenditure. It may help in identifying causal relationships and examine the factors that impact environmental expenditure.

Regression Analysis

Linear Model

Multiple linear regression analysis explores the relationship between EPE, the dependent variable and GDPPC, POP, URB and UNEW, the independent variables. The model aims to predict EPE based on the four independent variables.

Table. 3 shows the results from the linear regression model. GDPPC is significant and has a strong negative relationship with EPE, while URB has a strong positive relationship with EPE. It means that as GDPPC increases, EPE tends to decline. EPE tends to increase with an increase in urbanization rates. Al-Mulali and Ozturk (2016) and Shahbaz et al. (2013) also found that GDP is negatively associated with environmental spending especially in the long-run, while urbanization has a positive relationship with environmental expenditure.

Table 1. Regression Coefficients

Coefficients	Estimate	Std. Error	t-value	Pr (> | t |)
(Intercept)	-3.510e-02	9.168e-02	-0.383	0.70199
GDPPC	-5.385e-06	1.025e-06	-5.254	2.15e-07 ***
POP	2.610e-10	6.546e-10	0.399	0.69022
URB	1.376e-02	1.302e-03	10.571	< 2e-16 ***
UNEM	-1.031e-02	3.444e-03	-2.992	0.00289 **

Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Figure 9. Linear Regression Results

The F-statistic (p-value < 2.2e-16) indicates that the model is statistically significant. It shows that the independent variables collectively explain a significant portion of the variation in EPE. The regression model also reveals that UNEM is moderately significant, indicating a negative relationship with EPE as shown in Figure. 9. It shows that higher unemployment rates are associated with lower EPE. Apergis and Ozturk (2015) also found a negative relationship between unemployment and environmental expenditure in Asia. Fodha and Zaghdoud (2010) also reported a similar trend and argued that high unemployment diverts government resources away from environmental protection. Lastly, Figure. 9 shows that the variable POP is not statistically significant, which means that population size is not a significant indicator of EPE. This finding is similar to the investigation by Apergis and Ozturk (2015) and Pellegrini and Pellegrini (2011), where they found that population density does not impact environmental spending.

Interaction Effects

GDPPC and URB, GDPPC and UNEM

The interaction model expands the regression model by incorporating interaction terms between GDPPC and URB, and GDPPC and UNEM. It enables us to examine how the relationship between EPE and independent variables varies depending on the values of the other variables.

The adjusted R-squared value is almost similar to linear regression model which shows that the interaction terms do not significantly enhance the model's explanatory power. The interaction terms between GDPPC and URB are not statistically significant. It suggests that the relationship between GDPPC and EPE does not vary significantly depending on the URB level. Similarly, the interaction term between GDPPC and UNEM is also not statistically significant, indicating that the relationship between GDPPC and EPE does not vary significantly depending on the UNEM level.

GDPPC and POP, URB and UNEM

The model is extended further by including the interaction terms between GDPPC and POP, and URB and UNEM, allowing for further examination of the way the relationships between EPE and the independent variables vary depending on the other variables' values. The interaction term between GDPPC and URB, and GDPPC and UNEM remains non-significant in this extended model as depicted in Figure. 10. Similarly, the interaction term between GDPPC and POP is also not statistically significant. It shows that the relationship between GDPPC and EPE does not vary significantly depending on the POP level. The interaction term between URB and UNEM is also not statistically significant, suggesting that the relationship between URB and EPE does not vary significantly depending on the UNEM level.

The relationship between URB and EPE remains positive and statistically significant, despite accounting for interactions with other variables. This shows that increasing urbanization rates are associated with higher EPE, irrespective of the levels of GDPPC, POP or UNEM.

The adjusted R-squared value for the linear regression model and the models with interaction terms is approximately 0.1763, indicating that this model explains approximately 17.63% is the variation in the dependent variable. It shows that the independent variables are not able to account entirely for the variation and other factors may also influence it. Another explanation is that the relationship between EPE and the independent variables might be non-linear, which could affect the accuracy of the linear model. A quadratic model might provide a better fit because it allows for a non-linear relationship between independent and dependent variables. For instance, a point of diminishing returns may reach where an increase in GDPPC or other variables beyond a certain threshold result in a decrease in EPE. A quadratic model may capture curvilinear relationships and improve the model's explanatory power.

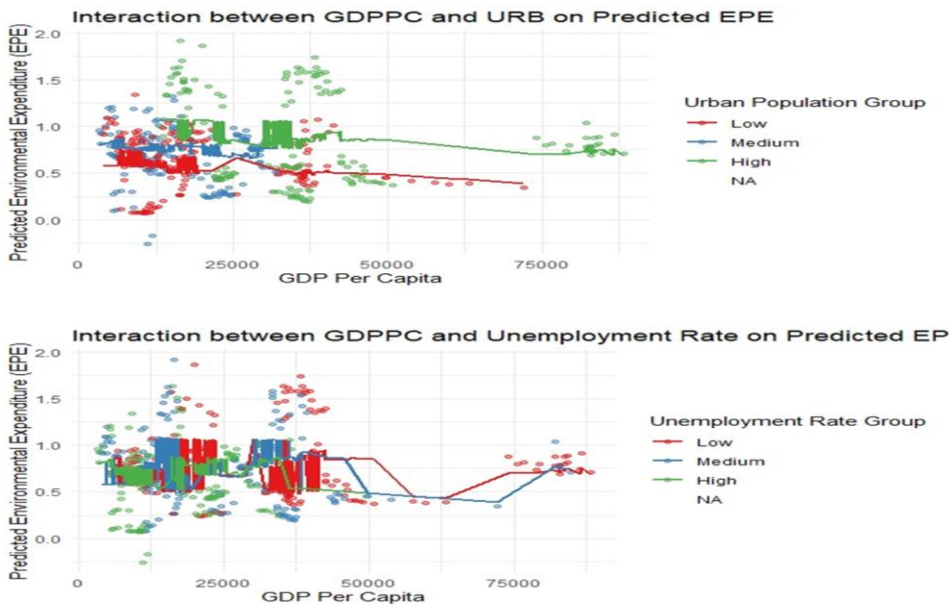

Figure 10. Interaction Effects

Table 2. Interaction Effects

Coefficients	Estimate	St. Error	t-value	Pr(>|t|)
(intercept)	-1.558e-01	3.203e-01	-0.486	0.62689
GDPPC_value	2.073e-06	8.190e-06	0.253	0.80031
URB_value	1.414e-02	4.356e-03	3.245	0.00125 **
UNEM_value	-1.123e-02	2.595e-02	-0.433	0.66546
POP_value	4.226e-09	2.773e-09	1.524	0.12815
GDPPC_value: RB_value	-3.769e-08	9.042e-08	-0.417	0.67699
GDPPC_value: UNEM_value	-6.429e-07	3.752e-07	-1.713	0.08726
GDPPC_value: POP_value	-1.285e-13	9.384e-14	-1.370	0.17134

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 '' 1
Multiple R-squared: 0.1903,
Adjusted R-squared: 0.1782
F-statistic: 15.77 on 8 and 537 DF, p-value: < 2.2e-16

Quadratic Model

The quadratic model is an extension of the linear model, incorporating squared terms for the independent variables. It helps in capturing non-linear relationships between EPE and the dependent variables.
The findings, as shown in Figure. 11 reveal that the adjusted R-squared value increased to 0.2944, indicating a substantial improvement in the model's ability to explain the variations in the environmental expenditure.

Moreover, the quadratic term for GDPPC indicates a non-linear relationship because the quadratic coefficient is positive in contrast to the negative coefficient in the linear coefficient. It shows an increasing relationship at higher levels of GDPPC. These findings resonate with the results of the quadratic model employed by Dogan et al. (2017) and Kaika and Zervas (2013) to determine the relationship between GDP and carbon emissions. These studies found that linear terms were negative, and the quadratic terms were positive. However, these studies found inverted U-shaped curves unlike this study.

The quadratic term for URB is also positive consistent with the findings by Wang et al. (2014). Interestingly, the quadratic term for POP is also significant like the linear coefficient but with opposite signs. Shao and Yang (2014) also reported a negative linear term and a positive quadratic term for population, while determining the relationship between population and environmental degradation. It shows that the relationship between EPE and POP is more complex. The quadratic term for UNEM is positive and significant in contrast to the negative coefficient of linear term which is in line with the findings by Apergis and Payne (2010).

The F-statistic (p-value < 2.2e-16) reveals that the model is highly significant and provides a better fit for the data in comparison to the linear model.

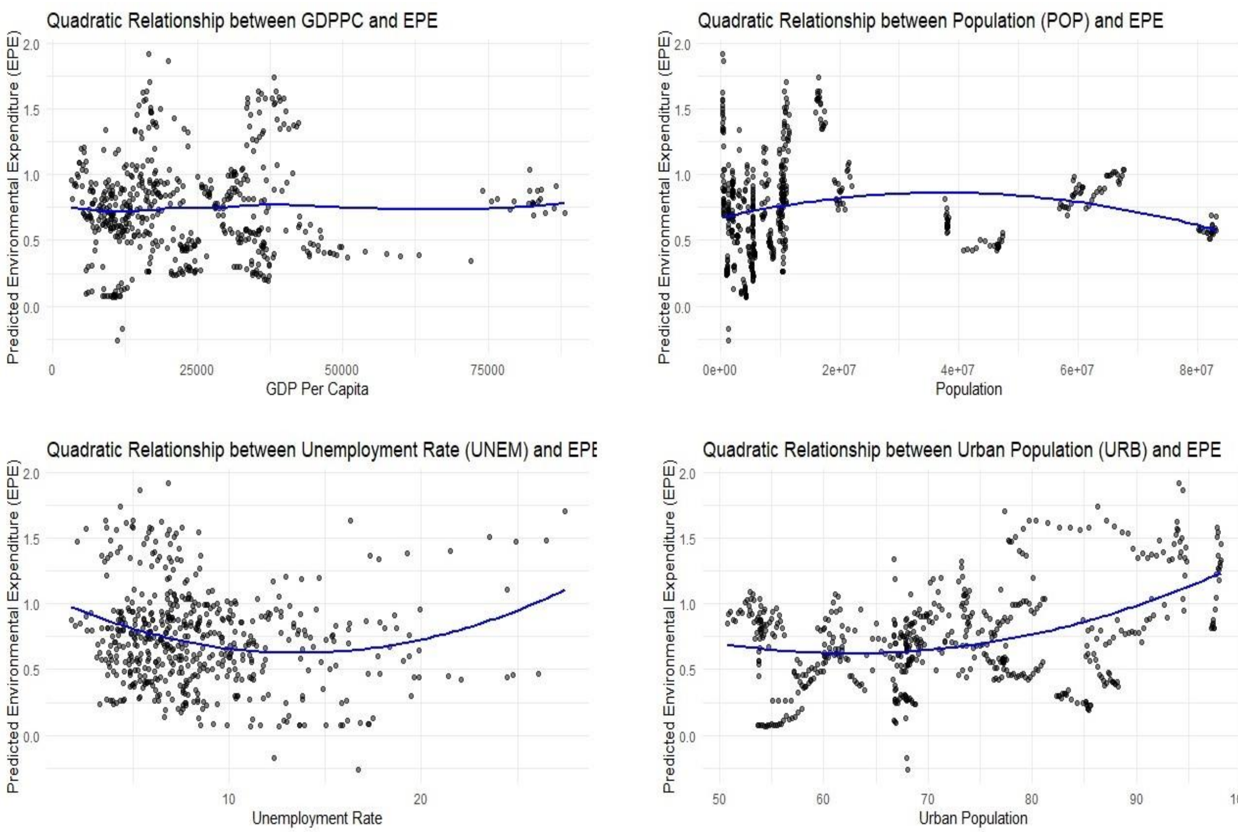

Figure 11. Quadratic Regression Model Results

The quadratic relationships between EPE and GDPPC, URB and UNEM show that increasing GDP per capita, urbanization and unemployment result in a decreased EPE initially, but after reaching a certain threshold, further increase may result in an increase in EPE. It may be due to factors like environmental regulations, technological advancements, government spending and public awareness. Unlike the suggested inverted U-shaped curve in the EKC hypothesis, the curve depicting the quadratic relationship between GDPPC and EPE appears to be more linear, indicating a consistent positive relationship. The relationship between EPE and POP is more complex and may depend on other factors.

Table 5. Quadratic Model Results

	Estimate	Std. Error	t-value	Pr(>|t|)
(Intercept)	3.143e+00	4.590e-01	6.847	2.07e-11 ***
GDPPC_value	-1.281e-05	2.682e-06	-4.775	2.32e-06 ***
GDPPC_squared	8.629e-11	3.111e-11	2.773	0.005739 **
URB_value	-6.783e-02	1.255e-02	-5.403	9.85e-08 ***
URB_squared	5.569e-04	8.509e-05	6.544	1.40e-10 ***
POP_value	1.077e-08	2.366e-09	4.553	6.56e-06 ***
POP_squared	-1.185e-16	3.208e-17	-3.693	0.000244 ***
UNEM_value	-6.542e-02	1.161e-02	-5.636	2.82e-08 ***
UNEM_squared	2.300e-03	4.644e-04	4.952	9.86e-07 ***

Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
Residual standard error: 0.3063 on 537 degrees of freedom
Multiple R-squared: 0.3048, Adjusted R-squared: 0.2944
F-statistic: 29.43 on 8 and 537 DF, p-value: < 2.2e-16

Figure. 12 compares the predicted EPE from the quadratic model to the actual EPE. The scatter plot shows that the model captures the general trend in the data but does not perfectly predict individual EPE values. The data points are upward-sloping, showing that as predicted EPE increases, actual EPE also tends to increase.

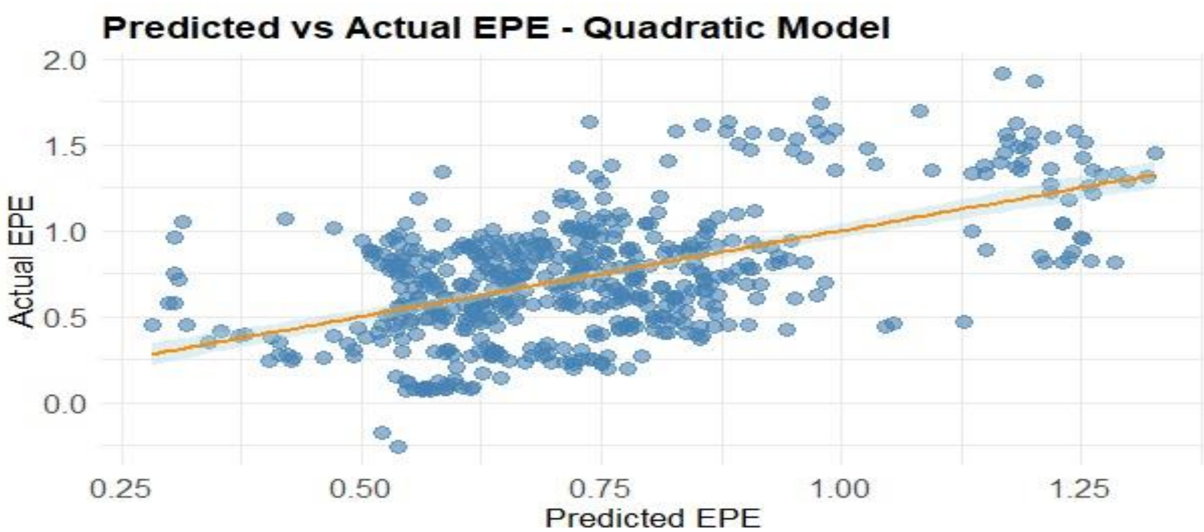

Figure 12. Predicted vs. Actual EPE (Quadratic Model)

Conclusion

This study aimed at determining the relationship between four socioeconomic indicators and environmental expenditure through a comprehensive analysis. The analysis revealed that urban population has consistent positive relation with environmental expenditure across linear and quadratic models. It implies that the EU countries with high urbanization rates tend to spend more on environmental protection initiatives. The findings showed that the relationship between GDP per capita and environmental expenditure is more linear in contrast to the inverted U-shaped expectation set by the EKC hypothesis. Although the quadratic model shows signs of non-linear relationship, the EKC's premise is still not supported. It necessitates further exploration by including factors beyond economic growth that may influence environmental expenditure. Furthermore, population size did not depict a statistically significant impact on environmental spending in both models while the unemployment rate has a negative relationship with environmental expenditure, indicating that higher unemployment rates are associated with lower environmental expenditure, possibly on account of economic constraints. The quadratic model offered a better fit for the analysis in comparison to the linear mode. However, the findings of the quadratic model suggest that although non-linear relationships exist among the variables, these may not necessarily be significant, specifically in the case of the relationship between environmental expenditure and GDP per capita. Nevertheless, the findings of this study carry important implications for policymakers. For instance, the strong positive relationship between environmental expenditure and urbanization rate reveals the importance of sustainable urban expansion in formulating environmental policies. Moreover, the lack of conclusive evidence for the EKC hypothesis reveals that policymakers need to consider the possibility that economic growth alone may not be sufficient to mitigate environmental deterioration. While this study provides valuable insights into the relationship between key socioeconomic variables and environmental expenditure, future studies may include additional variables to better understand the predictors of environmental expenditure. Furthermore, a comparison of these findings with those from other regions may shed light on the results' broader applicability. It is important to note the data's limitations and potential external factors influencing the findings of this study. Further research is needed to better understand the complex relationship between economic growth and environmental expenditure.

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