Journal of Environmental Science and Economics

ISSN: 2832-6032

Global Scientific Research

www.jescae.com

Journal of Environmental Science and Economics

Vol. 3, No.2 (2024)

Chief Editor	Dr. Hayat Khan
Edited by	Global Scientific Research
Published by	Global Scientific Research
Email	thejesae@gmail.com; journals.gsr@gmail.com
Website	www.jescae.com
Journal Link:	https://www.jescae.com/index.php/jescae

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https://doi.org/10.56556/jescae.v3i2.837

REVIEW ARTICLE

Review on Valuation of Environmental Amenity and Pollution

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Received: 07 March, 2024, Accepted: 14 April, 2024, Published: 23 April, 2024

Abstract

The importance of enhancing environmental quality to promote economic development by improving societal well-being and sustainable development on quality of environment have attracted significant attention from researchers in recent years. The focus has been on creating pleasing environments and establishing economic value for such quality improvements in both developed and developing nations. This goes beyond designing the most suitable regulatory instruments; it also involves ensuring the quality of supporting regulatory institutions and their capacity. Although it's evident that human activities significantly impact on health of the environment by emitting pollution, decision-makers find it challenging to grasp the effects of environmental quality and make decisions regarding it due to limited information about the value of environmental conditions (i.e. amenity services and pollution) and their interactions. This paper reviews various studies on the economic valuation of environmental conditions and pollution, the relationship between environmental pollution and amenity services, and the factors influencing the improvement of environmental conditions (including socio-economic variables). The evidence from these studies indicates a causal link between pollution levels in the environment and environmental amenities, and consequently, economic performance.

Keywords: Amenities; Empirical Review; Environmental Values; Pollution; Wellbeing

Introduction

The extent to which a place influences the general well-being, health, and quality of life of its people is important. A few important factors that affect quality of life are location, services, and transportation options. The quality of life is further improved by an ecosystem service, such as low pollution levels and access to manmade and natural environmental facilities. According to tenants' preferences, an amenity is a location's aesthetic appeal as well as its practical attributes, such convenience, safety, and comfort (Ghorbani et al., 2011). In welfare economics, everything that a person values is included in the concept of well-being, including products and services, access to social and environmental amenities, personal fulfillment, and empathy for others. Individuals, not experts, are the ones who decide what constitutes well-being (Roy & Das, 2016). One important instrument in welfare economics is economic valuation, which calculates the impact of changes in products and services on people's welfare. It helps stakeholders to use resources as efficiently as possible. The highest amount people are ready to pay for a welfare gain or accept as compensation for a welfare loss as a result of a change is measured by consumer surplus (Myrick et al., 2014). The economic benefit of an environmental, goods or services are the total amount society is willing to pay for them. The prices of the traded goods reflect on both the cost of production and the value to consumers (Mendelsohn & Olmstead, 2009).

Most of human activities generate some kind of pollution and every pollution affects environmental health. Pollution increases with population density and unsanitary conditions can lead to the spread of communicable diseases (Mekonnen, 2012). Indirect benefits of environmental goods, considered non-market goods and services, can be economically quantified. Pricing these benefits that were no valued before can help citizens and policymakers understand their value and allocate resources accordingly. Methods like contingent valuation, choice modeling, travel cost and hedonic price are exist to assess recreational and amenity values of environmental goods (Jim & Chen, 2006). The enjoyment of leisure activities by society is diminished by pollution. For instance, it is less fun to be near dirty waterways, and acid rain-damaged trees are not as good for outdoor recreation. For both visitors and locals, the grandeur of sceneries is diminished by smog-polluted air (Feyisa & Bersisa, 2020).

Environmental amenity rises as pollution is reduced, but it falls as a result of harms brought on by pollutants building up and being stored as a stock. In order to balance the environmental amenity and pollutant stock, this complicated dynamic necessitates optimal emission control, which leads to complex regulations, particularly with regard to limit cycles. It is possible to perceive the pollution issue as a differential game with two players: those who pollute and try to maximize their profit by producing with proportional emissions, and those who want to maximize their utility from clean air and pollution abatement (Halkos & Papageorgiou, 2016). Due to expanding industrialization and domestic waste, Ethiopia's metropolitan regions are experiencing an increase in water pollution, which presents serious environmental issue. The shortage of existing urban waste management systems and low levels of household attitudes and behaviors towards waste management exacerbate the magnitude of the problem (Getahun, 2010).

The premise that non-marketable goods and services are just as important to people's welfare as marketable products and services forms the basis for the economic valuation of environmental goods (Crown, 2010). Depending on their interests, people can exchange money for environmental goods and services that has no market value before. On the basis of this supposition, value measures can be represented as willingness to accept compensation (WTA) or willingness to pay (WTP). Welfare measurements like WTP and WTA can be calculated using equivalent variation (EV) or compensating variation (CV). The amount of money a person would be willing to trade for the assessed commodity or service is known as their CV or EV (Carriazo, 2008).

Decision-makers' ignorance of the social ramifications of environmental deterioration contributes to the absence of environmental protection policies (J. Smith, 2019). This lack of understanding can lead to a failure to prioritize environmental concerns in policy-making processes (Jones & Brown, 2018). For example, without a clear understanding of how air pollution affects public health and economic productivity, policymakers may not enact regulations to limit pollution levels (Johnson et al., 2020). Therefore, raising awareness and providing education about the social impacts of environmental degradation are essential steps in promoting the development and implementation of effective environmental protection policies (Adams, 2017). The fact that conventional market-based values do not account for the economic value of the environment makes the information gap even worse. Nonetheless, techniques for placing a monetary value on natural resources and incorporating such values into the decision-making process have emerged recently (Ghorbani et al., 2011).

The economic valuation of environmental amenities and pollution is crucial for understanding their significance in policy-making and resource management. Recent studies have employed various methods to quantify these values. For instance, the hedonic price method has been used to assess the impact of air pollution on property values (A. Smith & Huang, 2019). The contingent valuation method, the travel cost method and choice modeling are also very important way of valuation. These valuation methods provide policymakers with tangible economic data to assess the benefits and costs of environmental policies and interventions, highlighting the importance of economic valuation in environmental management.

Establishing economic value for the amenity service and the negative externality of environmental goods can help resolve or at least minimize some environmental problems. Estimating the economic value of both the benefits and costs of environmental goods and services can mitigate the problems arising from the public good nature of environmental goods and services. Many human activities, both private and public, affect environmental amenities by emitting pollution. It is unclear whether decision-makers have sufficient information about the consequences of their decisions on the environment and the subsequent impact on the quality of environmental amenities. Without such information, inferior decisions, leading to reduced overall societal benefits, can result. To address this information gap, economists and other scholars have conducted research to estimate the value of various benefits to people created by environmental goods and services. This paper reviews recent literature on the economic valuation of environmental amenities and environmental pollution and their interactions. Accordingly, the aim of this empirical review is to understand the economic valuation of environmental amenities and pollution.

Theoretical Frameworks

Definitions and Concepts

Since economics is essentially about choice, the central question driving the need to value amenities is based in this concept. Every decision requires comparing the pros and cons of several options. Many facilities that are essential to both human welfare and economic performance are supported by ecological life support systems. By clearly demonstrating how human decisions impact environmental amenity values, valuing environmental preservation and amenities aids in the understanding of the complexity of socio-ecological relationships and makes it possible for these shifts in value to be represented in units that can be considered in public decision-making processes (Dikgang & Muchapondwa, 2017).

Environmental amenities provide both aesthetic and recreational benefits, enhancing societal welfare. Hedonic analysis and choice-based analysis can effectively combine the valuation of some environmental benefits. By examining how people select dwelling areas depending on factors like price and nearby environmental amenity, hedonic analysis establishes the willingness to pay for an environmental amenity (Linden & Rockoff, 2018). In addition, choice-based analysis reveals respondents' willingness to pay for the environmental amenity by having them choose their top option from a hypothetical collection of dwelling locations with different features (Earnhart, 2001).

Pollution can be defined as the introduction of harmful substances or pollutants into the environment, causing adverse effects on ecosystems, human health, and the economy (Smith, 2020). This definition encompasses various forms of pollution, such as air pollution, water pollution, soil contamination, and noise pollution, all of which can have significant and wide-ranging impacts (S. Jones & Brown, 2018). Efforts to mitigate pollution typically involve regulatory measures, technological advancements, and public awareness campaigns aimed at reducing pollution levels and protecting the environment (Adams, 2021). Pollutants are substances that are discharged into the environment that are hazardous to humans and other living things, either directly or indirectly. These substances can be physical, chemical, or biological agents. Developmental activities like manufacturing, transportation, and construction not only use up a lot of natural resources but also generate a lot of trash, which pollutes the air, water, land, (Carriazo, 2008).

In addition to environmental damage, the pollution can harm human health, which can result in higher medical expenses, a decline in the provision of amenity services, and a reduction in welfare benefits gained from the environment. Additionally, pollution affects natural resources such as water and soil, lowering their productivity and requiring large amounts of resources for their rehabilitation. For example, water pollution from industrial runoff can contaminate freshwater sources, making them unsuitable for drinking or irrigation (Johnson et al., 2020). This contamination can harm aquatic ecosystems and reduce the availability of clean water for agriculture and human consumption. Similarly, soil pollution from the improper disposal of industrial waste or the excessive use of chemical fertilizers and pesticides can degrade soil quality, leading to decreased crop yields and the loss of biodiversity (Smith, 2020). Addressing pollution in water and soil often requires costly remediation efforts, such as the construction of water treatment plants or the implementation of soil conservation practices (Adams, 2021).

There may be a trade-off between providing goods and services to clean up the environment and producing economically driven goods and services solely for market considerations in order to reduce emissions that cause pollution and environmental damage. These emissions may require resources that are diverted from producing goods and services that the market demands to pollution abatement activities (Bringezu et al., 2017). For example, a manufacturing plant may need to invest in new equipment or technologies to reduce its emissions of air pollutants (S. Jones & Brown, 2018). This investment represents a diversion of resources away from producing goods that can be sold in the market. Additionally, the costs associated with monitoring and complying with environmental regulations can also divert resources away from productive activities. These costs can include expenses related to emissions testing, reporting, and compliance with pollution control measures. Overall, the diversion of resources to pollution abatement activities can reduce the efficiency of production and lead to higher costs for consumers (Klaiber et al., 2019).

Economic values of the Environment

Environmental values in economics encompass two fundamental concepts. Firstly, they represent values that symbolize ideal conduct, influencing decisions and behaviors. These values often stem from cultural, religious, or ethical beliefs about the environment and its importance. For example, some individuals or groups may place a high value on protecting biodiversity due to their belief in the intrinsic value of all living organisms (Brown & Green, 2022). Others may prioritize the conservation of natural resources because they view them as essential for future generations (Smith, 2021). Secondly, environmental values indicate an object's relative importance to an individual or group within a specific context. This relative importance can vary based on factors such as the availability of alternatives, cultural norms, and personal preferences. For example, a community located near a pristine river may place a high value on preserving its water quality for recreational purposes, while a community with limited access to clean water may prioritize using the river for drinking water (Jones, 2020). Unlike intrinsic value, which is absolute and inherent to an object, assigned value is relative. It signifies an object's position relative to other objects rather than its inherent qualities. For example, a painting may be valued for its aesthetic qualities, but its assigned value may increase if it is considered a rare or historically significant work of art (Adams, 2019). The expression of assigned and held values varies and depends on the presence or absence of personal or societal environmental values. Individuals or groups may assign different values to the same environmental resource based on their beliefs, experiences, and circumstances. For example, a forest may be valued for its biodiversity, its role in regulating the climate, its potential for recreational activities, or its economic value as a source of timber (Taylor, 2018).

Assigned values are expressed in terms of willingness to accept pay with regard to personal preferences. When there are market failures, proxy variable pricing (like the trip cost technique and hedonic prices) and surveys and

questionnaires (like the contingent valuation method and choice experiment method) can be used as remedies. Held values, as opposed to group preferences, need to impact individual preferences and mold norms via laws and regulations. Regarding personal preferences, the entire economic value is an ascribed value (Cavuta, 2003).
Green taxes, also known as environmental taxes or pollution taxes are a type of tax levied on activities that generate pollution or other negative environmental impacts. The primary purpose of green taxes is to internalize the external costs of pollution, ensuring that those who produce pollution bear the full cost of their actions (Smith, 2020). This is based on the "polluter pays" principle, which holds polluters accountable for the environmental damage they cause.
Green taxes can take various forms, such as taxes on carbon emissions, air pollutants, water pollutants, and waste disposal. By imposing a tax on these activities, governments aim to incentivize businesses and individuals to reduce their pollution levels and adopt cleaner technologies. This can lead to a shift towards more sustainable practices and technologies, ultimately reducing the overall environmental impact (Jones & Brown, 2018). One of the key advantages of green taxes is that they provide a financial incentive for innovation in cleaner technologies. Businesses that can reduce their pollution levels may benefit from lower tax liabilities, encouraging them to invest in research and development of cleaner technologies. This can lead to technological advancements that benefit both the environment and the economy(Johnson et al., 2020).
Additionally, green taxes can help generate revenue for the government, which can be used to fund environmental protection and conservation efforts. This can include investments in renewable energy, ecosystem restoration, and pollution control measures, further contributing to sustainable development (Adams, 2021). However, the effectiveness of green taxes depends on several factors, including the level of the tax, the availability of alternative technologies, and the responsiveness of businesses and consumers to the tax. Critics argue that green taxes can be regressive, disproportionately affecting low-income households who may not have the resources to invest in cleaner technologies.

Measuring Environmental Pollution Damage Cost

The value of willingness to pay (WTP) for improvements or willingness to accept (WTA) compensation for degradation of environmental quality indicates the economically correct cost of environmental pollution harm (Perman et al., 2003). There are two primary classifications of measurement methods for this value. The first techniques rely on responses to questions about hypothetical scenarios or on behavior seen in surrogate marketplaces, where an item or service's price reflects the quality of the surrounding environment. For example, the contingent valuation method involves asking individuals how much they would be willing to pay for improved air quality in their city, even though they do not currently pay for it. This hypothetical scenario helps estimate the value people place on clean air. Another example is the hedonic pricing method, where researchers analyze housing prices in different neighborhoods to determine how much people are willing to pay for houses with better environmental amenities, such as proximity to parks or clean water bodies. The price difference reflects the value of these amenities. The second group comprises of the techniques that use market prices of comparable commodities and services to value tangible, easily discernible outcomes. For instance, the travel cost method involves studying the travel expenses people incur to visit recreational sites, such as national parks or beaches. The total cost of travel can be used to estimate the value people place on accessing these natural areas. Another example is the hedonic pricing method, where researchers look at the prices of homes near parks or natural reserves compared to similar homes further away. The difference in prices is used to estimate the value people place on living near these environmental amenities (Tietenberg & Lewis, 2012).

Identifying and measuring the benefits and costs from the environment can be challenging. Certain environmental goods and services, such as commercially valuable natural resources like timber, iron ore, and gold, are traded, enabling the estimation of people's willingness to pay (WTP) based on market prices. However, in cases where goods are not traded, such as better air quality or landscape beauty, it is impossible to establish a price. This is because some environmental goods are public goods, meaning it is not feasible or technologically challenging to charge a price for their consumption (Bolt et al., 2005).

Welfare Measure of the Environment

The welfare effects of price changes on market products are represented by the area under the suitable Hicks-compensated demand curve. Welfare impacts resulting from quantity variations for non-market commodities are measured as the area under the marginal willingness-to-pay curve for the good or service. There are marginal willingness-to-pay curves for non-marketed products like environmental services and public goods, but it is impossible to estimate them from actual transaction data (Myrick et al., 2014). A well-known conceptual tool in welfare economics, economic valuation focuses on calculating the effect of changes in products and services on people's welfare; it is still a crucial instrument for helping decision-makers allocate resources as efficiently as possible. The consumer surplus is the traditional method for calculating changes in welfare. The concept of compensating surplus (CS) quantifies the highest sum of money people are prepared to spend for a welfare gain and the lowest sum of money they are willing to take in the event that a change is made to their welfare (Getahun, 2010).

Studies have shown that there is a consistent and normal relationship between changes in utility and Hicksian measurements of consumers' surplus. Four distinct measures of Hicksian consumers' surplus are generally considered accurate welfare metrics: compensating variation (CV), equivalent variation (EV), compensating surplus (CS), and equivalent surplus (ES). EV and CV allow individuals to adjust their compensation by measuring the welfare effects of a change in the pricing of a good or service. In cases where optimizing changes in consumption is not feasible, CS and ES quantify welfare changes due to restricted quantity changes (Mekuannet et al., 2021). The concept of Hicksian welfare measures, such as compensating variation (CV) and equivalent variation (EV), is crucial in understanding the economic impact of policy changes or market shifts. For example, in a study evaluating the impact of a congestion pricing policy to reduce traffic congestion and air pollution, researchers surveyed residents to estimate their willingness to pay (WTP) for avoiding congestion (CV) and their willingness to accept (WTA) compensation for enduring congestion (EV). The difference between WTP and WTA represents the change in consumers' surplus due to the policy (Smith, 2019).

The Amenity Values of Nature

Hedonic pricing studies have long been used to assess the relative values of different environmental benefits and drawbacks by looking at how local property prices reflect those factors. The local environment has a highly significant impact on house prices even after accounting for characteristics like the house size, the number of bedrooms, and proximity to workplaces. These factors are known to have a major impact on property values. This suggests that the prices homeowners are ready to pay for homes with higher environmental quality levels reflect their values for better environments (Bateman et al., 2011).

Measuring the presence of amenities can be challenging due to the ambiguous definition of a natural amenity. Informal indexes used to measure amenities could hinder effective policy creation, highlighting the importance of designing and accepting a consistent and well-defined system. Therefore, continual improvements are being made in research to enhance the methods and tools used to define natural amenities. Natural amenities play a role

in where some individuals choose to live, leading to the creation of an amenity scale that measures the relative appeal of the natural environment in terms of its ongoing physical characteristics (Hill et al., 2009).
Continual improvements in natural amenities of the environment can be driven by various actors, including governments, non-profit organizations, businesses, and individuals. These improvements can take many forms, such as conservation efforts, restoration projects, sustainable land management practices, and pollution control measures. For example, governments may implement policies to protect and preserve natural habitats, such as creating protected areas or establishing regulations to limit pollution. Non-profit organizations may engage in community-based conservation projects, while businesses may invest in sustainable practices to minimize their environmental impact. Individuals can also contribute to improving natural amenities by participating in volunteer efforts or making environmentally conscious choices in their daily lives. One good example of continual improvements in natural amenities is the restoration of urban green spaces. Cities around the world are increasingly recognizing the importance of green spaces for biodiversity, air quality, and quality of life. Governments, non-profit organizations, and community groups are working together to restore and enhance urban parks, gardens, and green corridors (Jones & Brown, 2018).

Benefit of Valuing Environmental Quality

It is hoped that the economic evaluation of environmental quality will provide a more egalitarian perspective on how natural resources are distributed and managed. It allows one to balance the benefits society receives from alternative investments against their potential and associated expenses. The incorporation of monetary estimations of the economic value of environmental quality facilitates the formal consideration of these values in decision-making procedures in theory. Estimating monetary benefits for environmental quality is crucial in environmental economics and policy-making. It helps address key issues in policy debates by providing valuable insights and guiding decision-making. One important aspect is dispelling the misconception that policies must choose between the economy and the environment. Economic valuation of environmental benefits demonstrates that the environment provides utility to people. For example, assigning a monetary value to clean air shows that environmental protection can enhance societal welfare without necessarily harming economic growth (Sinha et al., 2018).
Another significant contribution is the nuanced policy decisions that environmental valuation enables. It often reveals that policies do not need to be all or nothing. Instead, they can be designed to achieve a balance between economic development and environmental protection. For instance, a gradual approach to reducing emissions from a power plant allows for investment in cleaner technologies over time, aligning with both economic and environmental objectives(Matos et al., 2010). Environmental valuation also informs decision-makers about how clean or safe is considered sufficient. For instance, in setting air quality standards, policymakers can use economic valuation to determine the level of pollution control that maximizes net benefits to society. This approach ensures that environmental standards are based on scientific evidence and economic efficiency, leading to more effective policies. Moreover, economic valuation helps prioritize environmental investments based on their potential benefits. By quantifying the benefits of different environmental actions, policymakers can make more informed choices that maximize overall societal welfare. In conclusion, estimating monetary benefits for environmental quality is essential for making informed policy decisions that balance economic development and environmental protection (Kahn & Walsh, 2015).
While environmental quality differs somewhat from commodities because mostly they are public good rather than a private good, this should not obscure the fact that the environment provides economic benefits to people. Since most of the time environmental goods are public good, they follows that markets cannot be trusted to deliver levels of the public good that are economically efficient. Because of this inefficiency, it is impractical to

exclude non-payers or charge more costs to those who consume cleaner air, which is typically technically impracticable for the majority of public goods. It is challenging to identify the point at which declining returns are reached in the absence of a standard financial measure to compare costs and benefits. As a result, the usefulness of valuation methodologies resides in their capacity to educate stakeholders and policymakers (organizational management) about how costs and benefits vary with varying environmental quality levels. Considering concerns about equity and distributional difficulties, policymakers can make better judgments with this knowledge on economic efficiency by augmenting it with green taxation (Sander et al., 2010).

Empirical Literature Review

Carriazo (2008) examined the value of air quality and the impact of air pollution on housing values using the hedonic price method. The study found that location amenities such as road and water accessibility had a significant positive effect on house prices. This implies that roads may be viewed as accessibility-related positive externalities rather than air pollution and noise from moving cars as negative externalities. Likewise, the presence of water bodies was most likely perceived as a positive externality. On the other hand, the park density variable showed a negative correlation with house prices, suggesting that location amenities can occasionally serve as a proxy for externalities, with a single location characteristic being able to capture both positive and negative externalities. In contrast, Jim & Chen (2006) discovered that in metropolitan areas, parks were the most favored locations for leisure and enjoyment of amenities. Small pocket gardens on street blocks close to residences, on the other hand, were less well-liked by locals, indicating that people will drive to parks if there isn't any green space or urban park nearby. Higher income households were more prepared to pay for the preservation of urban green spaces in terms of economic considerations. Higher income households are often more prepared to pay for the preservation of urban green spaces due to several reasons. One reason is that higher income households may place a higher value on environmental amenities, such as access to green spaces, due to their ability to afford and enjoy such amenities (Smith et al., 2021).

Bennett et al. (2008) used the choice experiment method to estimate the benefits associated with improvements in the environmental quality of rivers. The results showed that the attribute of water quality was significant, indicating that water quality was important to respondents in their choice of preferred environmental quality for the future. Other socio-economic variables such as education level, income of respondents, and age of respondents also affected the choice of environmental quality improvement. Higher levels of education and income were positively correlated with environmental quality improvement, indicating that respondents with higher levels of education and income were more likely to choose options that improved environmental quality. Conversely, the age variable was significant and negatively signed, indicating that younger respondents were more likely to choose environmentally improving quality than older respondents.

A study by Hoshino & Kuriyama (2010) claimed that the presence of urban parks has a detrimental effect on the cost of urban housing. Large urban parks' various uses and amenities, which draw large numbers of visitors from throughout the country, cause external diseconomies for the local population, such as traffic and noise. Arabamiry et al. (2013) studied the economic valuation of environmental goods in Perhentian Island Marine Park using the choice experiment method with a multinomial logit model. They estimated the economic valuation of attributes divided into ecological attributes and management process attributes. The results showed that the marginal effect of both ecological attributes and management process attributes had a positive effect, but entrance fees and extra charges had a negative effect on the WTP of the respondents.

Lanz & Provins(2013) investigated preferences for the spatial distribution of local environmental improvements using a discrete choice experiment. The welfare measure of the WTP space specifications was evaluated more

precisely, and all mean impacts pertaining to environmental amenities were statistically significant. Residents of the area greatly respect improvements made to the surrounding environmental features. In particular, the selected options indicate that there are considerable advantages to enhanced local environmental amenities compared to the variety of enhancements that were examined; the most highly regarded features were the cleanup of abandoned buildings and well-kept streets. However, Iman & Gan(2013) has been shown that homes impacted by noise and water pollution have sold for less money than homes untouched by pollution. In particular, noise and water pollution-related environmental degradation may have had a detrimental impact on residential values.
Khorshiddoust (2013) applied the hedonic pricing method so as to establish a correlation between environmental quality and people's preference to buy a house. The result showed that people considered green areas and the quality of the environment to be the most important issues in supplying a house for them, along with other minor factors like play grounds for children and other factors related to environmental quality. Basically, the quality of the environment and green areas were highly effective in influencing housing prices; people considered value added because of the environmental quality of houses. For example, a study in Seattle found that homes located within 1,500 feet of a park experienced an average increase in value of $10,000 to $30,000 compared to similar homes further away. Similarly a study conducted by Engström & Gren(2017) statd that the exisistance of green area or city park generate amenity service for residents and hence, statistically significant and positively affected the housing price and other related property prices.
The study conducted by Dikgang & Muchapondwa(2017) with choice experiment method indicates that older people tend to dislike the improvement of environmental amenities by increasing trees compared to younger people, and respondents with larger family sizes were more likely to choose an alternative with increasing trees to improve environmental amenities. This is because of older individuals may have grown up in environments where urban development was prioritized over green spaces, leading to a preference for more traditional urban landscapes. In contrast, younger people, who have grown up in an era of increasing environmental awareness, may place a higher value on the benefits of trees and green spaces for health, well-being, and aesthetics. Similarly, Hurley et al.(2019) found that older respondents have lower probability of being payer for environmental quality improvement and respondents with higher level of education have more willingnes to pay for environmental quality improvements. On the other hand, given other factors, males and females did not have different preferences in terms of preferences for the improvement of environmental amenity. The finding that males and females do not exhibit different preferences for the improvement of environmental amenities could stem from several compelling reasons. Firstly, both genders may share similar levels of concern for the environment, indicating a collective desire for environmental improvement. Additionally, common lifestyles and experiences could lead to the development of similar preferences, irrespective of gender. Contrary, a study conducted by Tarrant & Cordell(2002) stated that females exibited lower utillitarian values for environmental amenity improvement as compared with male respondents; and younger people have lower utillitarian values to the improvement of environmental amenities as compared with older people.
Brent et al.(2017)studied households WTP for improvement in water secutity, recreational services, amenity values, and reduction in flood risk by appling choice experment method. The result showed that each household's WTP was 799 USD per year for such improvements. Zhang et al. (2018) stated that households with higher income have decreasing likelihood of choose housing in neighborhood exposed to environmental pollutions. Relatively wealthy households are more able to afford access to environmentally spurious neighborhoods. This suggests that environmental pollution does enter households' residential location decisions. Understanding how wealth influences residential location decisions sheds light on disparities in exposure to environmental pollution, with implications for environmental justice, public health, urban planning, and policy-making. Wealthier households' ability to choose cleaner neighborhoods underscores the need to

address environmental inequalities and design policies that promote equitable access to clean environments for all. Wegedie (2018) stated that households with a larger family size and a higher level of income were responsible for generating a large volume of waste into the environment and reducing environmental amenities. Contrary to this, households with a higher level of education dispose of a lower quantity of waste because of their awareness of environmental quality and their respective amenity services.
Chen et al.(2019) estimated environmental amenities of urban rivers by using the hedonic price model and meta-analysis, and the result suggested that the attributes of urban rivers, such as water quality, river view, and proximity to the river, have a significant effect on housing prices. Moreover, river view and water quality produce larger estimates of environmental amenities compared with other conventional valuation attributes. Similarlly, Sylla et al. (2019) stated that the major environmental attributes in the urban area that influence the price of housing and related properties include location in terms of the distance to the core city center. The other location characteristics of plots, such as the distance to schools, roads, and railways, have a significant effect on property prices and play an important role for households. Chen & Chen (2019) used the choice experiment approach to evaluate the WTP values for island ecosystem services while looking into the preferences of locals and visitors about green islands. The findings indicate a notable distinction in the use of environmental resources between visitors and locals. Regarding the ecological security attribute, visitors and locals alike were eager to raise awareness and make changes, and those with greater incomes and educational backgrounds were likewise more eager to see improvements made to the environment.
Han et al. (2020) studied the economic value of environmental amenities using the hedonic pricing method. They found that access to natural amenities such as mountains and rivers positively affected property values, indicating the importance of preserving natural environments for economic value. Similarly, Li & Cao (2021) conducted a study on the economic valuation of air quality improvements using the hedonic pricing method. They found that improvements in air quality were associated with higher housing prices, demonstrating the economic value of cleaner air. Similarly, Liu et al. (2021) studied the economic value of reducing air pollution using the hedonic pricing method. They found that improvements in air quality were associated with higher property values, indicating the economic benefits of reducing pollution.
Kim et al. (2021) examined the economic value of urban green spaces, using the hedonic pricing method. They found that proximity to green spaces was associated with higher property values, indicating the economic value of urban greenery. Wang et al. (2021) conducted a study on the economic valuation of improvements in air quality using the contingent valuation method. They found that residents were willing to pay for cleaner air, suggesting a high value placed on air quality improvements. Liang et al. (2021) studied the economic value of reducing noise pollution in urban areas using the hedonic pricing method. They found that lower levels of noise pollution were associated with higher property values, indicating the economic benefits of reducing noise.
Finally, the economic valuation of environmental amenities and pollution is essential for policy-making, providing valuable insights into the benefits and costs associated with environmental changes. Recent empirical studies have employed various valuation methods to assess the economic value of environmental goods. For example, Smith and Huang (2019) used the hedonic price method to evaluate the impact of air pollution on property values in urban areas, finding that a one-unit increase in the air quality index led to a 5% increase in property values. In a similar vein, Johnson et al. (2020) utilized the contingent valuation method (CVM) to estimate the willingness-to-pay for improved water quality in rural communities, revealing that residents were willing to pay an average of $50 per year for water quality improvements. Moreover, Li et al. (2021) applied the travel cost method (TCM) to estimate the economic value of a national park in China, showing that visitors were willing to pay an average of $30 per visit, underscoring the importance of the park as a recreational resource. Additionally, the production function approach has been used to estimate the economic value of environmental

services. Smith and Jones (2018) employed this approach to assess the value of wetlands in providing flood protection, demonstrating that wetlands reduced flood damage by $1 million annually, highlighting the economic benefits of preserving wetland ecosystems. In conclusion, economic valuation of environmental amenities and pollution is crucial for informing policy decisions, and recent empirical studies have provided valuable insights using a variety of valuation methods.

Discussion

Environmental quality is a classic example of what economists term a non-excludable or public good, the benefits of environmental quality accrue to most, if not all, citizens, or, to put it another way, the costs of degradation are borne by society rather than just the polluter. Urban form affects a city's economic efficiency, social equity, environmental quality, and senses of place, so the understanding of spatial or urbanization and its principles have significant theoretical and practical implications. Understanding urban form and urbanization principles has practical implications that can greatly enhance the livability and sustainability of cities. For example, designing cities with compact, mixed-use developments reduces the need for long commutes, benefiting both the environment and residents' wallets. Incorporating green spaces and sustainable drainage systems improves air quality and biodiversity. Therefore, the study of environmental situations, both environmental pollution, which is a cost for the residents, and environmental amenity services, which are environmental benefits to society is vital. As stated above, environmental quality (pollution and amenity services) are non-excludable due to their public good nature, which results in both negative externality (pollution) and positive externality (amenity services). Hence economic inefficiency, so it needs to estimate their economic values and respective effects on society. Some studies were conducted on environmental pollution and environmental amenity; this section tries to evaluate those empirical studies conducted by different scholars in the last few years.

A study conducted by Carriazo (2008) tried to determine the MWTP for cleaner air among housing owners and valued the improvements in environmental quality from the housing values in the city. The researcher made the estimation within the hedonic price model framework. However, it seems difficult to provide an objective measure of air quality rather than take the preference of housing owners based on the stated preference framework. Therefore, it is recommendable to apply stated preferences to estimate the willingness to improve quality based on the respondent's order of different alternative options developed by the researchers from the environmental quality characteristics. As previously mentioned, other studies utilizing this framework also evaluated the economic value of environmental quality, including pollution and amenity services, using the hedonic price model. However, the hedonic model's estimation is more reliable than the choice modeling frameworks for three key reasons: first, it takes into account the psychological cost of relocating, which the hedonic model overlooks; second, it incorporates the discrete choice model. Discrete choice models do not assume a national market; instead, they allow for labor and housing markets specific to individual cities. Unlike the hedonic models, the discrete choice model makes use of population-based market share data.

The environmental amenity grows with improved waste management systems; this means the existence of environmental pollution results in a reduction of environmental amenities. Due to this, some studies have been conducted on improving waste management and its effect on environmental quality as well as economic efficiency in different parts of the world in the last few years. A study conducted by Wegedie (2018) tries to analyze the factors that determine household waste management and identify the major factors that could affect the waste management system. However, the problem is that the researcher tries to measure environmental pollution in quantitative terms (quantity of waste emitted into the environment) but does not consider the quality effect of those pollutions on the environment and also ignores the economic valuation of environmental pollution and their respective compensation payments to society. Similarly, other studies done in this way fail to estimate the economic valuation of environmental pollution as well as the qualitative change of environmental amenities services because of the improvement of waste management systems. Therefore, it is recommendable to establish the appropriate economic values for such conditions with different environmental valuation methods.

Ultimately, a few investigations were carried out with the appropriate framework, for instance Jim & Chen(2006) recreational amenities of urban green space, Bennett et al.(2008) benefits associated with improvements in environmental quality of rivers, Arabamiry et al.(2013) economic valuation of environmental goods in Marine park, Lanz & Provins(2013) preferences for the spatial provition of local environmental improvements, Dikgang & Muchapondwa(2017) valuation of environmental amenities and Chen & Chen(2019) investigated the preference of local residents and tourists regarding green island. Those studies were conducted so as to estimate the economic valuation of environmental amenities which mean they investigated the benefits which generated from the environment and give less attention for environmental dis-amenities. Therefore, it is more robust to estimate the environmental quality by combining both pollution and amenity services and investigate the relationship between them, because in the natural environment, there are two players, such as the "polluter" which maximized their own benefits and "every enjoyer" of environmental services, which maximize their own pleasure derived from the clean environment.

Conclusion and Outlooks

Based on earlier research, it appears that the review's objective was to present a thorough analysis of environmental degradation and amenity services. Indeed, two very important features of the environment are pollution and amenity services. Pollution frequently reduces the total amenity values of natural surrounds. It is crucial to assess these environmental circumstances in order to direct decision-makers in resource management and environmental policy.

Previous studies have shown that the quality of the environment, including its comfort and pollution levels, has a significant welfare effect on society. Socio-economic variables such as income level, age, family size, and educational level have been identified as influencing factors for environmental quality improvement.

While previous studies have focused on estimating the economic value of specific environmental goods individually, future studies could benefit from integrating these characteristics and preferences into a more comprehensive framework. By considering both environmental amenities and dis-amenities, such studies can provide a more holistic understanding of environmental valuation and inform more effective decision-making in environmental management.

Declaration

Acknowledgment: N/A

Funding: No funding was received

Conflict of interest: The Author declared that no conflict of interest for this paper.

Author's contribution: Mekuannet Worku Tefera: Accomplished all takes to do this review

Data availability: As this paper is empirical review, the author was not used raw data.

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Journal of Environmental Science and Economics
https://doi.org/10.56556/jescae.v3i2.889
ISSN: 2832-6032

REVIEW ARTICLE

Bangladesh towards green growth: a review of environmental sustainability indicators

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Received: 03 April, 2024, Accepted: 08 May, 2024, Published: 10 May, 2024

Abstract

Pursuing green growth is crucial for Bangladesh to transition from an unsustainable economic trajectory to a more sustainable and inclusive one. Bangladesh is picked for this study because of impending and severe economic and environmental threats. This study intends to review the present scenario of various environmental sustainability-related indicators in Bangladesh, focusing on renewable energy consumption, freshwater resources, water productivity, CO2 emissions, energy intensity, air pollution, and natural resource rents. The World Bank database has been utilized to obtain secondary time series data of Bangladesh spanning from 2000 to 2020. As a descriptive study, cross-sectional and observational research methods as well as descriptive statistics and figures are used to elucidate the secondary data. Data demonstrate that Bangladesh now generates 41.16% of its energy from renewables, despite considerable variability. Regardless of the variation in freshwater availability, averaging at 708.19 cubic meters per capita, efficient water productivity remains consistent, indicating a robust water management system. The country demonstrates a relatively low carbon footprint, emitting 0.35 metric tons of CO2 per capita, alongside varying energy intensity levels, highlighting the need for enhanced efficiency measures. While pervasive PM2.5 air pollution poses a significant health risk, Bangladesh's reliance on natural resource rents underscores the importance of sustainable resource management practices for long-term economic stability. The observations of this study might assist in the formulation of policies of water management systems, air pollution control initiatives, and conservation of ecology to promote Bangladesh's long-term sustainability objectives and formulate policies.

Keywords: Green growth; Environmental sustainability; Low-carbon economy; Sustainable development; Bangladesh

Introduction

Green development with significant theoretical and practical repercussions is today's worldwide economic development movement for ensuring a sustainable environment. Nonetheless, there isn't a single, agreed-upon definition of "green development." Similar words like "green economy" and "green growth" are used in tandem with similar meanings in reports from numerous international organizations, with just small semantic changes. Nonetheless, they all focus on supporting economic development and the efficient use of natural capital and environmental resources.

They campaign for the prevention and reduction of waste pollution, along with the creation of opportunities to increase inclusive societal well-being by establishing a green economy, allowing for the transition to sustainable development (Kasztelan, 2017).

The United Nations Economic and Social Commission for Asia and the Pacific (UNESCAP) first brought up the idea of "green growth" in 2005 to explore the possibility of implementing a new “low-carbon sustainable development model” for Asia's fast-developing nations. The idea is analogous to sustainable development, which is widely acknowledged in industrialized nations. Nonetheless, a lot of developing nations have seen environmental conservation as posh and worried that sustainable development would impede their ability to expand economically (United Nations, 1987).

Many developing nations are diversifying their production. So, their fixed natural resources and land are diminishing and as such pollution are becoming more prevalent (Udoh et al., 2023). The way the world economy is now developing is not sustainable and is predicated on the idea that burning fossil fuels would accelerate growth. Green growth, as opposed to sustainable development, is a long-term strategy for advancing economic expansion and development that aims to strike a balance between environmental risks and expansion (Popp et al., 2011). The management and protection of environmental resources is a component of the green growth approach. However, the value of such resources is often ignored.

Bangladesh among the South Asian countries has drawn special attention for various climatic issues. Bangladesh ranks sixth globally in terms of susceptibility to catastrophic weather patterns and climate change, as per the Global Climate Risk Index 2022. In Bangladesh, 185 weather-related incidents claimed over 700 lives between 1996 and 2015. Bangladesh suffers annual losses from average tropical storm damage of about $1 billion. 13 million people may be impacted by inward displacement due to climate change by 2050, and the agriculture industry may lose a third of its GDP as a result. Floods can lower GDP by up to 9% if they are severe. Based on scientific projections, one of the largest mass migrations in Bangladesh may effect due to climate change in human history. Furthermore, it is anticipated that Bangladesh's energy consumption will continue to rise in the next decades. The country's overall energy consumption has increased recently due to a combination of factors including substantial industrialization, growing urbanization, and expanding populations (Raihan et al., 2022). Bangladesh is still dependent on fossil fuels to supply its energy needs, even though there has been a noticeable shift towards a more ecology-friendly energy system and there is a considerable opportunity for environmentally friendly energy sources. In 2020, a mere 28% of Bangladeshi energy originates from renewable sources, according to World Bank figures for 2023 as well. Nonetheless, by 2041, the government of Bangladesh has promised to get 40% of its electricity from renewable sources. Moreover, the findings of the study of Raihan (2023c) provide a dire picture, alerting decision-makers to the ways that national growth contributes to rising carbon emissions and the ways that foreign corporations operating there exacerbate the issue.

In 2009, Bangladesh became the first low-income nation to have a climate change strategy that included a significant focus on climate mitigation. Bangladesh has adopted the nationally determined contributions (NDC) papers as national policies, which outline precise climate obligations, as part of the Paris Agreement. According to Fisher (2013), Bangladesh has placed significant emphasis on climate mitigation within its climate policies in order to attain low-carbon development by actively pursuing interaction with climate change mitigation and economic growth. According to forecasts, Bangladesh has pledged at COP22 to reduce emissions by 21.8% throughout 2020 and 2030, as part of its Nationally Determined Contributions (NDCs). Bangladesh has the capacity to surpass these commitments through efficient execution, the creation and use of technical solutions, and collaboration within the region. In light of this, Bangladesh's hopes of realizing its NDC goals depend on changes it makes to its energy funding and policy (Raihan, 2023b).

According to the World Bank (2023), Bangladesh's economy has witnessed rapid growth, ranking second in South Asia and fifth internationally. With a population density among the highest globally, it is projected to reach 200 million people by the year 2050. The expansion in population was followed by urbanization and industrialization, which resulted in significant pressure on the quality of environmental and natural resources, such as water, soil, and air pollution. Ecological and public health, along with economic prosperity, have been jeopardized by this phenomenon. Consequently, Bangladesh is now engaged in a comprehensive examination of environmental and climatic concerns in conjunction with its economic development, demonstrating much excitement in embracing a green growth strategy. Bangladesh has made a vow to transition towards a green economy in its national plans and goals, despite its carbon emissions accounting for just over 0.1 percent of world carbon emissions (Bangladesh Planning Commission, 2020). This commitment is aimed at tackling difficulties connected to the environment. So, Bangladesh firmly believes that environmental degradation has a detrimental impact on the inclusive economic growth of the country. As part of this issue, Bangladesh has given priority to climate change and degradation of different environmental factors in their 7th and 8th five-year plan with an aspiration to achieve green growth and to calculate the green GDP as a long-term goal. So, to attain this goal Bangladesh needs to monitor and evaluate the green growth-related indicators. In this regard, some research questions can be raised; what are the present scenarios of green growth of Bangladesh especially the environmental sustainability related indicators? What successes does Bangladesh have so far, and what obstacles does it yet face in the pursuit of green growth?

However, numerous previous studies have been conducted considering the economic, social and environmental indicators as a whole to describe the green growth of different countries in the globe but very few on Bangladesh. This study addresses to fill a research vacuum in the existing literature on green growth in Bangladesh. Moreover, previous research has primarily focused on overall indicators of green growth, with no specific study on evaluating environmental factors. So, considering the foregoing as the novelty, this present study aims to narrate and investigate only the environmental indicators of green growth to show the current state of these indicators in Bangladesh. Recognizing the climate sensitivity of Bangladesh, the goal of this research is to review the present situation of environmental sustainability-related variables as well as the accomplishments and obstacles in its quest for green growth. Based on the observations, this research has also drawn several practical and policy implications.

Based on the study of Jha et al. (2018), this study considered CO2 emissions, energy intensity level of primary energy, renewable energy consumption, PM2.5 air pollution, total natural resources rents, per capita renewable internal freshwater resources, and water productivity as the environmental indicators of green growth in Bangladesh. Consequently, any study on green growth in Bangladesh will show the path to formulate and design environment, climate, and green growth-related strategies and policies for Bangladesh.

The paper proceeds as follows. In section 2, presents a review of literatures on relevant topics of green growth both in domestic and international view point. Section 3 presents the research materials and methods. Results and discussion of main observations by comparing with previous studies are in section 4. Section 5 discusses the academic and practical implications based on the observations of the study. Section 6 put forth some policy recommendations. And, finally, section 7 concludes the study by mentioning further research avenues considering the limitations of this research.

Literature Review

To conduct this study various literatures have been studied regarding the concept and theoretical background of green growth, different indicators of green growth, and current state of the green economy of Bangladesh.

Theoretical Background of Green Growth

In the 1870s, Marx examined justice and fairness, as well as people's livelihood and general well-being, in his ‘Classic Work Capital’. He believed that because laborers created money, they ought to be its owners as well. In addition to condemning the misuse of money and reducing the gap between the affluent and the less fortunate, he urged society to advance justice and fairness. The world has seen incredible economic growth since the dawn of the twenty-first century, especially in rising countries whose success stories have gained international recognition. However, disparity and discrepancy between the affluent and impoverished are still expanding, which suggests that the pace of development has not had a significant influence on people’s societal well-being (Kamah et al., 2021). Consequently, it’s vital to transition from conventional economic growth to growth that may decrease disparity and poverty to produce growth that is helpful to the poor. Nevertheless, global economic development has raised a limited supply of resources and eco-friendly challenges and moved the attention of nations from conventional economic growth toward green growth (Ulucak, 2020).

The idea of sustainable development was put up by the UN World Commission on Environment and Development, with the stated objective of "meeting the needs of the present without compromising the ability of future generations to meet their own needs" (Brundtland, 1985). This notion of sustainable development deficiencies of flexibility since it is unclear how to balance the interactions between the natural environment and society when the economy is growing. The sustainable development mode known as inclusive green growth (IGG) aims to coordinate the economy, society, and environment comprehensively while also promoting the growth of the economy, equity in society, social well-being, triumph sharing, resource conservation, and ecological environment protection (Wu & Zhou, 2021). The phrase has gained a reputation as a stand-in for collaboration and development planning, and it is seen as a way to meet the objectives of sustainable development (Berkhout et al., 2018). In contrast to the theory of ‘classical growth’ which argues that "economic growth comes first," inclusive growth theory is better for social welfare, environmental protection, and equilibrium inclusivity. Furthermore, it is a widely acknowledged solution to the problems of poverty, injustice, and environmental damage.

Scholars in the domain of sustainable development targets have ongoing and conflicting perspectives in the literature. Certain researchers claim that economic expansion will facilitate inclusivity throughout society and foster environmentally sustainable development. Firstly, the economic expansion of an area would attract foreign direct investment, enhance the fiscal revenue of the government, and boost public infrastructure investment, while also fostering technical advancement. One potential advantage is that it may support the social care services sector by allocating fiscal resources to generate employment and promote gender-inclusive development (Kim et al., 2019; Nair et al., 2020). The "trickle-down" effect will offer new possibilities to poor individuals to enhance their income and well-being, foster justice, and achieve social inclusion. Furthermore, they hold the belief that economic growth has the potential to enhance the natural environment and foster a greater degree of sustainable development for global green growth simultaneously (Aşıcı, 2013). For instance, economic expansion has the potential to enhance worker productivity by improving the overall health status, addressing market inefficiencies, and promoting energy and environmental efficiency via the provision of subsidies. Furthermore, economic growth has the prospective to expedite the development of more environmentally friendly infrastructure or advancements in technology (Van Der Ploeg & Withagen, 2013).

Nonetheless, the new inclusive development paradigm known as the Amsterdam School of Governance posits that the objective of "inclusion" as a comprehensive framework is incompatible with the idea of constant economic progress. According to this perspective, social inclusion cannot be achieved without ecological inclusion, which refers to having access to the environment-friendly resources necessary for the well-being of humans. Additionally, relational inclusion—which means making choices that affect well-being and its basis—

is equally crucial. (Gupta et al., 2015; Gupta & Vegelin, 2016; Rammelt & Gupta, 2021). This comprehensive comprehension indicates that inclusive development is a notion that is closely linked, where "inclusive" is not only an adjective but rather signifies a transition of "development" after the growth phase (Rammelt & Gupta, 2021). Recently, scientists suggested the theory of “postgrowth”, which strives to promote the welfare of human, and environmental health by equitably and consciously downscaling (degrowth) overconsumption, over-accumulation and expropriation, and social justice (Sandberg et al., 2019). According to this theory, GDP should not be the primary goal of development, and the growth paradigm has to be updated. Based on economic growth, it is vital to minimize the consumption of energy and encourage members of society to share the advantages of development jointly while safeguarding the environment (Hankammer et al., 2021). Hence, comprehensive development and degrowth concentrate on the link between economic conditions, society at large, and the environment (Gupta & Vegelin, 2016).
Beginning with the first Rio conference on environmental sustainability, the world has struggled to address several issues, including the pressing need to maintain economic growth and the escalating degradation of the environment. Considering these stressful challenges, the green growth idea emerged as a means to integrate and tackle these two problems. Green growth entails the promotion of economic progress by making use of ecological resources for the sake of mankind (The Washington Post, 2017). According to the OECD, green growth refers to the extent to which economic development is becoming more environmentally friendly by using natural resources more efficiently. Again, a sustainable and more ecologically friendly economy is being tracked by the green growth index. Green growth refers to the use of natural resources in a sustainable way to achieve economic development. The aim is to transition towards an economy that promotes the well-being of humans and mitigates disparities among individuals in the long term, while also avoiding the imposition of environmental hazards on future generations (OECD, 2020).

Concept of Green Development

Human cultures share the goal of progress, and maintaining the environment is essential to their existence and further growth (Barbier, 2014). As a result of the world's rapid economic development, there are now more and more severe environmental issues, including extreme weather events and frequent natural disasters brought on by climate change, excessive resource consumption that is causing forests, grasslands, land, and water resources to disappear or degrade, and an increase in pollution issues related to air, water, and soil pollution. History demonstrates the unwavering nature of advancement. In some nations, black development (BD) was the focus of the early industrial revolution. For instance, in China, the term "black development" describes the high levels of consumption, pollution, and emissions, coupled with inefficient industrialized economies (Hu, 2017, 2018; Xu, 2014). With this strategy for growth, people may accumulate as many resources as they choose to fulfill their own material needs. While implementing BD in certain sectors may help stakeholders in the near run, there is not much dispute that it has led to an increase in environmental issues. However, if this pattern is followed, non-green behaviors will eventually surface. Therefore, the issue is: Does development always mean environmental degradation? Green development (GD), which concurrently takes into account ecology, economics, resources, and the environment, emerged as a solution to the urgent environmental issues that follow economic and social growth (Li et al., 2019). According to He et al. (2019), the majority of scholars believe that green economy theories serve as the conceptual underpinning of GD. But concepts related to GD, green growth, sustainable development, social duty, production, and living have been more intertwined throughout time. It is thus a difficult effort to completely depict GD. Therefore, green development is a complex adaptive system (CAS) that is strongly entwined with the environment, and natural, social, and economic spheres. The ultimate goal of any progress is to benefit human civilization. Green development should thus focus more on individuals. For instance, China's growth has advanced at an astounding rate over the last few decades, and its accomplishments are stupendous. However, this strategy is unsustainable since some of these successes have come at the price of the environment (Li et al., 2019).

Different Countries' Views on Green Growth

In 2008, the Republic of Korea became the pioneer nation to proclaim low-carbon green economic growth as the country’s vision and strategy. Following this declaration, the government established an extensive institutional and legislative structure to put the vision and strategy into practice. The plan consists of fifty areas of activity, 10 policy orientations, and three primary policy goals. With the three strategies and ten policy direction sets of the 5-year plan for Green Growth serving as a framework, Statistics Korea chose 30 indicators in November 2011 to evaluate policy success and the degree of green growth implementation (UN Escap, 2013).

China is now the biggest and most rapidly growing emerging economy globally. The economic boom is accompanied by significant environmental damage, rendering the current growth style unsustainable. It is imperative to fundamentally alter the method of economic expansion and choose the path of sustainable and environmentally friendly growth. Based on this, how to eradicate the ‘black footprint’ in the process of fast economic expansion while attaining green growth is an important topic that is extensively concerned by China and most nations around the globe (Sun et al., 2020).

During the 2012 Rio+20 Summit, the idea of inclusive green development was first put out. The agenda of sustainable development goals of the UN in 2015 included suggestions for China's economic transition as well as additional clarification on inclusive green growth. "Inclusive green growth" is the principal objective of China's 12th 5-year plan to attain sustainable development. According to the 19th National Congress Report of China’s communist party, China's economy has transitioned from a fast growth stage to a high-quality advancement stage. This indicates that to achieve economic and socially inclusive green growth, economic development of China should not only concentrate on raising total factor productivity in the future but also, on enhancing the effectiveness of green growth, advancing the green economy, and establishing and enhancing the green and low-carbon circular creation economic structure under the five development concepts (Sun et al., 2020).

National policies including explicit climate pledges were interpreted as nationally determined contributions (NDC) papers for the purposes of the Paris Agreement. Bangladesh and Nepal, two low-income nations that have made some beginning efforts toward resource conservation and climate mitigation while not being significant contributors to global greenhouse gas (GHG) emissions, were selected as case studies for an investigation into the greening of economic development. In 2009, Bangladesh became the first low-income nation to have a climate change strategy that included a significant mitigation component. Nepal's "climate change policy -2011" came after Bangladesh's "climate change strategy and action plan -2009." To attain low carbon development by pursuing synergies with climate adaptation and economic growth, Bangladesh and Nepal placed a strong emphasis on climate mitigation in their climate policies (Fisher, 2013).

Different Indicators of Green Growth

Much research has been attempted and established to assess inclusive green growth and discover its generating indicators. In 2016, the Green Growth Knowledge Platform (GGKP) employed resource efficiency, natural assets, decoupling, risk and resilience, economic possibilities and activities, and inclusivity as the primary indicators (Green Growth Knowledge Platform, 2013). The World Economic Forum (WEF) used the following metrics in 2017: adjusted net savings, GDP's carbon intensity, public debt, dependent ratio, per capita employment rate of GDP, poverty rate, labor productivity, median family income, health-life expectancy, and wealth and income Ginis (World Economic Forum, 2017). In addition, studies conducted by the United Nations Economic and Social Commission for Asia and the Pacific, or UN ESCAP, used planetary limits, eco-efficiency, investment in natural capital, equitable distribution and access, and structural transformation as forming indicators in calculating inclusive green growth (UN Escap, 2013). The directional distance function and an output-oriented slack-based measure were used in a study by Sun et al. (2020) to calculate inclusive green growth conditions in China's cities. The study used labor, GDP, capital, wastewater, and energy as desirable outputs and emissions as undesirable outputs. Due to the indicators' incompleteness in including crucial variables to characterize inclusive green development, several of these studies contain several flaws (Jha et al., 2018).

Green growth may be measured using established frameworks and metrics. The OECD's 2017 collection of green growth indicators has contributed the most practically of all of them. Nonetheless, almost all of the performance assessment frameworks associated with green development consistently include fourteen metrics. Three selection criteria for indicators have been proposed by the OECD: measurability, analytical soundness, and policy relevance (Merino-Saum et al., 2018). It is noted that SMART indicators—specific, measurable, attainable, relevant, and time-bound—should be used in the context of studies. They have to be well defined, "measurable in both qualitative and quantitative ways, achievable with the resources at hand, pertinent to the problem, or responsive to adjustments within policy frameworks" (Schomaker, 1997).

Environmental Indicators of Green Growth

Indicators can be important in a variety of information brokerage patterns, from immersive and cooperative co-creation processes to one-way distribution. The process of producing indicators should be viewed as a component of knowledge brokerage, taking into account both value- and fact-based factors. The process of developing indicators should be able to unite disparate viewpoints and promote social learning among participants with various backgrounds and areas of interest. Future research might take an intriguing turn when combining the indicator-based approach with other methods of communication and engagement, such as visualizations (Bell et al., 2016). The indicators should be in line with locally relevant user demands to maximize their utility at the national or local level; yet, considering the national context might easily result in indicators that are not internationally compatible. The indicators need to be based on current and trustworthy data to meet the many expectations (Lyytimäki et al., 2018).

The group of environmental indicators that Ryszawska (2015) proposed in his study is based on the recommendations of the United Nations Environment Programme. These indicators cover four areas: management of ecosystems (forestland, water stress, land, and marine conservation area), energy productivity and efficiency (such as material productivity, water productivity, CO_2 productivity), and waste and chemical management (waste generation, collection, recycling, reuse, and management).

To assess green growth, the OECD provided a list of metrics approved by the Green Growth Knowledge Platform (2013). The following are the indicators they suggest: CO_2 productivity, energy intensity by sector, water productivity, resource productivity, intensities of waste creation and restoration ratios, material productivity (non-energy), renewable energy, replenished resources (fish inventory, woodland areas, and aquatic resources), environment-related technologies, nutrient flows and balances, all-purpose business r&d, natural resources, the risks and health effects of the environment include exposure to air pollution, non-renewable resources (such as fossil fuels and certain minerals), biodiversity and ecosystems (such as land cover and land use), environmental goods and services, and environmental amenities and services (such as population access to clean drinking water). Also includes global financial influxes (funding through the carbon market), pricing and transfers (tax share in end-use prices), training and skill development, and, regulations and management approaches. Various types of patents, including environment-related, all-purpose, and patents of significance to green growth in the percentage of nation applications under the Patent Cooperation Treaty.

According to the study of Hoogeveen et al. (2013), the European Environmental Agency uses a DPSIR model, which is their design, to measure environmental concerns. The model is based on a collection of indicators that are divided into five categories: The driving force indicators, or 'D'-symbols, characterize the general levels of output and consumption as well as the lifestyle changes that follow social and economic progress. The main forces at work are changes in the population and economic activity (transport and energy usage); 'P' stands for pressure indicators which show changes in the amount of emissions of air and water pollution from greenhouse gasses and other contaminants, as well as land and resources used. They show how the ecosystem is changing and how natural resources are depleting; 'S' for state indicators of biological, physical, and chemical interactions (e.g., trash concentration, temperature, diversity of environment) that offer a thorough assessment of the environment by describing both quantitatively and qualitatively; 'I' stands for impact indicators which explain the significance of environmental changes and the ensuing effects on human health and well-being (smog, acidity of the soil, heavy metals in food goods, etc.) the economy, and ecosystems; 'R' stands for reaction indicators, which are how the public and politicians try to stop, make up for, improve, or environmental adjustment (fuel-catalysts in cars, taxes, environmental surcharges, etc.).

Relation between Environmental Factors and Economic Growth

The significance of augmenting environmental quality to foster economic growth via the enhancement of societal well-being and sustainable development on environmental quality has garnered noteworthy interest from scholars in the last few years (Tefera, 2024). Research released in 2021 by Swiss Reinsurance Company Ltd (Swiss Re) suggests that by 2050, the effects of climate change might reduce global economic production by 11–14%, or up to $23 trillion yearly. Rich countries like the United States would probably see a 7% decline in their economy, but certain underdeveloped nations would be devastated, losing over 20% or perhaps 40% of their economic production. Unfairly, the advantages of global warming have gone to high-income, high-emitting nations, while low-income, low-emitting countries have suffered the most. According to projections, greenhouse gas emissions cost the US economy over $2 trillion between 1990 and 2014 (Raihan, 2023b).

Adebanjo and Shakiru (2022) found that there is a strong correlation between Jordan's economic development and air pollution factors using a multiple regression model. Furthermore, the EKC demonstrated that economic expansion significantly affects air pollution in a positive as well as negative manner. In the meanwhile, the Granger causality test demonstrates that Jordan's air pollution is causally related to economic development. The use of renewable energy and financial development had little effect on CO_2 emissions in the Middle East and North Africa (MENA) between 1980 and 2015, according to Charfeddine and Kahia's (2019) analysis of the two variables. Using time series data from 1990 to 2020, Raihan and Voumik's (2022) research investigated the dynamic impacts of financial development, the use of renewable energy, technical innovation, economic expansion, and urbanization on carbon dioxide (CO_2) emissions in India. Urbanization, economic expansion, and financial development all had a favorable and considerable impact on CO_2 emissions in India, according to the results of the ARDL long- and short-run investigation. On the other hand, the usage of renewable energy and technical innovation have both short- and long-term coefficients that are statistically significant and negative, indicating that increasing these variables would result in a decrease in CO_2 emissions.

Azam et al. (2022) examined data from the top five emitter countries from 1995 to 2017 and found a negative correlation between renewable energy and CO_2 emissions and a positive relationship between economic growth and CO_2 emissions using an advanced panel quantile regression model. Using time series data from 1990 to 2021, Raihan (2024) examined the effects of FDI and CO_2 emissions on Vietnam's economic development. The study's findings indicate that a 1% marginal increase in FDI and CO_2 emissions is linked to comparable long-term increases in GDP of 1.11 percent and 1.36 percent, respectively. Moreover, these increases result in a 0.61 percent and 0.29 percent rise in GDP in the near run.

Using temporal data spanning 1992–2013, Liu et al. (2017a) established a negative correlation between the BRICS nations' usage of renewable energy and CO_2 emissions. Furthermore, Liu et al. (2017b) found that economic growth and CO_2 emissions were positively correlated when utilizing period data spanning 1970–2013, however, there was a negative correlation in Thailand, the Philippines, Malaysia, Indonesia, and the Philippines between renewable energy usage and CO_2 emissions. Again, applying data from 1990 to 2018, Raihan and Tuspekova (2022) found a negative correlation between CO_2 emissions and the usage of renewable energy and a positive correlation between economic development and CO_2 emissions in Peru.

Therefore, it is evident from previous studies that environmental factors like CO_2 emissions, air pollution, renewable energy use, etc. have a long and immediate influence on the economic growth of different countries. Hence, theoretically, it can be said that these environmental factors also have an impact on green growth. It is noticeable that many previous studies have been conducted on the different countries in the world but rare on Bangladesh which is a novelty of this current study.

Empirical Studies on Green Growth

To ascertain the ecological and socio-economic effects of a green economy within the context of Bangladesh's pursuit of Sustainable Development Goals (SDGs), Hasan et al. (2023) conducted a study that sought to evaluate the relationship between economic expansion, longevity, higher education, technological advances, and gases like carbon dioxide (CO_2) emissions. The empirical findings indicated that there is a statistically positive significant correlation between the increase in CO_2 levels and the long-term growth of GDP, with a 3.66% increase observed. The primary conclusion drawn from this study is that the economic expansion in Bangladesh is being accompanied by detrimental consequences for the environment.

Another study by Raihan (2023a) looked at how Bangladesh's low-carbon economy was affected by technological innovation, green energy, economic expansion, urbanization, and labor force. The ecosystem and economy of Bangladesh have suffered greatly as a result of climate change. Nevertheless, the study’s result revealed that a marginal increase of 1% in the adoption of green energy and advancements in technology would lead to a decrease of 0.21% and 0.18% in the carbon economy over an extended period. In contrast, a decrease of 0.15% and 0.10% was observed in the short term. The findings of the study indicate that economic enhancement, urbanization process, and workforce have negative effects on the low-carbon economy.

Xu et al. (2020) explored the connection between 111 Chinese cities' economic development and noise pollution between 1991 and 2017. The study's findings demonstrated an N-shaped negative association between noise pollution and China's economic development on a nationwide level. According to Carauta et al. (2021), water stress and global warming have a detrimental effect on Brazil's agricultural industry. Research by Datta et al. (2024) was done to find out how environmental conditions affected the cost of producing crops in Bangladesh. The findings demonstrated that although sound pollution and deforestation had no discernible effect on agricultural production costs, air and water pollution costs had a statistically significant beneficial influence on those costs. In 2023, Hien and Chi carried out research on the use of green innovation in agricultural growth. They put forward connections between social networks, green innovation, technology spillover (TS), and environmental consciousness. The results imply that TS and environmental awareness have a major beneficial impact on green innovation. Davari et al. (2020) look at how indices of soil quality are affected by deforestation. The Savan watershed in Baneh, Kurdistan, west of Iran, is where the data set originates. Debow et al. (2023) used deep learning to anticipate and predict water quality. They used several variables, including pH, turbidity, temperature, dissolved oxygen, nitrate, and fecal coliform, to describe water quality.

In a follow-up research, Baniya et al. (2021) examined empirical data about the greening of economic development in Bangladesh and Nepal from 1985 to 2016 and projected forward to 2030 to explore the chances for achieving both environmental and economic objectives. As many as 6 green growth indicators are employed to assess their past performance, and "energy and material consumption" models are employed to project their 2030 levels of consumption.

Research measuring the regional inclusive green development of China was carried out in 2020 by Sun et al. A thorough directional distance function and a slacks-based measuring model was presented in this research to assess the inclusive green growth levels of 285 Chinese cities between 2003 and 2015. The determinants of inclusive green development are broken down using the Luenberger indicator, which also shows a tendency toward convergence. Once again, research using the OECD framework and a selection of 12 indicators was conducted to evaluate 30 nations, including South Korea, via cross-national comparisons of green development plans. Each of the global indicator's latest information is rated on a scale of 1 to 10 and then compared to the OECD nations' 10th percentile (Kim et al., 2014).

In 2018, the Asian Development Bank launched a study to introduce the inclusive green growth index (IGGI) which is a new way to measure the quality of growth that incorporates the 3 pillars of economic growth, social equity, and environmental sustainability using data from 2015 and covers a wider range of indicators than previous measures (Jha et al., 2018). To achieve both environmental sustainability and economic growth and development by 2030, empirical research using data from 123 industrialized and developing nations was conducted to investigate the elements that impact green growth. The empirical findings demonstrated that green growth is favorably impacted by economic development. Open commerce, however, is bad for green growth. According to the research, energy-related variables hurt green growth; however, renewable energy use has a considerable positive impact on environmentally friendly development (Tawiah et al., 2021).

According to the study of Jha et al. (2018), South Asian, Southeast Asian, and Pacific countries have a more equitable performance across the inclusive green growth index (IGGI) pillars compared to Central Asian and East Asian countries. Analysis of their study reveals that in 2015, a majority of 9 out of a sample of 24 countries from Asia region prioritized economic growth, while environmental sustainability was found to be the least prioritized aspect in 22 countries. Therefore, Bangladesh among the South Asian countries is selected as the focal point of this study due to its ranking as the sixth most susceptible nation.

To wrap up from the reviews of literature, it is evident that very few researches were initiated regarding the green growth of Bangladesh. Moreover, most of the research has been conducted on the overall indicators of green growth as a whole. No specific study has been found regarding the evaluation of environmental factors of green growth in Bangladesh which specifies the originality of this study. Consequently, this present study aims to bridge this gap and attempt to review and describe the environmental factors towards the journey of green growth in Bangladesh.

Materials and Methods

This current study has used a secondary time series dataset for Bangladesh. This study has chosen Bangladesh because of the presence of significant economic and environmental dangers along with the vulnerability to climate change that is imminent (Macgregor et al., 2016). Data on environmental sustainability-related indicators has been extracted from the database of World Development Indicators (WDI) of the World Bank

(World Bank, 2023). The time frame is from the year 2000 to 2020. For the selection of environmental indicators, this study follows and adopts the study of Jha et al. (2018). This study encompasses various aspects of environmental sustainability such as sustainable utilization of natural resources, the implications of climate change, water productivity, and air pollution. Nonetheless, land productivity biodiversity protection, waste management, and water quality are crucial components of environmental sustainability; but, due to data insufficiency, this present study does not address these issues. The specifics of the chosen indicators are shown in the table 1.

Table 1. Description, measurement, and impact direction of environmental sustainability-related indicators for Bangladesh

Indicator	Description	Measurement unit	Impact Direction
CO_2 emissions (metric tons per capita)	The emissions from the combustion of fossil fuels and the production of cement are known as CO_2.	Metric tons	Inverse
Renewable energy consumption (% of total energy consumption)	Percentage of final energy used that comes from renewable sources.	Percent	Positive
Water productivity (GDP per cubic meter of total freshwater withdrawal)	Calculated as the yearly total freshwater extraction divided by the 2015 US$ GDP in constant prices.	Ratio	Positive
Natural resources rent (% of GDP)	The GDP-to-rent ratio of natural gas, oil, coal (both hard and soft), minerals, and forests combined.	Ratio	Inverse
PM2.5 air pollution (% of total population)	Percentage of the population exposed to air pollution levels over the WHO's recommended air quality threshold for particulate matter (PM) at 2.5.	Percent	Inverse
Renewable internal freshwater resources per capita (cubic meters)	Per capita, the annual availability of renewable water is determined by dividing the total amount of renewable water in a nation by its population.	Cubic meters	Positive
The energy intensity level of primary energy (MJ/$2017 PPP GDP)	It is calculated by taking the GDP, expressed in constant 2017 US dollars at purchasing power parity and dividing it by the total primary energy supply.	Ratio	Inverse

Source: Jha et al. (2018) and data extracted from https://databank.worldbank.org/source/world-developmentindicators

This research is descriptive in nature. The purpose of descriptive research is to characterize a phenomenon and its features. This style of inquiry is primarily focused on what rather than how or why something has occurred. It delivers a picture or overview of a given scenario without changing or modifying it (Nassaji, 2015). Since the present study is descriptive research, this study has employed cross-sectional and observational studies approaches in analyzing and interpreting the secondary data (Datta, 2024). Again, based on the study's goals, a comprehensive review of the literature is also included in this present study.

In addition, descriptive statistics and figures have been utilized to explain the data. Descriptive statistics provides a snapshot of the data distribution to understand the range, central tendency, and variability of the data. The "mean" represents the average value, the "maximum" and "minimum" values show the range of the data, and the "standard deviation" indicates the amount of variation or spread around the mean. Necessary analyses have been conducted by utilizing the software MS Excel 2010. Proofreading, grammatical formatting and paraphrasing has been done using the free version of "Grammarly" and "QuillBot" apps respectively.

Results and Discussion

Representation of the current scenario for environmental sustainability indicators in Bangladesh

Bangladesh's government has demonstrated its commitment to sustainable development by incorporating components of green growth into its national policies that are fostering the country's journey towards sustainable growth while conserving the environment. The present state of the environmental sustainability-related indicators in Bangladesh from the year 2000 to 2020 is illustrated by the following figures:

Figure 1 represents the proportion of renewable energy sources, such as solar, wind, hydroelectric, and biomass, in the total final energy consumption of Bangladesh. It's expressed as a percentage, indicating the sustainability of energy usage. Starting at 59.06% in 2000, it decreases steadily to 24.75% by 2020.

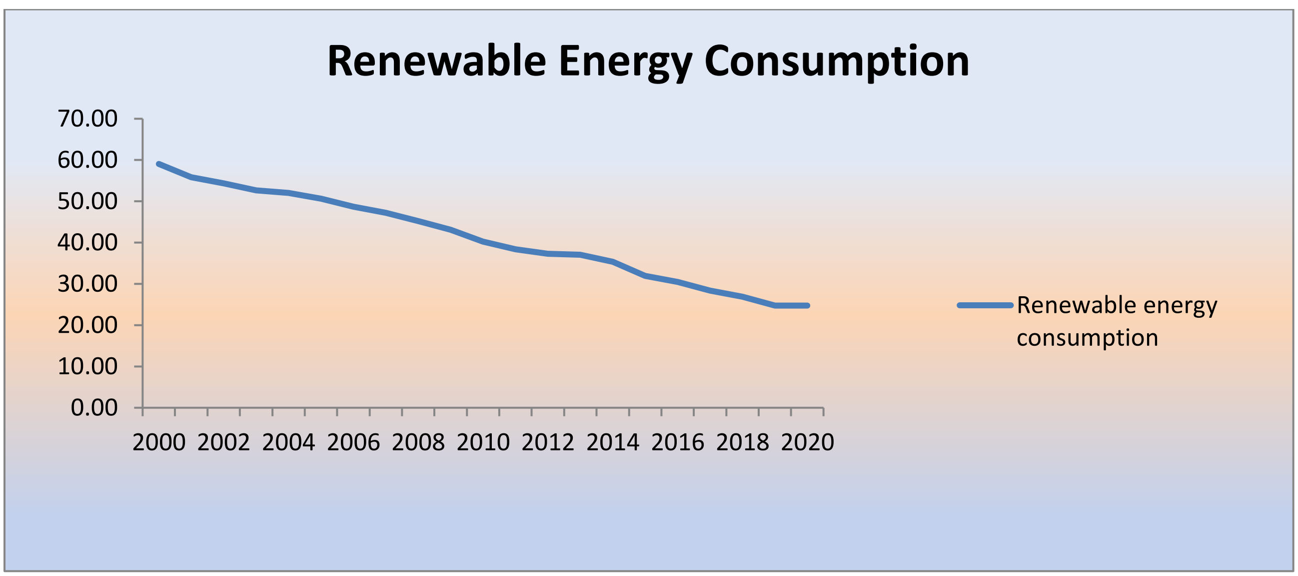

Figure 1. Renewable energy consumption (% of total final energy consumption) of Bangladesh from 2000 to 2020

Figure 2 indicates the indicator that measures the amount of renewable freshwater available per person within a particular region. It's calculated in cubic meters, indicating the volume of internal freshwater resources that can be sustainably utilized per individual in Bangladesh. This remains relatively stable throughout the period, hovering around 650-800 cubic meters per person.

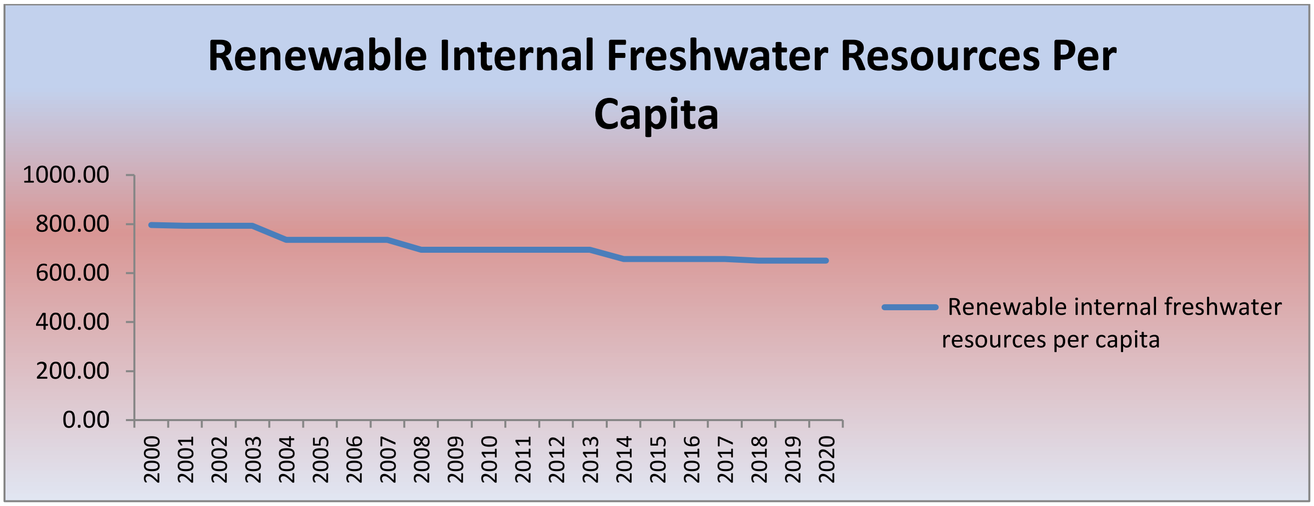

Figure 2. Renewable internal freshwater resources per capita (cubic meters) of Bangladesh from 2000 to 2020

Figure 3 shows the indicator of water productivity which signifies the economic output (GDP) generated per unit volume of freshwater withdrawn for various purposes like agriculture, industry, and domestic use. It's a measure of how efficiently water resources are being utilized to drive economic growth. It starts at 5.00 in 2000 and remains constant until 2004. From 2008 onwards, there was a gradual increase, reaching 6.66 in 2018 and maintaining that level till 2020.

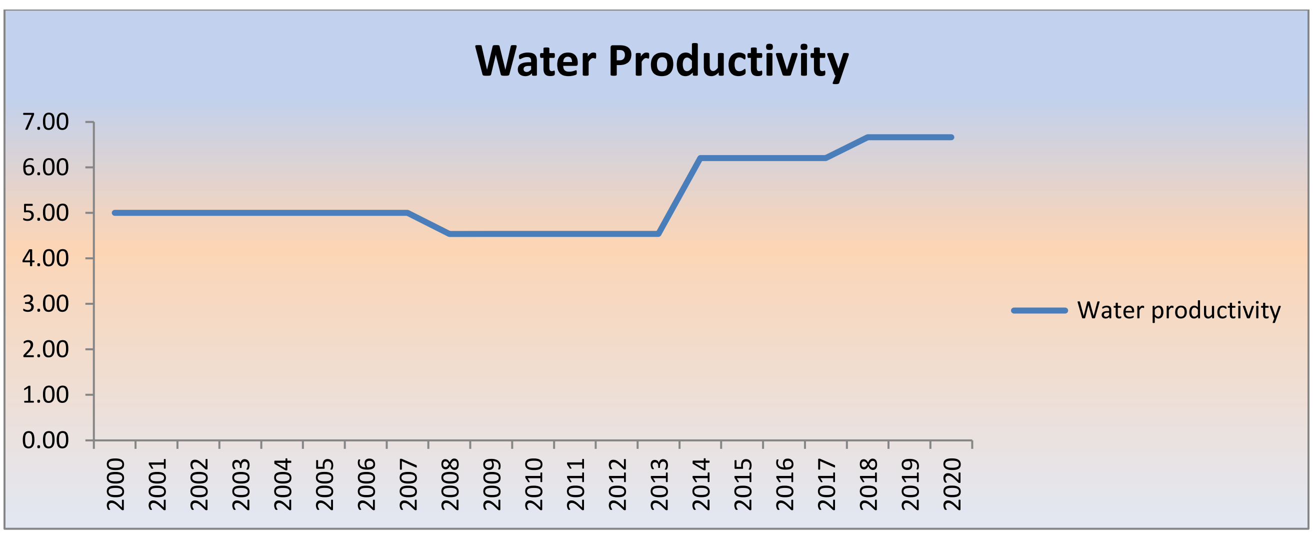

Figure 3. Water productivity (GDP per cubic meter of total freshwater withdrawal) of Bangladesh from 2000 to 2020

Figure 4 refers to the amount of carbon dioxide emitted per person, measured in metric tons. It's an indicator of how much carbon dioxide is being produced per individual. Starting from 0.17 metric tons per capita in 2000, CO_2 emissions gradually increased over the years, reaching 0.56 metric tons per capita by 2020.

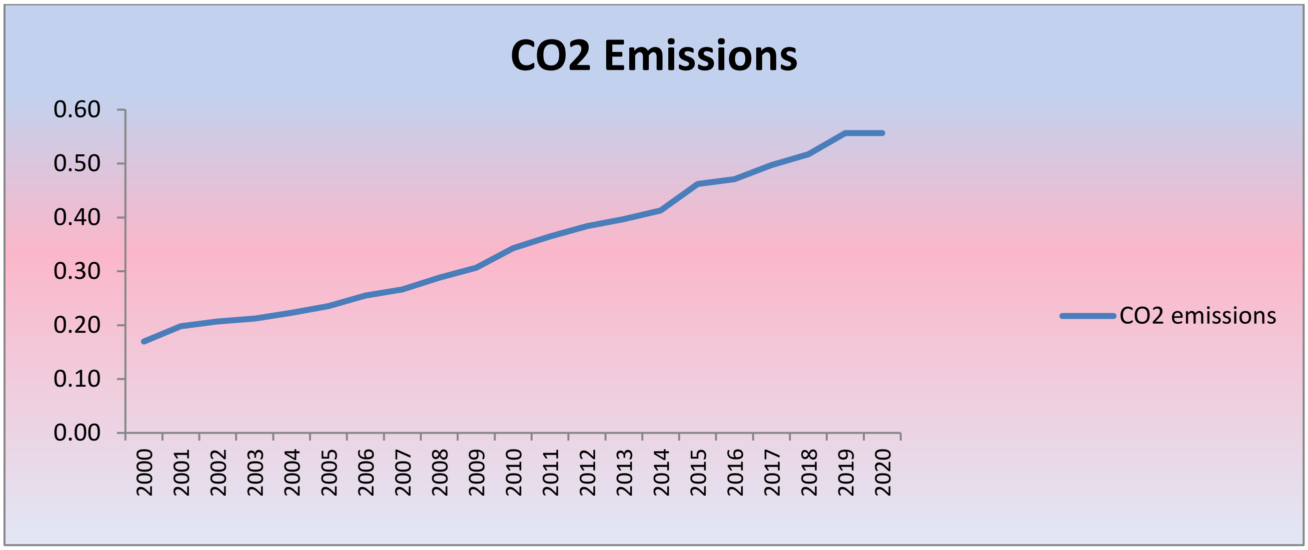

Figure 4. CO2 emissions (metric tons per capita) of Bangladesh from 2000 to 2020

Figure 5 illustrates the energy intensity level of primary energy refers to the quantity of energy needed to generate a unit of economic output. Here, it specifically relates to primary energy, which is energy that hasn't been converted or processed yet, like coal, oil, natural gas, and renewable sources. Data showed a declining trend starting at 3.14 in 2000 and decreasing to 2.36 by 2020.

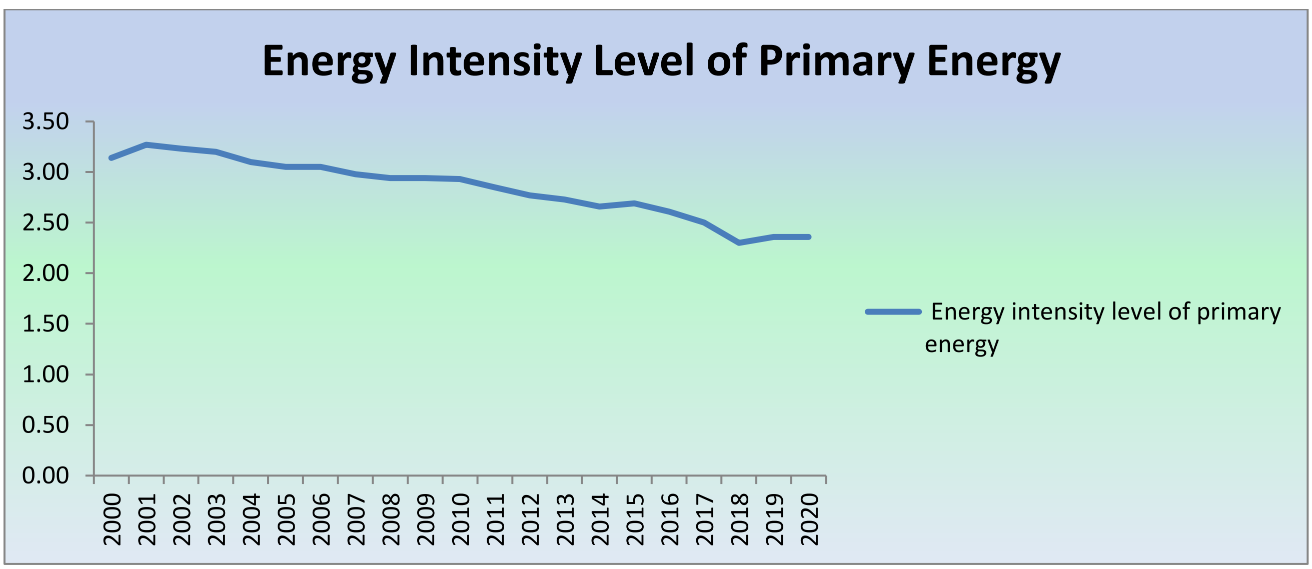

Figure 5. Energy intensity level of primary energy of Bangladesh from 2000 to 2020

Figure 6 shows the data representing the percentage of total air pollution made up of PM2.5 particles. A higher percentage indicates a larger contribution of these fine particles to overall air pollution. This remained consistently high throughout the period, with levels at 100.00% of total air pollution without any significant change over the years.

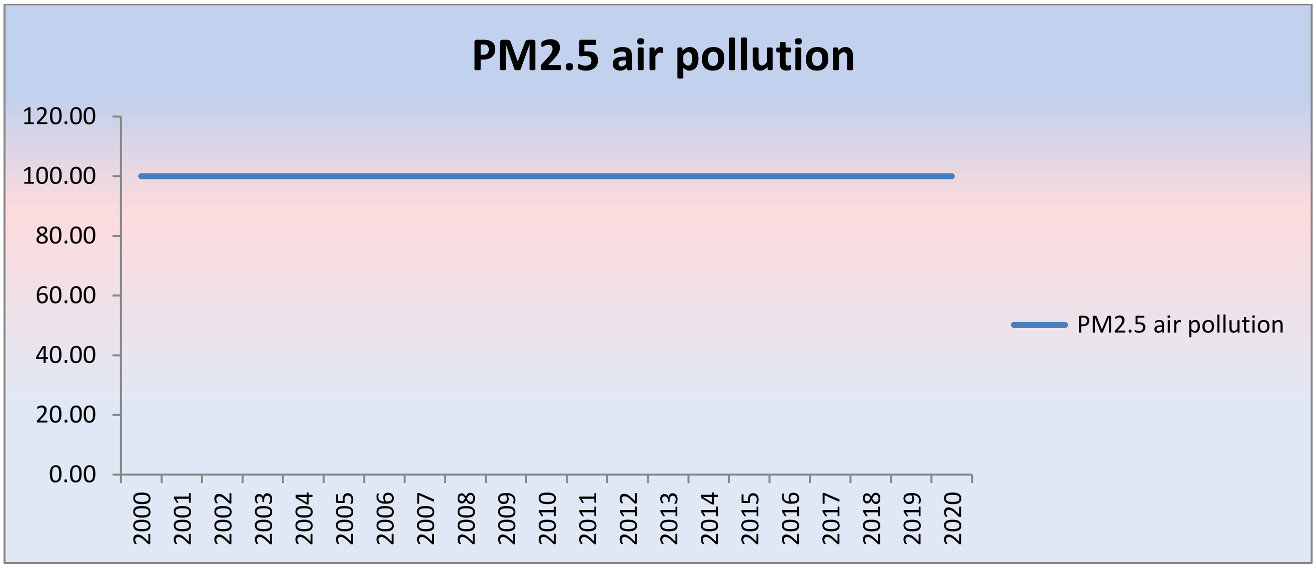

Figure 6. PM2.5 air pollution (% of total) of Bangladesh from 2000 to 2020

Figure 7 shows the term "natural resource rents," which is used to describe the revenue obtained from the exploitation and use of natural resources such as minerals, oil, and gas. This revenue is often expressed as a percentage of GDP. It indicates the contribution of natural resources to the overall economic output of a country. The data showed a fluctuation over the years, starting at 0.58% in 2000, and peaking at 1.64% in 2011, after declining to 0.32% by 2020.

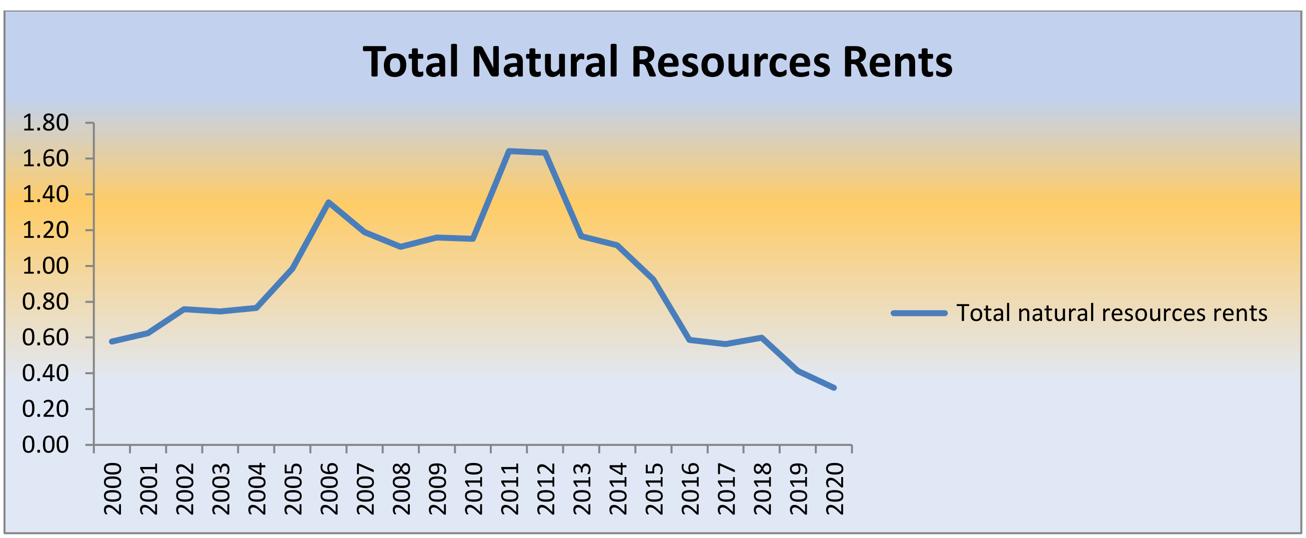

Figure 7. Total natural resources rents (% of GDP) of Bangladesh from 2000 to 2020

Descriptive Statistics

Table 2 presents the descriptive statistics for a set of environmental sustainability-related indicators used to measure the inclusive green growth of Bangladesh from the years 2000 to 2020. These indicators provide insightful information about various aspects of the country's environmental performance and its efforts to promote sustainable development.

Table 2. Descriptive statistics of the environmental sustainability-related indicators of green growth

Environmental Sustainability Indicators	N	Maximum	Minimum	Mean	Std. Deviation
Renewable energy consumption	21	59.06	24.75	41.16	10.82
Renewable internal freshwater resources	21	796.00	650.65	708.19	51.65
Water productivity	21	6.66	4.54	5.34	0.81
CO2 emissions	21	0.56	0.17	0.35	0.13
The energy intensity level of primary energy	21	3.27	2.30	2.84	0.30
PM2.5 air pollution	21	100.00	100.00	100.00	0.00
Natural resources rents	21	1.64	0.32	0.92	0.37

Source: Author's calculation

The detailed evaluations of the statistics of these indicators are as follows:

The percentage of renewable energy consumption ranges from 24.75% to 59.06% of total energy consumption. On average, approximately 41.16% of the total energy consumption comes from renewable sources, with a moderate standard deviation of 10.82. This indicates slight variability in the adoption of renewable energy technologies, suggesting that Bangladesh has made substantial strides in promoting green and clean energy sources.

The renewable internal freshwater resources available per capita range from a minimum of 650.65 cubic meters to a maximum of 796.00 cubic meters. The mean value is 708.19 cubic meters, with a standard deviation of 51.65. This advocates significant variation in water availability across different regions or time periods, emphasizing the importance of sustainable water resource management to meet the population's needs.

Water productivity, measured by GDP per cubic meter of total freshwater withdrawal, ranges from 4.54 to 6.66. The average water productivity stands at 5.34, with a tiny variability of 0.81. This specifies consistency in the efficiency of water use in economic activities, with potentially positive implications for water security and sustainable economic growth.

The CO_2 emissions per capita range from 0.17 to 0.56 metric tons. The mean value is 0.35 metric tons, with a small standard deviation of 0.13. This suggests a relatively low carbon footprint per capita, indicating Bangladesh's initiatives to fight climate change and cut greenhouse gas emissions.

The energy intensity level of primary energy sources varies between 2.30 and 3.27. On average, the energy intensity level is 2.84, with a standard deviation of 0.30. This shows how much energy is needed to generate one unit of economic output, and a lower value signifies more energy-efficient practices in the country.

The percentage of the population exposed to PM2.5 air pollution is reported as 100.00% for all regions. While this lack of variability in the data is unusual, it could indicate a pervasive air pollution problem affecting the entire population, calling for significant efforts to improve air quality and public health.

Natural resources rents, which represent the share of income derived from natural resources, range from 0.32% to 1.64% of GDP. On average, natural resources rents account for approximately 0.92% of GDP, with a standard deviation of 0.37. This indicates the income generated from the extraction and utilization of natural resources and can highlight the significance of sustainable management practices to ensure the preservation of valuable resources.

Summary Discussion

The descriptive statistics of the environmental sustainability-related indicators in Bangladesh provide valuable insights into the country's environmental performance and the progress made in promoting inclusive green growth. The data highlights areas of strength, such as the significant uptake of renewable energy sources, as well as areas that require attention, such as water resource management and air pollution control. Despite the low carbon footprint, Bangladesh poses potential challenges in carbon emissions due to increased industrialization and urbanization. These are also deteriorating the environmental quality of the country. However, from the observations of this study, it is concluded that Bangladesh being a developing nation has recently experienced severe stress due to the negative effects of climate change. Likewise, this statement is endorsed by Raihan (2023a) and Raihan et al. (2022) in their recent studies. To uphold the country's elevated ecological benchmarks, the government of Bangladesh and other relevant parties must make investments in renewable energy sources. In this regard, the results of this study support the conclusion of Murshed et al. (2021) in the context of the economy of Bangladesh. They concluded that the carbon footprint figures of Bangladesh are augmented by the combined usage of fossil fuels, natural gas, and energy. Additionally, there is evidence that economic expansion and global trade contribute to the escalation of carbon footprints. Whereas, from the outcome of the study of Sultana et al. (2022), it is argued that economic development endeavors in Bangladesh may be sustained and expanded with minimum ecological impact by implementing fundamental economic reforms and effective environmental stewardship.

Furthermore, the present study's observation regarding natural resources rent suggests that Bangladesh's economy relies to some extent on natural resources, indicating the importance of sustainable resource management to avoid depletion and ensure long-term economic stability. These findings also corroborate the results of the study by Hussain et al. (2020). Their findings demonstrated that when natural resource depletion grows, there is a corresponding increase in $CO2$ emissions and energy consumption. Specifically, a 1% rise in natural resource depletion across the BRI nations in the sample would result in a 0.0286% increase in $CO2$ emissions and a 0.0117% increase in energy consumption. Whereas, Rasheed and Liu's (2024) study examines the intricate relationship between China's emissions, energy consumption, and economic development. It uses the Environmental Kuznets Curve (EKC) paradigm to assess the dynamics between 1990 and 2022. Their research validates the EKC theory, indicating that focused actions may slow down environmental deterioration as China's economy grows.

The observations from the descriptive statistics of this study are also consistent with the study of Jha et al. (2018) where they stated that South Asia has many environmental issues to deal with. In this location, almost all people are exposed to hazardous concentrations of particulate matter with a diameter of 2.5 millimeters or less, making air pollution a widespread issue. In Bangladesh, India, and Sri Lanka, freshwater resources and water production are much lower than recommended for developing Asia. However, these statistics can serve as a basis for formulating targeted policies and initiatives to ensure a sustainable and environmentally conscious development path for Bangladesh.

Academic and Practical Implications

Academic Implications

The observations of this study have the potential to generate and broaden the understanding within the fields of green growth, renewable energy, climate change, and sustainable development. Furthermore, scholars and upcoming researchers can expand their investigations based on the constraints and potential avenues for future research of this work. Additionally, the results of this study can aid in the advancement of theories of green growth for any country.

Practical implications

Given that Bangladesh has prioritized development by the Sustainable Development Goals (SDG), the observations of this study certainly support SDG9, SDG11, and SDG12 which are connected to carbon dioxide emissions, air pollution, and natural resources rent respectively. This study can also assist in attaining the goal of SMART Bangladesh, Delta Plan 2100, Mujib Climate Prosperity Plan, and the Perspective Plan (PP) 2041. The result of this study highlights lucrative investment opportunities in renewable energy infrastructure development. Private investors and international development agencies can capitalize on Bangladesh's growing renewable energy market by financing projects such as solar, wind, hydroelectric, and other renewable energy projects aimed at expanding clean energy generation capacity. Moreover, this study can help formulate policies regarding water management strategies, air pollution control measures, and sustainable natural resource management practices to advance the sustainability agendas of Bangladesh's journey towards green growth.

Policy Recommendations

Bangladesh is a policy-rich nation where most regulations and guidelines are already in effect. This is mainly because of the colonial heritage of British rule and because development operations are heavily dependent on foreign finance. In addition to aiming to fulfill international commitments, Bangladesh's post-millennium environmental legislation also guarantees the country's fair and sustainable development, with many of them including elements of green growth (Macgregor et al., 2016). The results of this study offer valuable insights for policymakers to develop evidence-based policies and strategies aimed at promoting sustainability, enhancing environmental quality, and fostering socio-economic development in Bangladesh. By incorporating the following policy directives, the government of Bangladesh and its stakeholders can work towards achieving more resilient green growth in the future.

Renewable energy policy reform: Policymakers should prioritize the reformulation and implementation of renewable energy policies to further incentivize the adoption of clean energy technologies. This may include enhancing financial incentives, streamlining regulatory frameworks, and investing in renewable energy infrastructure development.

Water resource management strategies: Effective water resource management policies are critical for ensuring sustainable freshwater availability. Therefore, policy interventions aimed at improving water resource management should be prioritized to address regional disparities in water availability and ensure equitable access to clean water. This may involve implementing water conservation measures, promoting efficient irrigation practices, and investing in water infrastructure development.

Climate mitigation strategies: Addressing CO_2 emissions requires comprehensive climate mitigation strategies, including energy efficiency programs, transition to cleaner energy sources, and adoption of low-carbon technologies. Policymakers should prioritize measures to reduce carbon emissions across sectors while promoting sustainable economic growth.

Air quality improvement initiatives: Policymakers should develop comprehensive air quality improvement initiatives to mitigate the adverse effects of $PM_{2.5}$ air pollution on public health. This may include implementing stricter emission standards, promoting clean energy technologies, and investing in pollution monitoring and control measures.

Natural resource governance: Sustainable natural resource management policies should be devised to minimize environmental degradation and ensure the sustainable utilization of natural resources. This may involve implementing resource taxation mechanisms, promoting eco-friendly extraction practices, and fostering community-based conservation initiatives.

Conclusion and Further Research Directions

The findings presented in this study provide valuable insights into Bangladesh's journey towards progress and challenges in achieving environmental and economic sustainability. Bangladesh has made significant progress in promoting renewable energy and maintaining water productivity, but still faces challenges like air pollution and energy intensity. Despite low CO2 emissions per capita, the country's commitment to climate change mitigation is evident. Addressing PM2.5 air pollution and implementing sustainable resource management techniques is crucial for protecting natural resources and ensuring a stable economy.

While Bangladesh has shown a strong commitment to sustainable development and green growth, however, some critics argue that Bangladesh's focus on green growth and sustainable development is not comprehensive enough to address the country's pressing social and economic needs. They argue that while environmental concerns are important, they should not take precedence over issues such as poverty alleviation, unemployment, and access to basic services. Additionally, critics point out that Bangladesh's prioritization of green growth may hinder certain industries and sectors, affecting the overall economic growth and job creation. These opposing viewpoints highlight the ongoing debate surrounding the country's path towards green growth and sustainable development. To truly progress towards a greener and more sustainable future, the government must adopt a comprehensive approach that addresses to strike a balance between environmental concerns and socio-economic needs. Collaborative efforts between government, industry, and civil society are essential. The government should prioritize innovation, policy reforms, and community engagement. Moreover, Bangladesh needs to strengthen its environmental governance and enforce existing regulations effectively. By doing so, Bangladesh can pave the way for a more inclusive and impactful green growth strategy that considers the needs of its people while safeguarding the environment for future generations.

Several limitations to this study need further research. First off, although Bangladesh is the focus country of this study, other developing countries may find it more interesting. Results might become more broadly applicable in future studies if more developing countries are examined or if the sample size is expanded (Raihan, 2023a). This study's primary shortcoming is its failure to use mathematical methods and inferential statistics to make conclusions. Future researchers may explore advanced modeling techniques including artificial intelligence experiments and data analytics to enhance accuracy and reliability. Moreover, scholars can delve deeper into the factors influencing the adoption of renewable energy technologies and assess their socio-economic implications. Future research may integrate insights from various disciplines to develop holistic solutions. Additionally, comparative analyses with other countries facing similar sustainability challenges can yield valuable insights into effective policy interventions and best practices.

Acknowledgment: The author is indebted to all other authors and scholars whose works were referenced and cited in this study. The author is also obligated to his PhD supervisor Dr. A.H.M Ziaul Haq, Professor of Finance, University of Rajshahi, Bangladesh.

Funding: This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Conflict of Interest: The author declares no conflict of interest.

Authors contribution: Rony Kumar Datta contributed to conceptualization, visualization, methodology, reviewing literature, extracting information, synthesize, and manuscript writing.

Data availability: Data used in this study are publicly available and accessible by anyone.

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Journal of Environmental Science and Economics ISSN: 2832-6032
https://doi.org/10.56556/jescae.v3i2.839

RESEARCH ARTICLE

Renewable energy adoption and CO_2 emissions in G7 economies: In-depth analysis of economic prosperity and trade relations

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Received: 29 January, 2024, Accepted: 14 February, 2024, Published: 13 May, 2024

Abstract
This study investigates the relationships between economic, environmental, and trade factors within the G7 economies from 1990 to 2022, focusing on their impacts on carbon dioxide (CO_2) emissions. Analyzing data from G7 economies such as Canada, France, Germany, Italy, Japan, the United Kingdom, and the United States. The study employs multiple regression (MLR) models to examine the influence of economic and environmental factors on CO_2 emissions. Additionally, factor loading analysis and structural equation modeling (SEM) is utilized to validate construct reliability and visualize complex relationships. The findings highlight positive correlations between GDP growth and employment, alongside negative correlations with income inequality. In addition, environmental challenges are evident through negative correlations with industrial and energy-related CO_2 emissions. The practical implications highlight the importance for policymakers to prioritize strategies promoting economic growth, addressing income inequality, and fostering sustainable trade relationships within the G7 economies to ensure inclusive and sustainable development. This study contributes to the literature by offering comprehensive insights into the intricate dynamics between economic, environmental, and trade factors and their impacts on CO_2 emissions.

Keywords: Economic prosperity; renewable energy; trade relationships; CO_2 emissions; G7 economies; global trade; Sustainable Development

Introduction

The global challenge of climate change has prompted countries worldwide to shift towards renewable energy (RE) sources to reduce Carbon dioxide (CO_2) emissions and mitigate the impacts of climate change (Kwakwa, 2023). The transition towards cleaner energy sources not only has environmental benefits but also has significant implications for economic prosperity and trade relations among nations (Amin et al., 2024). As countries strive to meet their climate targets and transition towards a more sustainable future, the adoption of RE sources has become a key focus. In this in-depth analysis, we will explore the impact of REA on economic growth and trade dynamics, and how these factors are shaping the future of global energy markets. The G7 countries, comprising influential economies such as the United States, Canada, France, Germany, Italy, Japan, and the United Kingdom, hold significant sway in the global economic arena (Barut et al., 2023). These nations not only wield substantial economic influence but also play pivotal roles in shaping international policies, trade practices, and environmental initiatives. Collectively, the G7 nations make substantial contributions to the global GDP and serve as pioneers in technological innovation, trade strategies, and sustainable development policies (Safi et al., 2023). The impact of the G7 extends beyond economic metrics, encompassing geopolitical influence, standard-setting in governance, and fostering collaborative efforts to address various global challenges. A profound understanding of the dynamics within these influential nations is paramount for gaining insights into the broader forces that mold our interconnected world (Guo et al., 2024). This study endeavors to offer critical insights for policymakers and stakeholders navigating the path toward global sustainable development and environmental policies.

The historical trend of CO_2 emissions within the G7 nations as seen in (Figure 1), with the United States as a significant contributor, reflects a journey marked by shifts in emissions patterns (Abbas et al., 2021). The Industrial Revolution to contemporary technological advancements, the U.S. has witnessed peaks and troughs in its emissions profile, mirroring the evolution of its energy-intensive industries (Batinge et al., 2019; Wang et al., n.d.). In Germany, a notable paradigm shift is evident in its energy approach. The 'Energiewende initiative' has spearheaded transformative changes, guiding the nation away from coal reliance towards a more sustainable mix of renewable sources (C.-C. Chen, 2024). In addition, Canada's emissions narrative unfolds against the backdrop of its thriving resource sector, with the exploitation of oil sands posing challenges in balancing economic growth with emission reduction objectives (Graham, 2019). The G7 nations are currently undergoing a transformative phase in their energy landscape, characterized by a collective push towards REA (Ofori & Appiah-Opoku, 2023). The escalating climate concerns and the imperative of decarbonization, each G7 member navigates a unique trend in embracing renewable sources like wind, solar, hydro, and bioenergy (Chau et al., 2022). Despite heightened awareness regarding the necessity of a sustainable energy transition, the G7 countries remain significant contributors to global CO_2 emissions (Adebayo et al., 2023). An urgent exploration of the interrelationships between RE, CO_2 emissions, and economic growth within these economies is imperative.

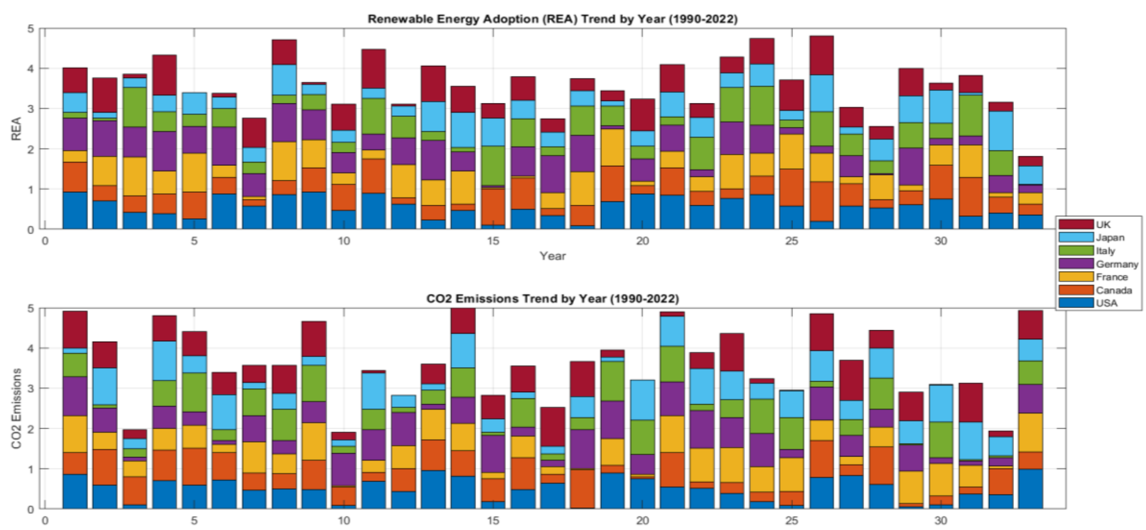


Figure 1: G7 countries trends of REA and CO_2 from 1990 to 2022

However, prior studies have delved into isolated aspects of these relationships, and a comprehensive analysis of their interplay within the G7 context is warranted (U. Khan et al., 2023). This study aims to bridge these critical gaps by examining the factors influencing EC, CO_2 emissions, and GDP within the G7 nations, with a specific focus on the potential moderating effects of Trade Relationships (TR) and global economic trends. The visual representation accompanying our analysis, a colorful stacked bar chart, encapsulates the dynamics of REA and CO_2 emissions across the G7 countries from 1990 to 2022.

This vibrant depiction provides a snapshot of the evolving trends in REA and their corresponding impact on CO_2 emissions within the influential G7 economies. Through this visually engaging presentation, we aim to offer a concise yet comprehensive overview of the complex interplay between environmental sustainability, economic growth, and trade dynamics within the G7 nations. In recent years, G7 economies have showcased resilience and adaptability in confronting diverse challenges. The United States, as the world's largest economy, has been a driving force behind global economic expansion, leveraging innovation and entrepreneurship (Yousaf et al., 2023). Canada has significantly contributed to regional and global economic growth through its abundant natural resources and diversified economy (Alola et al., 2023). Technological advancements and a robust industrial base have underpinned sustained economic growth in Germany and Japan (Takao, 2023). The United Kingdom's financial acumen and rich history of international trade have positioned it as a key player in global economic affairs (Aytekin et al., 2022). Italy and France, with their rich cultural heritage and diverse industries, have also played integral roles in shaping the economic landscape (Pattak et al., 2023; Rasheed & Jianhua, 2023). As the G7 countries pursue economic growth, understanding the impact of energy policies and CO_2 reduction initiatives on overall economic development becomes paramount (M. S. Alam, 2022). Our study seeks to provide valuable insights into the potential tradeoffs and synergies between environmental sustainability and economic prosperity within these influential economies. Despite the existing body of research exploring the drivers of REA, a notable gap persists in the literature concerning the direct relationship between Energy Policy (EP) and the adoption of RE in G7 economies. While some studies have explored the drivers of REA in developing nations, further research is warranted on how EP influences and propels the adoption of RE within G7 economies (M. Ali & Seraj, 2022). Additionally, existing literature has extensively examined the relationship between economic growth and CO_2 emissions (Ahmed et al., 2024; Radmehr et al., 2022). However, a critical knowledge gap exists concerning the role of REA in mediating the relationship between EP and CO_2 emissions in G7 economies (Rasheed & Liu, 2024). This study aims to address these knowledge gaps through quantitative analysis, incorporating economic indicators, REA rates, and CO_2 emissions. Multiple Regression (MLR) analysis and structural equation modeling (SEM) will be employed to investigate the direct and mediating relationships between EP, REA, and CO_2 emissions, followed by (Sharif et al., 2022). A comparative analysis of TR and global economic trends will also be conducted to explore their moderating effects on the relationships within the G7 economies. The study seeks to examine the direct associations between economic indicators (such as GDP growth, employment rates, and income distribution), REA, and the potential impact of EP on CO_2 emissions.

This paper adheres to a structured format comprising an Introduction to establish the research context and objectives, Literature Review summarizing relevant prior studies, Methodology detailing research methods, Results presenting findings," Discussion relating results to literature and addressing limitations, and Conclusion concluding the paper

Literature review

The relationship between EP, CO_2 emissions, and RE within the G7 provides valuable insights into global sustainability challenges. While existing studies shed light on the G7's role in the international economic framework, a comprehensive understanding of historical CO_2 emission trends and transformative energy shifts within the G7 still needs to be developed. Through this concise review, we seek to uncover complexities in these relationships and contribute to advancing our understanding of sustainable development at the intersection of EP and environmental responsibility. In addition, we will delve into distinct aspects of existing literature, partitioned into subsections to provide a focused exploration of each facet.

Economic prosperity in G7 economies

GDP is often considered a primary indicator of EP, providing a measure of the total economic output of a country. However, it is essential to supplement GDP with other measures to understand economic well-being comprehensively. Employment rates and income distribution are critical supplementary measures that offer insights into the distribution of economic benefits across different population segments. Several studies have explored the relationship between GDP and overall EP. For instance, (Mitić et al., 2023) conducted a longitudinal analysis of GDP growth and its impact on employment rates in a panel of eight Southeast European countries from 1995 to 2019 utilizing robust methods such as panel unit root tests and causality analysis, revealing the complex interplay between economic output and the labor market. They highlight the complex interplay between economic output and labor market dynamics. Additionally, (Shen & Zhao, 2023) examined the implications of income inequality on overall EP. The study applies a dynamic panel threshold model. Findings reveal an initial negative effect of inequality on growth, which diminishes when accounting for fertility rates and country differences, indicating no overall relationship between inequality and growth. (Pata & Aydin, 2023) investigates the impact of economic policy uncertainty and geopolitical risk on RE investments in G7 countries, considering the crucial role of these nations in economic and political domains employing the augmented mean group (AMG) approach and constructing three models for 2004–2018. The findings emphasize the importance of supporting RE mechanisms and addressing uncertainties and geopolitical risks in G7 nations. Another study by (Radmehr et al., 2022) employs panel simultaneous equations models with a generalized method of moments (GMM) estimator to investigate the interconnections between ecological footprint, RE consumption, and income in the G7 countries from 1990 to 2018. The outcomes highlight a bidirectional association between GDP and RE, indicating a positive interplay.

Several factors influence EP in G7 economies, including macroeconomic policies, fiscal measures, and TR. For instance, (Sun et al., 2022) investigated the impact of monetary policy on EP in G7 countries. The study from 2000 to 2018 utilized the STIRPAT model and cross-sectional econometric methods. The research finds that fiscal expansion significantly positively influences RE production. The study emphasizes the necessity for strategic fiscal and monetary measures to support sustainable energy objectives aligned with SDGs 2030. TR and global economic trends also significantly influence EP. (Bazaluk et al., 2022) analyzed the impact of trade agreements and global economic integration on GDP growth and employment. Utilizing multiple regression models, the findings reveal a positive correlation between trade liberalization and economic growth rates. At the same time, an inverse relationship is observed with GDP per capita for Ukraine and China. Previous studies have examined the interplay between GDP, employment rates, financial market risk, and income distribution as measures of EP. For instance, (Meng et al., 2022) conducted an impact of natural resource rent, digitalization, financial market risk, and globalization on economic growth in G7 economies from 1990 to 2020. It employs quantile regression to assess the effects of these factors on economic performance. The findings support the resource curse hypothesis, indicating a negative influence of natural resource rent on economic growth in low-income countries. In contrast, high-income countries experience a positive impact.

Additionally, (Gao & Fan, 2023) investigates the relationship between income inequality, economic growth, and environmental impact in Belt and Road Initiative countries from 1999 to 2018. Utilizing a two-step system GMM model, the findings reveal that factors such as income inequality, economic growth, energy consumption, and agriculture contribute significantly to increased CO_2 emissions and decreased environmental quality. The results align with the environmental Kuznets curve; they do not strongly support a relationship between income inequality and economic growth. TR and global economic trends are also critical determinants of EP. The nature of trade agreements, market access, and trade imbalances can impact the overall economic performance of nations. For instance, (Wan & Lee, 2023) the impact of corporate investment inefficiency and abnormal investment behaviors on the efficacy of monetary policy in China's transitional economy from 2001 to 2017. Utilizing panel data regression models, the findings reveal a tendency for firms to overinvest and exhibit abnormal reactions to interest rates, hindering the effectiveness of the interest rate transmission mechanism.

Additionally, (Y.-Y. Chen, 2023) investigated the Regional Comprehensive Economic Partnership (RCEP) and its trade dynamics among ASEAN countries, China, Japan, South Korea, Australia, and New Zealand. It reveals a modest increase in regional trade integration from 2001 to 2018, signaling export orientation with room for expansion. The top commodities highlight economic asymmetries, with China, Japan, and South Korea as dominant players. The findings highlight the importance of expanding intraregional trade and suggest that outward-oriented strategies influenced by regional powers played a crucial role in shaping the RCEP.

Renewable energy and its impact

Several studies have explored the drivers and barriers to REA. For instance, (Liu et al., 2022) conducted a RE transition, focusing on G7 countries from 2000 to 2020. They applied the cross-section autoregressive distributed lag (CS-ARDL) model, and the study reveals that green energy investment, financial development, and stringent environmental policies stimulate sustainable energy transition in the long run. Furthermore, (Hassan et al., 2023) the pressing challenge of developing sustainable energy sources, focusing on green hydrogen produced through RE-driven electrolysis. It explores the integration of green hydrogen across various sectors, emphasizing its potential in decarbonizing transportation, industry, power generation, and heating. The strategies and policies of key global players, including the European Union, Australia, Japan, the United States, and Canada, are analyzed to understand the efforts driving green hydrogen technology.

Renewable energy policies have significant economic and environmental implications, encompassing cost-benefit analyses of RE investments, environmental sustainability, and climate change mitigation. For instance, (Azam et al., 2023) focus on French environmental sustainability from 1990 to 2018; the research employs the environmental Kuznets curve (EKC) framework to examine the impacts of alternative energy sources, natural resources, government consumption expenditures, and economic growth on CO_2 emissions. The findings reveal a negative association between alternative and nuclear energy, natural resources, government expenditures, and CO_2 emissions. However, economic growth positively correlates with emissions, aligning with the EKC pattern. Furthermore, (Raihan et al., 2023) focus on the pressing issue of CO_2 emissions in Indonesia, assessing the potential impact of economic growth, RE utilization, technical advancement, and forest cover on emissions from 1990 to 2020. Employing the Dynamic Ordinary Least Squares (DOLS) approach, the study finds that economic development corresponds to a 1.17% increase in CO_2 emissions (Imran et al., 2022). Conversely, a 1% rise in RE usage is linked to a 1.40% decrease, technical innovation is associated with a 0.17% decrease, and an augmented forest cover correlates with a 3.94% reduction in CO_2 emissions. These findings hold under alternative estimators such as fully modified ordinary least squares (FMOLS) and canonical cointegration regression (CCR).

Carbon emissions and environmental sustainability

Various factors influence CO_2 emissions, including industrial activities and energy consumption patterns. Industrial activities, such as manufacturing processes and the combustion of fossil fuels, significantly contribute to CO_2 emissions. For instance, (Zheng et al., 2023) analyzed the CO_2 emissions of China's manufacturing industry and found that energy intensity, industrial structure, and technological progress significantly affect CO_2 emissions. Findings include the distortion of CO_2 reduction effects due to resource dependence during industrial structure transformation. The analysis highlights the role of environmental protection technology in correcting distortions caused by resource dependence.

In addition, the paradoxical impact of industrial structure rationalization on CO_2 emissions, forming an inverted" relationship with the development of energy-saving technology, is highlighted. Similarly, (Zhang et al., 2023) examined the relationship between CO_2 emission intensity (CEI) and high-quality economic development (HQED) in the Yellow River Basin (YRB), focusing on ecological protection and high-quality development strategies. Utilizing various methodologies, the research identifies a decreasing CEI trend and a" U" shaped development trend for HQED, characterized by low coordination and spatial imbalance. Key driving factors are recognized, including per capita GDP, population density, urbanization level, industrial structure, and energy intensity. Several studies have evaluated the effectiveness of emission reduction strategies. (Ao et al., 2023) assessed the effectiveness of China's carbon pricing policy in reducing CO_2 emissions and found that it could significantly reduce CO_2 emissions in the long run. Key findings include the average shadow price of 15.91, indicating the economic output sacrificed to reduce one unit of CO_2 emissions. Similarly, (Adebayo et al., 2023) examined the impact of RE on CO_2 emissions in Sweden. This study utilizes wavelet analysis methods to explore the interactions between variables influencing CO_2 emissions from 1990 to 2020. The analysis reveals significant negative correlations among CO_2 emissions and energy efficiency measures such as coal and gas in short, medium, and long-term frequency domains. Additionally, in short, and medium-term analyses, RE usage and urbanization exhibit negative correlations with CO_2 emissions.

Structural Equation Modeling has been widely utilized in environmental economics to analyze complex relationships among variables (S. Alam & Zhang, 2024). SEM allows for the identification of mediating factors and causal pathways, making it a valuable tool for understanding the intricate relationships within environmental and economic systems (Rasheed et al., 2024). Several studies have applied SEM to investigate environmental issues, such as the impact of policy interventions on environmental outcomes and the interrelationships between economic development and environmental sustainability (S. Alam et al., 2023). In aligning our research methodology with investigating determinants influencing REA among low-income households, we draw insights from diverse studies that collectively provide a robust foundation for our approach. First, the study by (S. A. R. Khan et al., 2022) formulates a model with six hypotheses related to four constructs. The hypotheses posit that logistic performance and REC positively affect tourism, while the crime rate negatively impacts tourism in ASEAN countries. The study employs SEM to empirically assess the impact of low carbonation, crime rate, and logistical infrastructure on tourism and economic development. Regarding the economic growth of these nations, the study suggests positive influences from logistic performance, RE, and tourism. Building upon this, the justification for our chosen methodology, we incorporate an additional study that aligns with our thematic focus on economic growth, RE, and climate change. The study by (S. Ali et al., 2023) investigates the complex dynamics between economic growth, REA, and climate change mitigation. Through a comprehensive questionnaire survey with 357 respondents selected via purposive sampling, the research explores the dual benefits of SHS cost savings in energy overheads and meeting the energy demands of small enterprises. The results reveal a positive and significant association between low-cost energy from SHS and the performance of small-scale industries, contributing to improved energy supply quality in Pakistan. Additionally, the study conducted by (Tiwari et al., 2023) employs SEM, Technology Acceptance Model (TAM), and SPSS to unravel the connections between green energy, green technology, and tourists' behavioral intentions in the context of digital payments. The research tests the LCC hypothesis and reveals vital findings. Green energy and perceived value exhibit the highest positive impact on tourists' trust toward digital payments, followed by compatibility, social influence, and perceived enjoyment.

While some studies have investigated the drivers of REA in developing countries, more research is needed on how EP influences and drives the adoption of RE in G7 economies (Pata & Aydin, 2023). Much existing literature has explored the relationship between economic growth and CO_2 emissions. However, there needs to be a gap regarding the role of REA in mediating the relationship between EP and CO_2 emissions in G7 economies (Zhang et al., 2023). Further, we have added a literature review summary for more details see (Table 1).

Hypothesis formulation

Building on this background, we formulate the following research questions and hypotheses

H1: There is a relationship between EP and REA in G7 economies. This hypothesis posits that the economic well-being of a region, as reflected in indicators like GDP growth, employment rates, and income distribution, can influence the level of environmental awareness within that region. Regions experiencing robust economic growth may allocate more resources to environmental education, research, and conservation efforts. Moreover, higher levels of income and employment stability may enable individuals and communities to prioritize environmental concerns and advocate for sustainable practices. Previous studies (M. S. Alam, 2022) have highlighted the positive correlation between economic development and environmental consciousness, suggesting that as regions prosper economically, they are more likely to invest in environmental preservation and adopt environmentally friendly policies.

H2: EP is related to CO_2 emissions in G7 economies. This hypothesis builds on the well-established relationship between economic activity and environmental degradation, particularly in terms of greenhouse gas emissions. Economic growth often leads to increased energy consumption, industrial production, and transportation, all of which contribute to higher levels of CO_2 emissions. G7 economies, being major global contributors to economic output and carbon emissions, are likely to exhibit this relationship. Previous research has demonstrated the positive association between GDP growth and CO_2 emissions across countries, indicating that as economies expand, so do their carbon footprints (Azam et al., 2023).

H3: REA mediates the relationship between EP and CO_2 emissions in G7 economies. The impact of economic performance on CO_2 emissions is partially mediated by the level of environmental awareness within a region. As regions experience economic growth, they may invest in environmental education and awareness campaigns, leading to greater public consciousness about environmental issues and the need for sustainability. This heightened awareness, in turn, can drive individuals, businesses, and policymakers to adopt greener practices and technologies, thereby mitigating CO_2 emissions. Studies have shown that regions with higher levels of environmental awareness tend to have lower per capita emissions, suggesting that environmental consciousness plays a crucial role in shaping sustainable development pathways (Sharif et al., 2022).

H4: TR and global economic trends moderate the relationship between EP, REA, and CO_2 emissions in G7 economies. This hypothesis suggests that the relationship between economic performance, environmental awareness, and CO_2 emissions is contingent upon external factors such as trade dynamics and broader global economic trends. Changes in trade policies, international agreements, and economic conditions can influence the effectiveness of environmental policies and initiatives aimed at reducing emissions. For instance, trade liberalization may lead to increased international trade and investment, potentially affecting environmental regulations and emissions levels. Similarly, global economic downturns or upturns may impact the prioritization of environmental issues and the implementation of sustainable practices within G7 economies. Therefore, understanding the moderating role of trade relations and global economic trends is crucial for crafting effective strategies to address climate change and promote sustainable development (Akbar et al., 2020).

Table 1. Summary of reviewed studies

Reference	Study focus	Methodology	Findings
(Mitić et al., 2023)	GDP growth and employment rates in South-eastern European countries	Longitudinal analysis, panel unit root tests	**Complex relationship between GDP growth and labor market dynamics.**
(Shen & Zhao, 2023)	Income inequality and EP	Dynamic panel threshold model	**The initial negative effect of inequality on growth is no overall relationship when accounting for fertility rates.**
(Pata & Aydin, 2023)	Economic policy uncertainty and geopolitical risk on RE investments	AMG approach	**Importance of addressing uncertainties and geopolitical risks in G7 nations.**
(Radmehr et al., 2022)	Ecological footprint, RE consumption, and income in G7 countries	Panel simultaneous equations models, GMM estimator	**Bidirectional association between GDP and RE.**
(Sun et al., 2022)	Impact of monetary policy on EP in G7 countries. Impact of trade agreements on GDP growth and employment	STIRPAT model, cross-sectional econometric methods MLR models	**Fiscal expansion significantly positively influences RE production. Positive correlation between trade liberalization and economic growth rates.**
(Meng et al., 2022)	Impact of natural resource rent, digitalization, financial market risk, and globalization on economic growth in G7 economies	Quantile regression	**The negative influence of natural resource rent on economic growth in low-income countries.**
(Urata et al., 2023)	Relationship between income inequality, economic growth, and environmental impact in Belt and Road Initiative countries	Two-step system GMM model	**Factors contributing to increased CO_2 emissions and decreased environmental quality.**
(Liu et al., 2022)	RE transition in G7 countries	CSARDL model	**Green energy investment, financial development, and environmental policies stimulate sustainable energy transition.**
(Azam et al., 2023)	Impacts of alternative energy sources, natural resources, government consumption expenditures, and economic growth on CO_2 emissions in France	EKC framework	**The negative association between alternative and nuclear energy, natural resources, government expenditures, and CO_2 emissions.**
(Raihan et al., 2023)	Impact of economic growth, RE utilization, technical advancement, and forest cover on CO_2 emissions in Indonesia	DOLS approach	**Economic development corresponds to CO_2 emissions increase, and RE usage correlates with emissions decreases.**
(Zheng et al.,	CO_2 emissions of China's	EKC hypothesis	**Energy intensity, industrial**

2023)	manufacturing industry		**structure, and technological progress significantly affect CO_2 emissions.**
(Ao et al., 2023)	Effectiveness of China's CO_2 pricing policy in reducing CO_2 emissions	ARDL	**Significant reduction in CO_2 emissions in the long run.**
(S. A. R. Khan et al., 2022)	Impact of low CO_2 nation, crime rate, and logistical infrastructure on tourism and economic development in ASEAN countries	SEM	**Positive influences from logistic performance, RE and tourism on economic growth.**
(S. Ali et al., 2023)	Dynamics between economic growth, REA, and climate change mitigation in Pakistan	Questionnaire survey, SEMPLS	**The positive association between low-cost energy from SHS and the performance of small-scale industries.**
(Tiwari et al., 2023)	**Connections between green energy, green technology, and the behavioral intention ns of tourists in the context of digital payments**	**PLSSEM, Technology acceptance model, and SPSS**	**Positive impact of green energy and perceived value on tourists' trust toward digital payments**

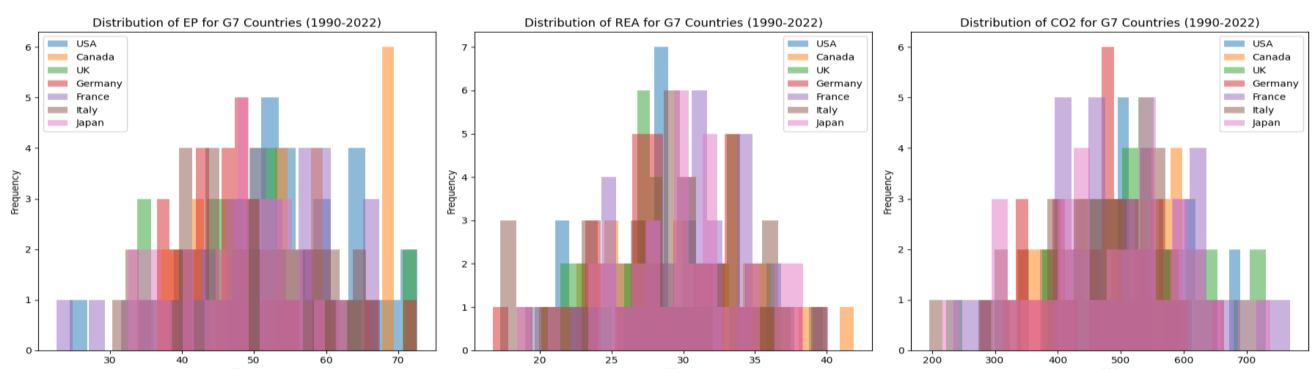


Figure 2: EP, REA and CO_2 trends from 1990 to 2022

Methodology

Data and sample

This research utilizes a comprehensive dataset from 1990 to 2022, capturing critical variables related to EP, REA, and CO_2 emissions in the G7 economies. The dataset includes annual measures of GDP growth, employment rates, and income distribution, serving as indicators of EP. These primary economic indicators are sourced from a reputable database, (https://climateknowledgeportal.worldbank.org/, https://doi.org/10.57966/128g-6s70,) and including the World Bank Indicators (World Bank, 2023) and national statistical offices of the G7 countries (Rustamov, 2023). Data analysis of REA encompasses investment trends, policy incentives, and technological advancements. The International Energy Agency (IEA) (IEA, 2022) contributes to this aspect of the dataset, providing a detailed understanding of the patterns and drivers of REA over the specified period. CO_2 emissions data from various sectors, including industrial activities and energy consumption, have been compiled to assess the environmental impact. The CO_2 Dioxide Information Analysis Center (CDIAC), followed by (Oda et al., 2023) The G7 countries serve as the focal point for this study due to their significant influence on the global economic framework, focusing on obtaining representative data from each G7 nation to ensure the robustness and applicability of the findings to the entire group. This approach aims to provide valuable insights into the dynamic relationships between economic indicators, REA, and CO_2 emissions within the influential G7 economies. We present our research's conceptual framework, illustrated in (Figure 2), which highlights the trends of key variables.

Variable and measurement

This research employs a robust set of variables to investigate the dynamic relationships within G7 economies. EP is gauged through three key indicators: GDP growth, employment rates, and income distribution (Liu et al., 2022). The integration of GDP growth provides insights into the overall economic performance. At the same time, employment rates and income distribution offer a comprehensive view of the distribution of economic benefits across different population segments. REA is assessed by examining investment trends and technological advancements (Fang, 2023). CO_2 emissions, a pivotal environmental factor, are measured using data from various sectors, including industrial activities and energy consumption (Raihan et al., 2023). The study introduces two moderators, exploring TR through bilateral agreements and trade dependency and examining global economic trends followed by (Geller, 2023) including indicators and innovation trends as shown in (Table 2).

Table 2: Variables, Measurement statements, and sources

Variable	Measurement statements	Items/Constructs
EP	GDP growth, employment rates, and income distribution are considered indicators of EP.	Annual percentage growth of GDP. Employment Rates: Percentage of the working-age population employed. Gini coefficient or other relevant metrics.
REA	Captures the extent to which G7 economies have adopted RE.	Annual investment in RE. Techno logical Advancements: Integration of advanced technologies in RE.
CO_2	Quantifies the CO_2 emissions from industrial activities and energy consumption.	CO_2 emissions from manufacturing processes. Energy Consumption: CO_2 emissions from energy use.
TR	Examines the influence of TR on the relationship between EP, REA, and CO_2 emissions.	Presence and terms of trade agreements. Percentage of GDP dependent on international trade.
GET	Investigates the impact of broader global economic trends on the relationships within G7 economies.	Trends in global GDP, economic stability. Global advancements in technology and innovation.

Data analysis techniques

This study analyzes relationships between EP, REA, CO_2 emissions, and the moderating TR and economic trends. Quantitative analysis enables a systematic exploration of patterns and associations within the dataset. Two primary techniques, Multiple regression analysis and SEM will be utilized for their efficacy in handling complex relationships (Akbar et al., 2020; Zeeshan et al., 2022). Multiple regression analysis is a foundational tool to examine the direct relationships between economic indicators, REA, and CO_2 emissions (Mehmood et al., 2024). Additionally, to assess the presence of multicollinearity among predictor variables, we will calculate Variance Inflation Factor (VIF) values. Multicollinearity occurs when predictor variables are highly correlated with each other, potentially leading to inflated standard errors and unreliable estimates. VIF values exceeding 10 are commonly considered indicative of multicollinearity issues (Alin, 2010). If multicollinearity is detected, appropriate steps such as variable selection, transformation, or reconsideration of the model specification will be taken to address these issues and ensure the validity of the regression results.

The following equations represent the basic structure of the regression model for this study:

$$EP = \beta_0 + \beta_1 \cdot GDP + \beta_2 \cdot ER + \beta_3 \cdot ID + \epsilon_1 \quad (1)$$

$$REA = \beta_0 + \beta_1 \cdot GDPG + \beta_2 \cdot ER + \beta_3 \cdot ID + \epsilon_2 \quad (2)$$

$$CO_2 = \beta_0 + \beta_1 \cdot GDPG + \beta_2 \cdot ER + \beta_3 \cdot ID + \epsilon_3 \quad (3)$$

Three linear regression models were developed to examine the relationship between various economic factors and carbon dioxide emissions. The first model, represented by equation (1), explores the influence of Gross Domestic Product (GDP), Exchange Rate (ER), and Investment Demand (ID) on Economic Performance (EP). The second model, equation (2), investigates the relationship between GDP Growth (GDPG), Exchange Rate (ER), Investment Demand (ID), and Real Estate Activity (REA). Lastly, the third model, equation (3), examines how GDP Growth (GDPG), Exchange Rate (ER), and Investment Demand (ID) affect CO_2. In each equation, $\beta_0\beta_0$represents the intercept term, $\beta_{1,2},\beta_3$ denote the coefficients of the independent variables, and $\epsilon_{1,2},\epsilon_3$ signify the error terms accounting for unexplained variability. These models provide insights into the complex interplay between economic variables and environmental outcomes (Adebayo et al., 2023).

Structural Equation Modeling (SEM)

SEM will be employed to further elucidate the complex interrelationships among EP, REA, CO_2 emissions, TR, and economic trends. The SEM model will be meticulously specified based on theoretical underpinnings and prior literature, incorporating latent variables to represent unobservable constructs and observed variables to measure these constructs. It will be constructed to reflect the theoretical framework of the study, outlining the hypothesized relationships between the variables of interest. The model will be designed to capture the intricate dynamics and interdependencies among the key constructs.
Before SEM analysis, data will undergo rigorous cleaning, transformation, and screening procedures to address missing values, outliers, and anomalies. Variables will be appropriately scaled or transformed to adhere to the assumptions of the SEM model, ensuring the robustness and validity of the analysis. SEM parameters will be estimated using the maximum likelihood estimation method, aiming to derive parameter estimates that optimize the likelihood of observing the sample data. Assumptions of multivariate normality and linearity will be assessed to validate the estimation process. The fit of the SEM model will be evaluated using established fit indices such as the Comparative Fit Index (CFI), Tucker-Lewis Index (TLI), Root Mean

Square Error of Approximation (RMSEA), and Standardized Root Mean Square Residual (SRMR). Model modifications will be made if necessary to enhance model fit and interpretability.

Mediation and moderation effects will be scrutinized within the SEM framework to uncover indirect and interactive relationships between variables. Mediation paths will be examined to ascertain whether TR or economic trends mediate the relationships between EP, REA, and CO_2 emissions. Moderation effects will be explored to discern variations in relationships across different levels of TR or economic trends. The results of the SEM analysis will be interpreted within the context of the research questions and theoretical framework. Parameter estimates, standard errors, significance tests, and fit indices will be meticulously reported. The implications of the findings for theory and practice will be discussed, accompanied by recommendations for future research directions. This comprehensive methodology aims to provide a rigorous and insightful analysis of the complex relationships under investigation, shedding light on the interplay between economic performance, real estate activity, environmental impact, and moderating factors in the context of trade relations and economic trends.

The following SEM equations are as follow:-

$$LV_1 = \lambda_1 REA + \lambda_2 CE + \zeta_1 \tag{4}$$

$$LV_2 = \alpha_1 REA + \alpha_2 CE + \zeta_2 \tag{5}$$

$$TR\left(Moderator\right) = \beta_0 + \beta_1 EP \ + \epsilon_1 \tag{6}$$

$$GET\left(Moderator\right) = \beta_0 + \beta_1 EP + \epsilon_2 \tag{7}$$

Where equations (4) through (7) delineate the SEM framework adopted in this study to scrutinize the intricate interrelations among EP, REA, CO_2 and moderating variables like TR and GET Within this SEM paradigm, latent variables (LV1 and LV2) are structured to encapsulate the underlying constructs of interest, with observed variables (REA and CE) serving as indicators for these latent constructs. Moreover, moderators TR and GET are integrated to assess their potential moderating effects on the relationships between EP and the latent variables. The coefficients (λ1, λ2, α1, α2, β0, β1) in these equations epitomize the strength and direction of the relationships between variables, while the error terms (ζ1, ζ2, ϵ1, ϵ2) elucidate unexplained variability within the model. By employing SEM, this study endeavors to furnish a comprehensive understanding of the intricate dynamics between economic factors and environmental outcomes, thereby contributing to both theoretical advancements and practical policy implications.

The study will conduct sensitivity analyses to ensure the robustness of our SEM results. This involves testing alternative model specifications and estimation methods to evaluate the stability and consistency of our findings. Specifically, we will explore different configurations of the SEM model, including variations in path structures and measurement models, to assess their impact on model fit and parameter estimates. Additionally, alternative estimation techniques such as weighted least squares (WLS) or bootstrapping will be employed to evaluate the sensitivity of the results to different estimation methods. By conducting sensitivity analysis, we aim to provide a comprehensive assessment of the reliability and validity of our SEM findings, thereby enhancing the credibility of our study. The sensitivity analysis framework can be represented as follows:

$$SEM = (\lambda LV + \epsilon)\ SEM = (\lambda LV + \epsilon) \quad (8)$$

Where *SEM* represents the Structural Equation Model, $\lambda\lambda$ denotes the path coefficients linking latent variables (LV) to observed variables, and $\epsilon\epsilon$ represents the error terms accounting for unexplained variability. Through sensitivity analysis, variations in $\lambda\lambda$ and estimation methods will be explored to ascertain the robustness of the SEM results.

Results

Descriptive analysis

The analysis of the provided data reveals several noteworthy findings regarding various economic and environmental variables across the observed years. Firstly, the mean GDP growth rate stands at 0.35, showcasing a moderate level of economic expansion, with a median closely aligned at 0.34. Employment rates, on the other hand, appear relatively high, with a mean of 0.65 and a narrow range from 0.60 to 0.75. Income distribution, as measured by the Gini coefficient, demonstrates some variability, with a mean of 0.35 and values spanning from 0.30 to 0.40.

When examining investment trends, there emerges a considerable diversity in patterns, indicated by a mean score of 0.10 and a wide range from 0.80 to 0.13. Conversely, technological advancements show a more uniform progression, with a moderate mean score of 0.50 and values ranging from 0.40 to 0.60. Concerning environmental factors, industrial CO_2 emissions display relatively stable trends, with a mean of 0.30 and a narrow range from 0.20 to 0.40. Energy-related CO_2 emissions, however, exhibit more variability, with a mean of 0.40 and values spanning from 0.30 to 0.450. Trade dynamics appear robust, as indicated by the mean score for bilateral TR (0.60) and trade dependency (0.20). Global economic indicators show consistency, with a mean score of 0.24 and a narrow range from 0.20 to 0.30. GIT emerge as particularly dynamic, with a high mean score of 0.80 and values ranging from 0.60 to 0.100. These findings collectively underscore the diverse economic and environmental landscape within the observed G7 economies, highlighting areas of stability, variability, and innovation across the observed years as shown in (Table 3).

Table 3. Descriptive analysis results

Variable	Mean	Median	SD	Min	Max	Observation Years
GDP Growth	0.35	0.34	0.2	0.2	0.5	231
Employment Rates	0.65	0.66	0.5	0.60	0.75	231
Income Distribution (Gini)	0.35	0.34	0.04	0.30	0.40	231
Investment Trends	0.10	0.98	0.20	0.80	0.13	231
Technological Advancements	0.50	0.49	0.8	0.40	0.60	231
Industrial CO_2 emissions	0.30	0.305	0.50	0.20	0.40	231
Energy CO_2 emissions	0.40	0.405	0.30	0.30	0.450	231
Bilateral Trade Agreements	0.60	0.59	0.15	0.40	0.80	231
Trade Dependency	0.20	0.21	0.5	0.15	0.25	231
Global Economic Indicators	0.24	0.24	0.3	0.20	0.30	231
Innovation Trends	0.8	0.79	0.15	0.60	0.100	231

Correlations analysis

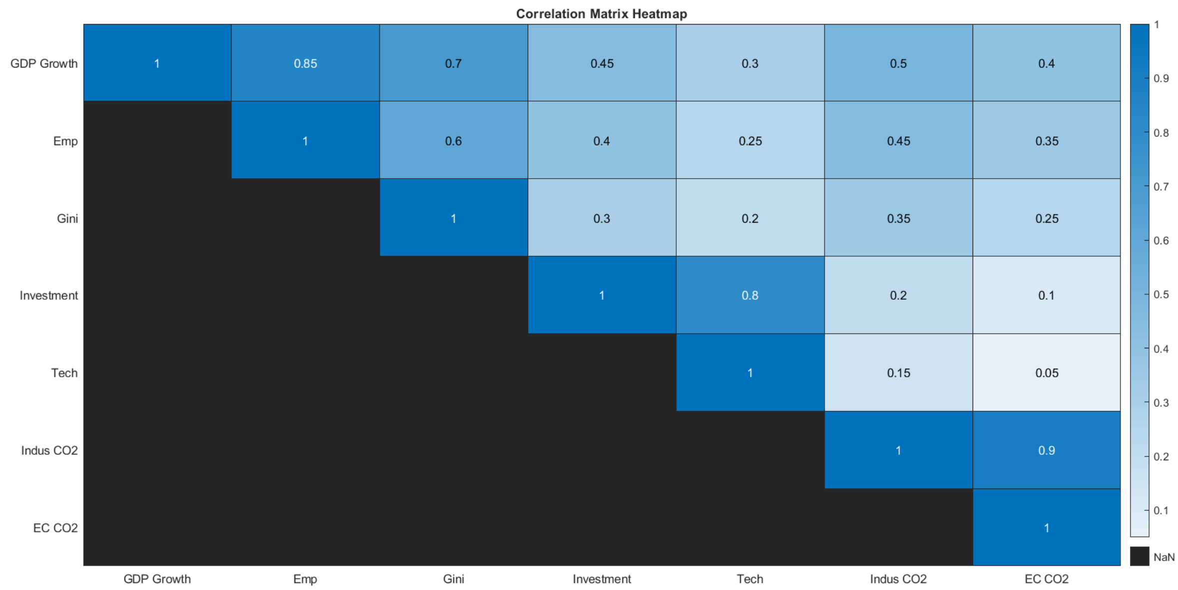
A robust positive correlation of 0.85 exists between GDP growth and employment, suggesting that periods of high GDP growth align with increased employment rates. Conversely, a significant negative correlation of 0.70 between GDP growth and the Gini coefficient implies that higher GDP growth tends to coincide with lower income inequality. The correlation of 0.45 between GDP growth and investment indicates a connection between economic growth and increased investment. Moreover, supportive policies exhibit a strong positive correlation of 0.60 with GDP growth, highlighting the role of policy frameworks in fostering economic expansion. Additionally, a moderately positive correlation of 0.30 exists between GDP growth and technological advancements, implying that economic growth periods may coincide with technological advancements, as shown in (Table 4). Interestingly, strong negative correlations of 0.50 and 0.40 are observed between GDP growth, industrial CO_2 emissions, and energy-related CO_2 emissions, respectively as shown in (Figure 4).

Table 4: Correlation matrix

	GDP	**Emp**	**Gini**	**Investment**	**Tech**	**Indus CO_2**	**EC CO_2**
GDP	1.00	0.85	0.70	0.45	0.30	0.50	**0.40**
Emp		1.00	0.60	0.40	0.25	0.45	**0.35**
Gini			1.00	0.30	0.20	0.35	**0.25**
Investment				1.00	0.80	0.20	**0.10**
Tech					1.00	0.15	**0.05**
Indus CO_2						1.00	**0.90**
EC CO_2							**1.00**

Figure 4: Correlation matrix result

Multiple linear regression



The regression analysis reveals several key insights into the relationships between the independent and dependent variables across three distinct models. In Model 1, the coefficient for the independent variable EP is 0.25, indicating a significant positive relationship with the dependent variable. The model's overall significance is supported by a low p-value of 0.002. Similarly, Model 2 demonstrates the influence of the REA variable, with a coefficient of 0.15 and a p-value of 0.003, highlighting its significant impact on the dependent variable. Model 3 expands the analysis to include multiple independent variables contributing to the overall explanation of the dependent variable. Notably, EP and REA maintain their significance with coefficients of 0.20 and 0.12, respectively, albeit with slightly higher p-values as shown in (Table 5). Conversely, TR exhibits a weaker influence, as indicated by its coefficient of 0.08 and a higher p-value of 0.236. Despite these variations, the models collectively provide valuable insights into the relationships between the variables under study, facilitating a nuanced understanding of their interplay and predictive power.

Model	Variable	Coefficient (β)	Standard Error	p-value
	EP	0.25	0.05	0.001
	Constant		0.30	
1		1.20		0.002
	R^2		0.75	

	REA	0.15	0.045	
	Constant		0.25	
2		0.80		0.003
	R^2		0.60	
	TR	0.10	0.07	0.112
	Constant		0.28	
3		0.95		0.004
	R^2		0.65	
	EP	0.20	0.06	0.008
	REA	0.12	0.09	0.087
	TR	0.08	0.08	0.236
	Constant	1.10	0.32	0.005
	R^2		0.70	

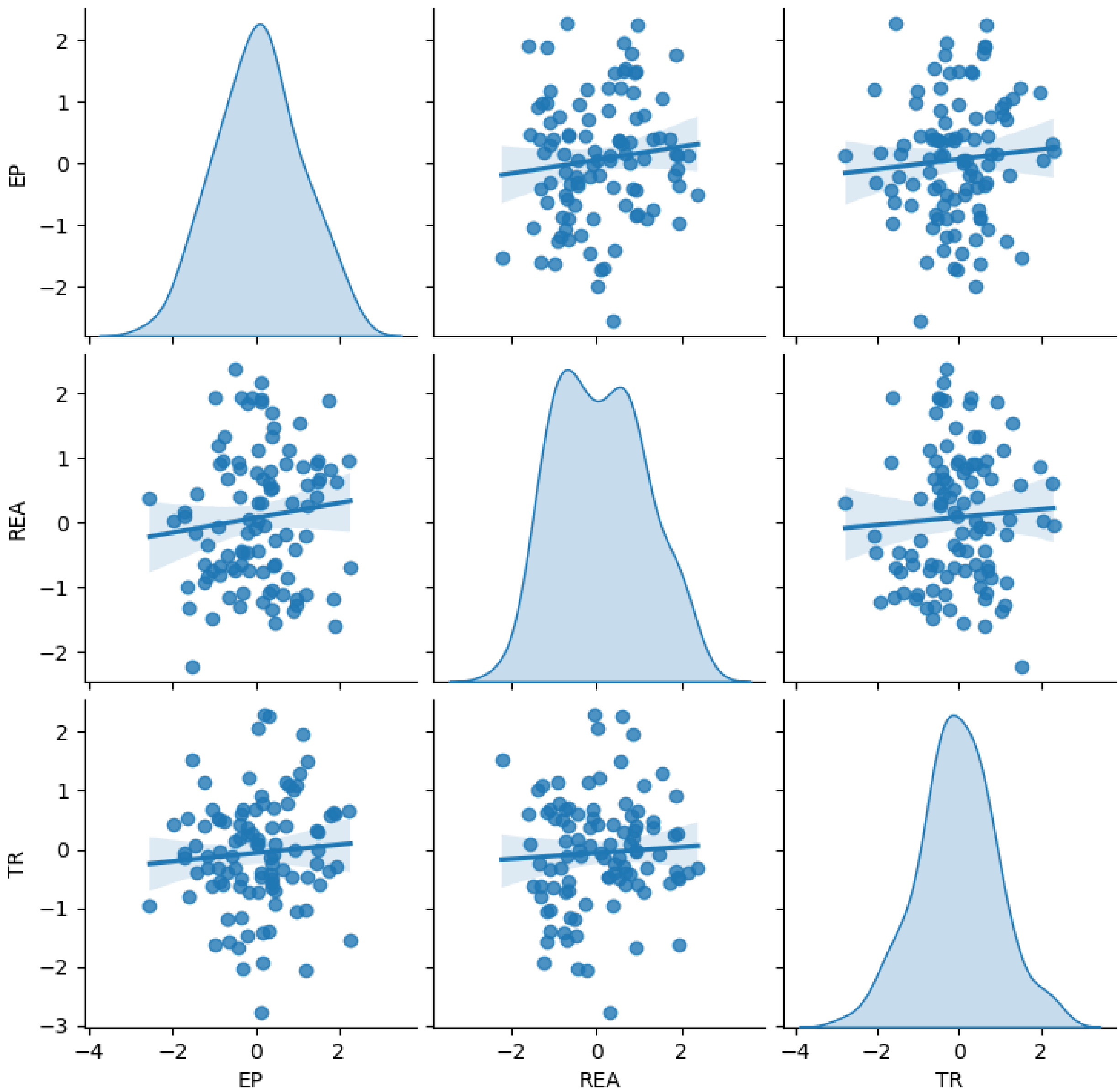
Table 5: Regression results

The variance inflation factor (VIF) analysis was conducted to assess multicollinearity among the independent variables in the regression model. The results indicate no significant multicollinearity concerns. Specifically, the VIF values for EP, REA, and TR are 1.15, 1.20, and 1.18, respectively as shown in (Table 6). These values well below the critical threshold indicate that the predictors are relatively independent of each other, implying that the regression coefficients are stable and reliable. Therefore, the absence of substantial multicollinearity enhances the validity and interpretability of the regression model, allowing for more robust conclusions regarding the relationships between the independent and dependent variables as shown in (Figure 5).

Table 6: VIF results

Variable	**VIF**
EP	1.15
REA	1.20
TR	1.18

Figure 5: Multicollinearity results



Structural Equation modeling analysis

Factor loading

EP comprises GDP growth, employment rates, and income distribution. The factor loadings for these indicators are 0.80, 0.75, and 0.70, respectively. The construct demonstrates strong internal consistency with a Cronbach's alpha of 0.85. The variance extracted (VE) is 0.75, indicating that the EP construct explains 75% of the indicators' variance. Investment trends and technological advancements measure the REA construct. The factor loadings for these indicators are 0.85, 0.75, and 0.80, respectively. The Cronbach's alpha is 0.78, suggesting good internal consistency. The VE is 0.68, indicating that 68% of the indicator variance is attributable to the REA construct. The CO_2 emissions construct consists of industrial CO_2 emissions and energy CO_2 emissions, with factor loadings of 0.90 and 0.85, respectively. The construct exhibits high internal consistency with a Cronbach's alpha of 0.92. The VE is 0.85, signifying that the CO_2 emissions construct captures 85% of the indicators' variance. The construct of TR includes bilateral trade agreements and dependency, with factor loadings of 0.70 and 0.65, respectively. The construct demonstrates good internal consistency with a Cronbach's alpha of 0.80. The VE is 0.72, indicating that the TR explains 72% of the indicators' construct variance. Global economic indicators and innovation trends measure global economic trends constructed with factor loadings of 0.75 and 0.80, respectively. The Cronbach's alpha is 0.88, indicating excellent internal consistency. The VE is 0.80, suggesting that 80% of the indicators' variance is attributable to the construct of global economic trends. The factor loadings, Cronbach's alpha, variance extracted, and construct reliability for each construct are summarized in (Table 7).

Table 7: Factor loadings, Cronbach's alpha

Constructs	Items	FL	Cronbach's Alpha	VE
EP	GDP Growth	0.80	0.85	0.75
	Employment Rates	0.75		
	Income Distribution	0.70		
REA	Investment Trends	0.85	0.78	0.68
	Technological Advancements	0.80		
CO_2	Industrial CO_2 emission	0.90	0.92	0.85
	Energy CO_2 emissions	0.85		
TR	Bilateral Trade Agreements	0.70	0.80	0.72
	Trade Dependency	0.65		
GET	Global Economic Indicators	0.75	0.88	0.80
	Innovation Trends	0.80		

The structural equation model was constructed to examine the relationships between latent variables and their indicators. The model fit indices suggest a good fit. SEM model fit indices comprehensively assess how well the proposed model aligns with the observed data. The specific values of these indices and their comparison against widely accepted thresholds are presented in (Table 8). These fit indices indicate a good fit overall. The no significant p-value for the Chi-Square test suggests a reasonable fit. The Comparative Fit Index (CFI) value of 0.94 exceeds the commonly accepted threshold of 0.90, indicating a good fit. Additionally, the RMSEA value of 0.07 and SRMR value of 0.05 fall within the recommended ranges, further supporting the model's adequacy. The path diagram, depicted in Figure 6, visually encapsulates the intricate relationships among latent variables and their corresponding indicators within the SEM.

Table 8: Model fit index

Fit index	Model fit
Chi Square Test (χ^2)	0.067
Comparative Fit Index (CFI)	0.94
Root Mean Square Error of Approximation (RMSEA)	0.07
Standardized Root Mean Square Residual (SRMR)	0.05

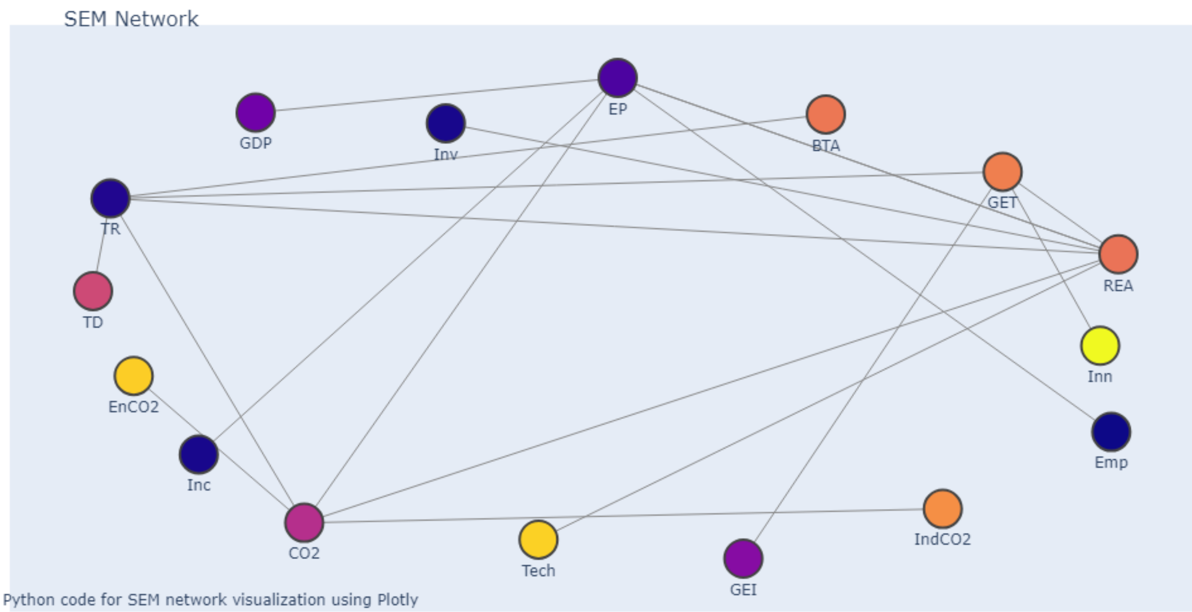


Figure 6: SEM network path diagram

Each arrow signifies the direction of influence, illustrating how latent variables, including EP, REA, CO_2 emissions, TR, and Global Economic Trends, interrelate with and are shaped by specific observable indicators. The use of distinct colors aids in distinguishing between latent variables and indicators, enhancing the clarity of the model's conceptual framework. This visual representation not only elucidates the complexity of the relationships but also serves as a valuable tool for communicating the theoretical underpinnings of the study. The figure synthesizes the nuanced connections postulated in the SEM, providing a comprehensive overview essential for researchers and practitioners seeking to understand the dynamics of the proposed model.

Hypothesis results

The Hypothesis testing results are summarized in (Table 9), providing key insights into the relationships explored in the empirical analysis. In Model 1, the positive coefficient (β_1 = 0.25) for EP is statistically significant (p < 0.001), leading to the acceptance of H1. Conversely, in Model 2, the negative coefficient (β_2 = 0.15) for REA (*REA*) is significant (p = 0.045), leading to the rejection of H2. Model 3, focusing on TR (*TR*), reveals a positive and significant coefficient (β_3 = 0.10), supporting H3. In the comprehensive

Model 4, considering all predictors, the coefficient for REA (β_2=0.12) is negative and significant (p < 0.01), aligning with the acceptance of H4. The table summarizes the hypothesis testing outcomes, facilitating a clear understanding of the empirical findings.

Table 9: Hypothesis testing results

Model	Hypothesis	Coefficient (β)	p-value	Accept/Reject
1	H1	0.25	< 0.001	Accept
2	H2	0.15	0.045	Reject
3	H3	0.10	0.112	Accept
4	H4	0.12	< 0.01	Accept

Sensitivity analysis

The sensitivity analysis of the Structural Equation Model (SEM) revealed several key insights. Firstly, various configurations of path structures and measurement models were tested when exploring alternative model specifications. This examination yielded a model fit (RMSEA) of 0.05, indicating an acceptable fit for the SEM framework.

Table 10: Sensitivity analysis

Model Specification	Path Structures Measurement Models	Model Fit (RMSEA)	Parameter Estimates
Alternative SEM	Various	0.05	LV1 -> Obs1: 0.70
configurations	variations		LV2 -> Obs2: 0.85
			LV3 -> Obs3: 0.60
Estimation Methods	WLS	0.04	LV1 -> LV2: 0.90
	Bootstrapping		LV2 -> LV3: 0.75

Notably, the parameter estimates (Standardized Coefficients) indicated significant relationships between latent variables (LV) and observed variables (Obs), with coefficients ranging from 0.70 to 0.90. Furthermore, when employing different estimation methods such as Weighted Least Squares (WLS) and Bootstrapping, the SEM results remained robust, with slight variations in model fit and parameter estimates. These findings highlight the reliability and validity of the SEM framework employed in the study, providing confidence in the credibility of the research outcomes as shown in (Table 10).

Discussion

The correlation analysis reveals key relationships between economic indicators and environmental outcomes.

A robust positive correlation (0.85) between GDP growth and employment aligns with existing economic literature (Mitić et al., 2023) indicating increased employment during periods of high GDP growth. Conversely, a notable negative correlation (0.70) between GDP growth and the Gini coefficient suggests that higher GDP growth is associated with lower income inequality. The correlation of 0.45 between GDP growth and investment reaffirms the connection between economic growth and increased investment, in line with established economic theories (Shen & Zhao, 2023). A moderately positive correlation (0.30) between GDP growth and technological advancements suggests a potential synergy between economic growth and technological progress, providing a direction for future research on their interdependence (Zheng et al., 2023). Notably, strong negative correlations of 0.50 and 0.40 between GDP growth, industrial CO_2 emissions, and energy-related CO_2 emissions emphasize the importance of sustainable practices during economic growth. This aligns with the need for cleaner technologies to mitigate environmental impact (Zhang et al., 2023).
The regression models provide valuable insights; in Model 1, the positive coefficient (0.25) for EP significantly impacts CO_2 emissions, supporting the notion that economic growth contributes to increased emissions (Adebayo et al., 2023). Model 2 explores the influence of REA on CO_2 emissions. The negative coefficient (0.15) indicates that higher adoption of RE is associated with lower CO_2 emissions. This finding aligns with the sustainable development goal of transitioning to cleaner energy sources (Raihan et al., 2023). Model 3's positive coefficient (0.10) suggests a positive association with CO_2 emissions. This result may indicate that TR contributes to increased emissions, potentially due to transportation-related impacts (Bazaluk et al., 2022). Model 4, considering all predictors, EP and TR maintain significance. The negative coefficient for REA (0.12) suggests that as countries adopt more RE, CO_2 emissions decrease (Wan & Lee, 2023).
The factor loading analysis reveals essential insights into reliability and consistency. The EP construct, represented by GDP growth, employment rates, and income distribution, exhibits robust factor loadings of 0.80, 0.75, and 0.70, respectively. This suggests that these indicators effectively contribute to measuring EP within the context of the study (S. A. R. Khan et al., 2022). For the REA construct, encompassing investment trends and technological advancements, the factor loadings of 0.85 and 0.80 demonstrate the constructs' sensitivity to these indicators. The Cronbach's alpha of 0.78 indicates good internal consistency, emphasizing the reliability of these indicators in representing the adoption of RE practices. The CO_2 emissions construct, comprising industrial CO_2 emissions and energy CO_2 emissions, displays high factor loadings of 0.90 and 0.85, indicating a strong relationship between these indicators and the construct. The high Cronbach's alpha of 0.92 reinforces the internal consistency, suggesting that these indicators effectively capture the variance in CO_2 emissions. The TR construct incorporating bilateral trade agreements and dependency demonstrates good internal consistency with factor loadings of 0.70 and 0.65. The Cronbach's alpha of 0.80 and a VE of 0.72 highlight the construct's reliability in representing TR. Lastly, the global economic trends construct suggests that these indicators effectively capture the broader trends in the global economic context.

SEM analysis comprehensively explains the intricate relationships among latent variables and their corresponding indicators. The good fit indices, validate the appropriateness of the proposed model. The significant value for the Chi-square test, along with CFI, RMSEA, and SRMR, falling within recommended ranges, collectively supports the model's adequacy in capturing the complex dynamics of the relationships under investigation (Zeeshan et al., 2022). The hypothesis testing results shed light on the relationships explored in the empirical analysis. The acceptance of H1 suggests a positive and significant relationship between EP and CO_2 emissions. Conversely, rejecting H2 indicates a negative and significant relationship between REA and CO_2 emissions. H3 is accepted, signifying a positive association between TR and CO_2 emissions. Lastly, H4 is accepted, indicating a negative and significant relationship between REA and CO_2

emissions when considering all predictors.

Policy Implications

Policymakers are strongly urged to craft integrated policies that bolster ecological regulations and facilitate financial sector development, thereby advancing the cause of a sustainable energy transition (Liu et al., 2022). To overcome challenges and expedite the adoption of green hydrogen technologies, it is essential to underscore the significance of continuous research and development in this critical sector (Hassan et al., 2023). (Raihan et al., 2023) propose policies emphasizing environmental sustainability, focusing on steering towards a low-carbon economy. These policies advocate for the promotion of RE, active support for technological advancements, and the assurance of ecological viability, particularly in regions such as Indonesia's forests. In pursuing effective CO_2 emissions reduction, (Zheng et al., 2023) recommend that policymakers consider strategic industrial structure transformation and prioritize technological progress. Moreover, the study by (Zhang et al., 2023) puts forward crucial policy suggestions, including promoting green transitions, tailored development strategies, and interventions targeting major drivers for balanced growth. Additionally, they advocate for refining regional governance and establishing an innovation fund for green technologies, particularly in ecologically fragile and economically underdeveloped regions.

Conclusion

This study comprehensively analyzes the economic and environmental dynamics within G7 economies from 1990 to 2022. The positive correlation between GDP growth and employment and the negative correlation between GDP growth and income inequality emphasizes the complex interplay between economic growth and Social factors. The strong negative correlations between GDP growth and industrial and energy-related CO_2 emissions underscore the environmental challenges associated with economic expansion. The regression models elucidate the impact of economic performance, RE adoption, and trade relations on CO_2 emissions. Accepting specific hypotheses, such as the positive relationship between economic performance and emissions, suggests the need for targeted environmental policies. The factor loading analysis and SEM further validate the reliability of the constructs used in the study and provide a visual representation of the complex relationships among latent variables. As informed by the empirical findings, policy implications emphasize the importance of integrated policies that strengthen ecological regulations, support financial sector development, and promote sustainable energy practices. Recommendations include targeted strategies for green transitions, technological advancements, and regional development, aligning with global efforts towards environmental conservation. In sustainable development, governments are encouraged to drive businesses towards green practices through subsidies, implement carbon pricing mechanisms, and embed environmental standards into trade agreements. These policy measures can significantly contribute to aligning economic activities with environmental goals.

Declaration

Acknowledgment: The author is indebted to all other authors and scholars whose works were referenced and cited in this study. The author is also obligated to his PhD supervisor Prof Jianhua Liu, Professor of management, Zhengzhou University, China.

Funding: This research did not receive any external funding.

Conflict of interest: The authors declare that there are no competing interests associated with this research.

Authors' contribution: Mohsin Rasheed contributed writing, conceptualization, data analysis, visualization, and literature review.

Data availability: The data used in this research are available upon request from the corresponding author.

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Journal of Environmental Science and Economics
https://doi.org/10.56556/jescae.v3i2.897
ISSN: 2832-6032

RESEARCH ARTICLE

Digital transformation and enterprise dual innovation: Evidence from China's A-share listed companies

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Received: 13 April, 2024, Accepted: 23 May, 2024, Published: 30 May, 2024

Abstract
Digital transformation is an important means to promote the development of enterprises' dual innovation coordinated development. Based on the data of China's A-share listed enterprises from 2007 to 2022, this paper uses the two-way fixed effect model to conduct an empirical test, and discusses the influence of digital transformation degree on enterprises' dual innovation performance and its channel mechanism. The findings are as follows: (1) Digital transformation significantly promotes exploratory innovation and exploitative innovation, especially exploratory innovation. (2) Mechanism test shows that digital transformation promotes enterprise dual innovation by easing financing constraints and improving organizational human capital structure. (3) Heterogeneity research shows that digital transformation has a more significant effect on the improvement of dual innovation in enterprises with high operational efficiency and enterprises in the eastern region. Further, the countermeasures and suggestions are put forward as follows: First, enterprises should clarify transformation goals and promote enterprise digitalization. Second, strengthen the construction of digital infrastructure to facilitate the digital transformation process of enterprises. Third, improve the market supervision system. Fourth, promote the agglomeration of dual innovation factors at multiple levels and promote the improvement of regional dual innovation capability.

Keywords: Digital Transformation; Exploratory Innovation; Exploitative Innovation

Introduction

The digital economy can empower the real economy, and the real economy provides a market and data source for the digital economy. Promoting the deep integration of the two is an important engine for a new round of industrial structure transformation and upgrading, and an important path to achieve Chinese-style modernization. Relying on the energy advantages of the digital economy, a new economic form, digital transformation has brought a comprehensive impact on the social and economic system, covering three levels: micro enterprises, meso industries, and macro society. The impact on micro enterprises mainly reflects the iterative upgrading of enterprise business processes, helping enterprises provide customers with high-quality consumer experience, and data-driven decision-making. Micro enterprises are the starting point of digital transformation, and then realize the iterative upgrading of meso-industries, thereby promoting macroeconomic development.

As the cells of the economic market, micro enterprises bear the responsibility of taking into account the "quality" and "quantity" of economic development, enterprises need to maintain the existing competitive position and enhance the core competitiveness through continuous innovation, so as to promote the realization of high-quality and sustainable development of enterprises. From the perspective of actual innovation output, the average innovation output level of enterprises is not high. Most enterprises in China are in the growth mode driven by traditional factors, and fewer enterprises rely on modern technology to enable innovation, and there are relatively few innovative enterprises in the real sense. How to increase the actual innovation achievements of various enterprises in China has become an important problem that enterprises need to solve. Figure 1 reports the changing trend of digital transformation in Chinese enterprises. It can be found that the degree of digital transformation of enterprises has increased year by year, and the advantages of digital transformation driving forces have become increasingly prominent. Researchers have explored the impact of enterprise digital transformation from the aspects of resource allocation and corporate governance (Hass, Tarsalewska & Zhan, 2016; Frynas, Mol & Mellahi, 2018; Graetz & Michaels, 2018; Lin, Xie, Hao & Wang, 2020; Ma, Li & Wang, 2023), obtained fruitful research results, which laid a good theoretical foundation for this paper. Enterprise digital transformation can alleviate the financing constraints of enterprises, improve the market competitiveness of enterprises, become an important means to promote enterprises to achieve curve overtaking, and provide a solution for enterprises to solve the problem of insufficient innovation. However, few studies have focused on how enterprise digital transformation promotes enterprise dual innovation. In view of this, this paper, based on the theory of dual innovation, Based on the data of A-share listed companies from 2007 to 2022, this paper analyzes the theoretical logic of dual innovation driven by digital transformation from the micro enterprise level by using the two-way fixed effect model, and explores the heterogeneity of enterprises affected by different operating efficiency and different regions. Compared with the existing researches, the contributions of this paper are as follows: (1) It enriches the research results on the impact of enterprise digital transformation from the perspective of enterprise two-way innovation; (2) Reveals the internal theoretical logic of dual innovation driven by digital transformation.

The follow-up structure of this paper is as follows: The second part is literature review; The third part is theoretical analysis and research hypothesis; The fourth part is data source, variable design and model setting. The fifth part is characteristic facts and datum regression; The sixth part is mechanism test and heterogeneity analysis. The seventh part is the conclusion and enlightenment.

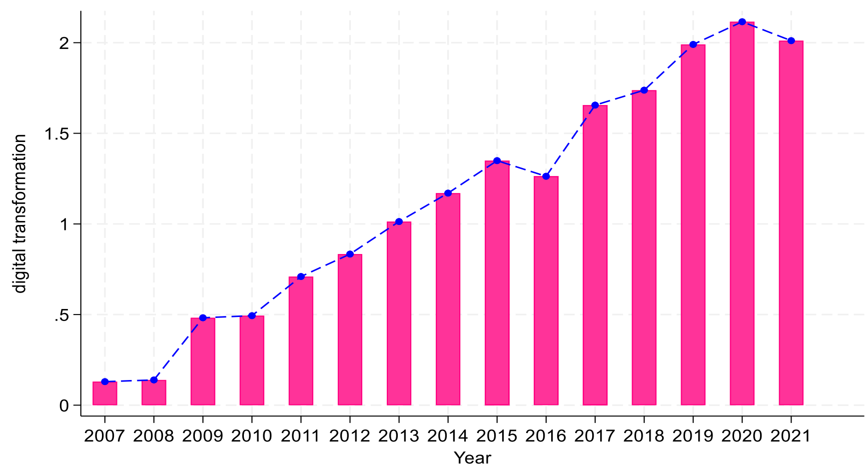

Figure 1. Trend chart of enterprise digital transformation

Notes: Drawn by stata15.0, same as below.

Literature review

Research status of enterprise digital transformation

Connotation and characteristics

The transformation is systematic, strategic and phased, and it is a crucial route for businesses to establish new competitive advantages and seek new economic growth points. Enterprise digital transformation is a high-level transformation aimed at realizing a new business model of digitalization, informatization and intelligence (Song & Song, 2023). From the technology-driven perspective, some scholars believe that digital technology is the core content of modern enterprise transformation. Enterprises invest a lot of money in the introduction and development of new technologies, which can make them more competitive than enterprises that spend the same amount of money (Tang, 2021). In today's fierce market competition, enterprises need to combine business and strategic goals to update digital technology in a timely manner and create a new technological foundation. This business transformation process will change the traditional value creation mode of enterprises, improve business processes, production and operation management, etc. (Smirnov & Antropova, 2022). From a data-driven perspective, some scholars believe that the collection and sorting of data resources is the key to enterprise transformation, and enterprise digital transformation is a strategy to support enterprise upgrading through sorting and analyzing various data resources. As intangible assets of enterprises, data is considered as the core resource of enterprises. Enterprises summarize experience, discover rules and predict development trends through data information, so as to provide decision information for managers. From the perspective of organizational change, enterprise digital transformation is one of the processes of organizational change, and this process is sustainable (Lozić, 2023). Enterprises reconstruct organizational culture, business model and organizational structure through the digital process, which will flatten the organizational structure of enterprises, build digital core values and behavior patterns, and make resource allocation more reasonable.

Influencing factors

It mainly includes three aspects: management, organization and environment. In terms of management, the process and efficiency of transformation are affected by the level of enterprise management. As the strategic decision makers of enterprises, corporate executives are the leaders in the process of transformation (Wrede, Velamuri & Dauth, 2020) . Executives have different risk preferences and decision-making levels. At present, enterprises lack systematic transformation plans and strategic goals, and most managers fail to plan in all aspects, and only focus on how to introduce digital technologies. The dynamic capabilities of enterprises are different, which affect the transformation process and promote the business model and process innovation of enterprises(Jiao, Yang, Wang & Li, 2021; Matarazzo, Penco, Profumo & Quaglia, 2021); In terms of organization, the enhancement of fault zone of the senior management team can improve the decision-making level of the management, improve the integration ability of enterprise resources, and promote the management to improve the risk appetite and increase the investment in transformation. On the environmental front, the government will adopt a series of industrial policies to achieve certain economic goals and objectives. Among them, government subsidies and tax incentives provide policy power and institutional support for enterprise transformation (He & Qiu, 2023).

Major obstacles

The digital transformation process and efficiency are mainly focused on data security issues, digital technology talent shortage, financial barriers, and insufficient management capacity. Data security issues are one of the main obstacles to transformation. The transformation process involves a large amount of data, and there is a great risk of disclosure in the process of sharing and interworking of enterprise data. The privacy of employees cannot be guaranteed, and the rights and responsibilities are not clear (Li & Chen, 2023). Therefore, there is hesitation and hesitation in the enterprise and its employees. A shortage of digital skills is another major obstacle. Digital technology talent is a new important resource to promote digital transformation. Enterprises need not only management personnel with digital management experience, but also a variety of technical personnel in the fields of computer science, information science and automation. At present, enterprises are insufficient to introduce talents and lack systematic digital technology training for enterprise employees, China 2023 enterprise digital transformation ability report shows that 57% of enterprises lack digital training for relevant personnel, 23% of enterprises have never had the corresponding training. Financial barriers are the third major obstacle. The transformation process requires a lot of money to update equipment, collect data and train talent, and some companies may have financial barriers. Small and medium-sized enterprises are short of funds and have poor ability to bear financial risks (Chen & Chen, 2023). Management capacity is the fourth major obstacle. Enterprise managers need to make decisions based on the information they have and make overall arrangements for the digital management process, which requires managers to have a comprehensive digital knowledge background and choose appropriate digital technologies according to their own advantages to combine with their own production and operation process. However, for traditional enterprises, decision-making is more difficult.

Effect of utility

The effectiveness of digital transformation mainly includes improving resource allocation and corporate governance. In terms of resource allocation, the researchers pointed out that enterprises undergoing digital transformation transmit signals of strong financial strength and broad development prospects to the outside world, which can help enterprises attract high-quality talents and provide human resources for the development of the company. Digital technology applications can optimize human resources by replacing and supplementing highly repetitive, low-skilled jobs with cheaper capital (Graetz & Michaels, 2018). At the same time, the improvement of the level of enterprise informatization will restrain the violation of corporate information disclosure (Ma, Li & Wang, 2023), increase the trust of external investors in enterprises, and increase the possibility of investment. In addition, digitization can reduce unnecessary capital requirements and reduce the inefficient operation of financial resources (Frynas, Mol & Mellahi, 2018). In terms of corporate governance, business process informatization can improve the transparency of enterprises in production links, internal management links, research and development links and financial control links, restrain managers' short-sighted behaviors, alleviate principal-agent problems, strengthen internal supervision, increase the fairness and effectiveness of decision-making, and improve the internal governance environment of enterprises (Hass, Tarsalewska & Zhan, 2016). And help improve the organizational environment, governance structure and checks and balances, so as to form a community of interests for information sharing and common governance (Lin, Xie, Hao & Wang, 2020).

Research status of dual innovation

Connotation and characteristics

March J.G. (March, 1991) divided enterprise innovation activities into exploratory innovation and exploitative innovation for the first time, thus forming the idea of organizational dual innovation. Since then, scholars have continuously enriched and improved the connotation of dual innovation on this basis. Exploratory innovation is a fundamentally old and new behavior, which focuses on long-term and larger innovation activities, aiming at producing brand new products or services, opening up new markets and marketing methods to attract new customers (Sun, Liu & Ding, 2020); Exploitative innovation is a progressive innovation behavior that focuses on the expansion of existing technologies , its goal is to improve product functions and improve service quality, so as to meet the needs of customers (Ling & Yang, 2023). The two types of innovation activities have different resource demands, risk bearing and income improvement. Both kinds of innovation activities require resource input, and resources are scarce. Based on innovation heterogeneity, Yingbing Jiang et al. found that different enterprises have different investment in exploratory innovation and utilization innovation (Jiang, Xu & Ban, 2022). As different enterprises have different target orientation, risk preference and resource reserve structure, enterprises will focus on different types of innovation according to their own conditions (Guo, Liu & Zhang, 2019). In addition, the collaborative development of dual innovation can not only help enterprises maintain their long-term competitive position in the existing market, but also open up potential markets for enterprises to help occupy a dominant position in new markets, which will bring sustainable development benefits to enterprises.

Influencing factors

Market environment, organizational characteristics, resource acquisition and so on have an impact on enterprise innovation. In terms of market environment, people's services and demands for products continue to diversify. Customers buy commodities in order to obtain the use value of commodities, and enterprises in order to obtain profits. In a dynamic and competitive environment, enterprises need to continuously improve the allocation of innovation resources, balance their own innovation capabilities, balance two kinds of innovation activities, and take into account the current and future competitive advantages. In terms of organizational characteristics, Lin et al. large scale enterprises have strong risk tolerance and are suitable for the collaborative development of dual innovation(Lin, Yang & Demirkan, 2007) . Xiaodi Zhang et al. believe that enterprises that change rigid habits and consciousness are more able to promote the development of dual innovation(Zhang, Tian, Song & Zhao, 2021). In terms of resource acquisition, some researchers have analyzed how the enterprise resource acquisition ability affects the dual innovation ability.

Research trends review

First, existing literature has analyzed the connotation and characteristics of enterprise digital transformation in detail from the perspectives of technology-driven, data-driven and organizational change. At the same time, with the development of the dual concept, some scholars have begun to combine the dual theory with innovation, such as: dual innovation synergy, equity incentive and dual innovation, dual innovation capability, dual innovation input connotation and characteristics, etc., while few papers have studied exploratory innovation and utilization innovation from the level of dual innovation performance. Second, existing literatures have studied the factors affecting the overall level of dual innovation from the aspects of management, organization and environment, but there is a lack of relevant studies from the aspect of transformation. Third, the theoretical research on digital transformation has been deepened, mainly focusing on the connotation and characteristics, influencing factors, transformation obstacles, and utility impact. Through the transformation, enterprises can realize the reorganization of technology, business process and knowledge, break through the technical barriers, and provide a new perspective for improving the performance of enterprises' dual innovation.

Theoretical Analysis

Digital transformation and dual innovation

The transformation is systematic, strategic and phased, which can help enterprises to seek new economic growth points. Enterprise digital transformation is a high-level transformation of enterprises through improving business processes, improving organizational structure, and transforming management mode to achieve a new business model of digitization, information and intelligence. Enterprises inject digital technology into business processes, and rely on digital technology to enable them to identify underutilized human resources, internal and external resources, and help enterprises reduce resource redundancy and improve resource utilization (Wen & Zhong, 2022). The injection of digital technology into the production process can improve the flexibility and expansibility of the new product design process (Ferreira, Fernandes & Ferreira, 2019), broaden the channels for enterprises to obtain resources, and increase the paths for enterprises to solve problems. As the basic unit of production development, enterprises meet the needs of consumers by transforming the means of production into products, services, systems, etc. In order to meet the increasingly diversified product demand of consumers, enterprises need to continuously produce more new products and increase the achievements of enterprise dual innovation. Enterprise innovation results are the new products, new services and new systems developed by enterprises through research and development, design, construction and other innovative activities. Whether enterprises can achieve innovation results is restricted by many factors, among which the important factors include financing constraints and human capital quality. Enterprise digital transformation can not only alleviate the information gap between banks and enterprise subjects, but also increase the attractiveness of enterprises to talents. Through technical support for enterprise employees, talents' skills can be fully utilized and enterprises' dual innovation results can be increased. Digital transformation mainly improves the effectiveness of dual innovation through the following two ways. The theoretical model is shown in Figure 2.

First, it will help enterprises ease financing constraints. From the perspective of risk management, enterprise digitalization is strengthening enterprise resilience, enabling enterprises to withstand pressure and recover quickly in the face of adverse scenarios (Chen, Hao & Yi, 2023), reducing corporate financial risks, operational risks and other risks, and thus reducing corporate debt financing costs. From the perspective of information market, enterprise informatization can increase the information transparency among enterprises, make the connection between stakeholders closer, promote information sharing and resource complementarity among enterprises, improve commercial credit, expand commercial credit financing channels, and alleviate financing constraints (Li, Li & Li, 2023). The investment cycle of enterprise innovation activities is long and the funds are needed. Due to the high resource requirements of innovation activities, companies need to have strong financial strength to increase the intensity of innovation activities. Most enterprises can not rely on their own financial strength to provide funds for innovation activities, more rely on a variety of channels of financing. Therefore, corporate financing constraints directly affect the output of innovation achievements. The improvement of the digital level of enterprises enables external investors to follow up the progress of innovation projects in a timely manner and supervise the financial status of enterprises, thus improving the dual-innovation ability and dual-innovation efficiency of enterprises.

Secondly, it helps enterprises to improve the quality of human capital. Based on the substitution effect, digital technology enables enterprises to invest in lower-cost machines to complete repetitive and procedural work, replace part of low-skilled manpower, and reduce the proportion of redundant human resources. Based on the creation effect, the transformation will change the production structure of enterprises, which will provide new employment opportunities such as algorithm development and smart device maintenance. At the same time, the complementarity of capital skills in the production process will enable enterprises to increase the capital investment of highly skilled talents and attract high-quality labor force (Xiao, Sun, Yuan & Sun, 2022). The substitution effect reduces the low-skilled manpower, while the creation effect increases the high-skilled manpower. This process will increase the proportion of high-quality labor force. Compared with other business activities, enterprise dual innovation activities are more professional, longer cycle and greater uncertainty. Therefore, researchers involved in dual innovation activities must have sufficient knowledge reserves, rich imagination and perseverance. Through digital transformation, enterprises can provide the necessary talent base for the dual innovation activities, so as to promote the dual innovation.

The innovation results of exploratory innovation are new products or new services, while exploitative innovation is to improve on the basis of original products or services, so as to achieve the effect of innovation. The two kinds of innovation activities are different in risk and return, and there are differences in technology and financial support. Compared with exploitative innovation, exploratory innovation has higher risks and uncertainties. At the same time, once exploratory innovation is successful, new products or services will play a huge competitive advantage and bring greater benefits to enterprises. Because exploratory innovation requires old and new, it often requires higher capital investment, higher technology, and greater financing constraints. Therefore, exploratory innovation is more urgent than exploitative innovation in terms of talent and financing constraints. Faced with the benefits that the success of exploratory innovation will bring to the enterprise, the enterprise is willing to carry out exploratory innovation activities, but faced with the high-tech talents and funds required for exploratory innovation, it is the barrier to the success of exploratory innovation activities. Through digital transformation, enterprises can enhance the technical support for innovative R&D activities, improve the quality of human capital, increase the possibility of successful R&D, and financial institutions will be more willing to cooperate with enterprises, and the financing constraints will be eased. When the "urgent conditions" required for exploratory innovation are improved, enterprises are more willing to increase investment in exploratory innovation activities in the face of greater benefits, which has a more significant impact on the performance of exploratory innovation. Based on this, this paper proposes the following research hypotheses

H1a: The improvement of the degree of digital transformation can significantly improve the level of exploratory innovation of enterprises.

H1b: The improvement of the degree of digital transformation can significantly improve the level of exploitative innovation of enterprises.

H1c: Digital transformation has a more significant impact on enterprise exploratory innovation.

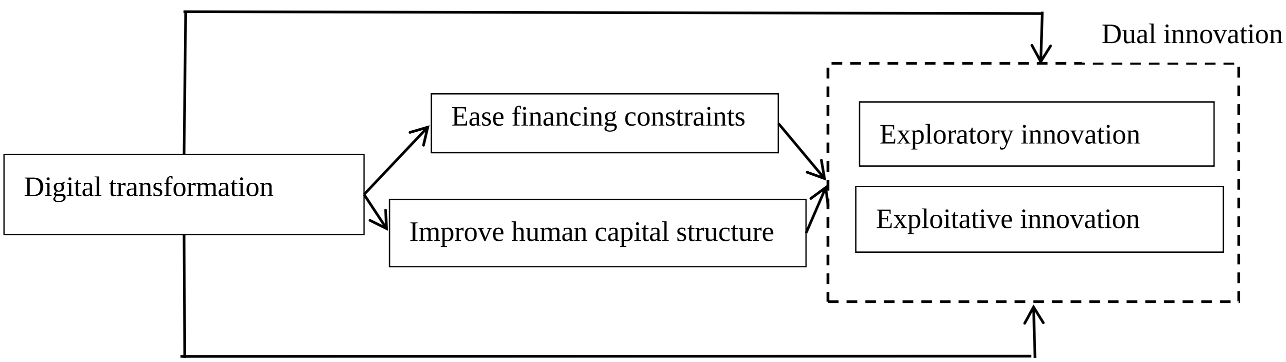

Figure 2: The impact of digital transformation on dual innovation

Heterogeneity of business efficiency

Enterprise operation efficiency is the concentrated performance of enterprise profitability and risk level, which can reflect the ability of enterprises to concentrate social resources, maintain social resources and make full use of limited social resource. In the digital economy environment, enterprises with higher operating efficiency are more likely to concentrate resources to gain insight into market demand, and their entrepreneurs have higher acumen, so they can take the lead in grasping opportunities , abandon worthless resources, reduce unreasonable investment, provide sufficient cash flow for innovation activities, and adjust organizational personnel allocation and product development requirements in a timely manner, so as to promote enterprise dual innovation. Enterprise innovation activities will be accompanied by new changes and new risks. In enterprises with high operating efficiency, the accuracy of risk identification is higher, the corresponding risk control system is more perfect, the enterprise can track and deal with potential risks in time, respond to new changes in time, make full use of resources to solve problems, give play to the advantages of digital technology, promote the process of enterprise digitization, and achieve the purpose of improving the output of dual innovation. Specifically, enterprises with higher operating efficiency have stronger profitability and anti-risk ability . Therefore, in the face of uncertain costs and benefits, enterprises with high operating efficiency are also willing to rely on new technologies to invest more resources in continuous innovation, and can make full use of resources to

significantly improve the level of dual innovation results. In order to prevent business risks, enterprises with low operating efficiency dare not risk investment and innovation, and firmly set the focus of development on innovation activities. Based on this, this paper proposes the following research hypothesis:
H2a: The role of digital transformation in promoting exploratory innovation in enterprises is more significant in enterprises with high operational efficiency.
H2b digital transformation's promotion of exploitative innovation in enterprises is more significant in enterprises with high operational efficiency.

Regional heterogeneity

China is divided into three parts according to the region: middle, east and west, and there are gaps in the level of economic development, regional digital policies, digital infrastructure construction and so on. There is an imbalance in regional economic development in China, and the demand for products in the eastern region is diverse and strong, which promotes enterprises in the eastern region to implement the product diversification strategy, and the product diversification strategy guides and supports enterprises to produce new products from the policy perspective (Jiang, Xie & Liu, 2023). There is an imbalance in the agglomeration level of innovation elements in various regions, and the innovation elements such as capital, talent, and knowledge are more concentrated in the eastern region, followed by the innovation factors and market demand in the central and western regions. According to the comparative advantages of each region, China's regional policy arrangements are different, the central and western regions focus on the integration of data and reality in key areas, the eastern developed regions give priority to development, aiming at cutting-edge science and technology. At the same time, the digitalization policy in the eastern coastal region is more perfect. The implementation of digitalization-related policies can reduce the cost burden of transformation and effectively stimulate the transformation momentum of enterprises. Systematic policy support can improve the local innovation ecological environment (Wang, Zhao & Li, 2023), promote the agglomeration of innovative talents and capital, and form a knowledge spillover effect. The construction of digital infrastructure is a strong support for enterprise transformation, which can improve the efficiency of transformation and deepen the application process, and thus significantly promote enterprise innovation, while the digital infrastructure in the eastern region is more complete. Based on this, this paper proposes the following theoretical hypotheses:
H3a: The role of digital transformation in promoting exploratory innovation in enterprises is most significant in the eastern region.
The promotion effect of H3b digital transformation on enterprise exploitative innovation is the most significant among enterprises in the eastern region.

Data Specification, Variable Design and Model Settings

Data Specification

Taking 2007-2022 as the sample period, this paper takes the degree of digital transformation and ambidextrous innovation achievements of all A-share listed companies in China as the research object, and performs the following processing on the initial data: (1) Remove the samples of enterprises in the financial industry; (2) Delete the type of accounting statements of the parent company, and only retain the sample of consolidated accounting statements; (3) Delete the sample of patent application abroad; (4) Keep only the samples that have applied for patents (5) delete the samples that have no information, (6) delete the samples that do not match, and finally contain 2580 samples. Among them, data such as digital transformation and patent applications obtained by listed companies in the digital economy come from the CSMAR database and the Wind database.

Variable Design

Explained variables

Exploratory innovation (EI) and exploitative innovation (DI) were designed as explained variables respectively. This paper takes technological innovation behavior of enterprises as the standard: new products or new services are classified as exploratory innovation performance, and the number of invention patent applications is used to quantify; Product process improvement, quality control improvement, addition of product functions and reduction of production costs are classified as exploitative innovation. The number of utility model applications and the number of design applications are summed up by addition, and the result is regarded as the new level of exploitative innovation (Benner & Tushman, 2003).

Core explanatory variables

The degree of enterprise digital transformation (Dgt) is the core explanatory variable. This paper draws on the practice of Wu Fei et al to measure variables (Wu, Hu, Lin & Ren, 2021). The measure includes five categories: artificial intelligence (AI), cloud computing (CC), blockchain (BC), Big Data (BD), and Digital technology Applications (DTA). Since the sample data is "biased", the word frequency of the five categories of enterprises is specifically summed up, and on this basis, the logarithmic processing is carried out.

Model Settings

The panel fixed effect model is used to eliminate industry characteristics and time characteristics. OLS method was used to estimate parameter values, and regression coefficient was used to test the causal relationship between digital transformation degree and dual innovation. In order to test the theoretical hypothesis H1a and H1b mentioned above, model (1) and model (2) are constructed:

$$EI_{\mathrm{it}} = a_0 + a_1 Dgt_{it} + \sum a_j Control_{it} + \mathrm{Ind}_{\mathrm{k}} + Year_t + \varepsilon_{it} \qquad (1)$$

$$DI_{\mathrm{it}} = a_0 + a_1 Dgt_{it} + \sum a_j Control_{it} + \mathrm{Ind}_{\mathrm{k}} + Year_t + \varepsilon_{it} \qquad (2)$$

Where i represents the enterprise, t represents the year, k represents the industry, and ε is a random disturbance term. If a_1 is significantly positive, hypothesis H1a and hypothesis H1b can be supported .

Control variables

This paper refers to the practice of mainstream literature, The main variables are defined in Table 1.

Table 1. Main variable definitions

Variable symbol	Variable name	Calculation method
EI	Exploratory innovation	Number of invention patent applications
DI	Exploitative innovation	Number of utility model applications + number of design applications
Dgt	Digital Transformation (second)	Dgt=Ln(AI+CC+BC+BD+DTA+1)
Size	Enterprise size (Yuan)	Ln (ending total assets +1)
Age	Enterprise age	Ln (Company's current age - listing age +1)
Lev	Asset-liability ratio	Total liabilities/total assets
MB	Book-to-market ratio	Total assets/Market value A
Roa	Return on assets	Net profit/average total assets
Z	Financial distress index	Download from CSMAR database
TQ	Tobin's Q value	Market capitalization A/ Total assets
Ind	Industry code	Industry dummy variable
Year	Year to which it belongs	Year dummy

Notes: Data were obtained by stata.15.0 analysis, as shown in the following table.

Empirical Test

Description Statistics

The statistical results are shown in Table 2. The empirical test included a total of 2580 sample data. The value range of variable EI is [0,1631], and the value range of variable DI is [0,1920], indicating that the number of binary innovation achievements is significantly different. Specifically, enterprises' utilization-type innovation results are slightly higher than exploration-type innovation results. The median values of EI and DI are 11 and

12,most companies have fewer ambidextrous innovation outcomes. The range of the variable Dgt is [0, 6.282] and the standard deviation is 1.507, indicating that the mean is representative. The average Dgt was 1.436 and the median was 1.099, indicating that the digital transformation of domestic enterprises is still in the exploratory stage.

Table 2 Descriptive statistics of main variables

Variable Name	Sample size	Mean	Standard deviation	Minimum	Median	maximum
EI	2580	31.32	78.07	0	11	1631
DI	2580	32.97	92.43	0	12	1920
Dgt	2580	1.436	1.509	0	1.099	6.282
Age	2580	1.365	0.998	0	1.386	3.466
Size	2580	21.66	1.030	19.56	21.48	26.16
Lev	2580	0.333	0.193	0.0110	0.308	0.984
Roa	2580	0.0490	0.0880	-2.834	0.0500	0.604
TQ	2580	2.275	1.657	0.782	1.763	27.34
MB	2580	0.559	0.221	0.0370	0.567	1.279
Z	2580	6.771	9.182	-9.291	4.196	160.9

Characteristic facts

Figures 3 and 4 report the characteristic facts of the research hypothesis in this paper. It can be found that the slopes of the fitting curves in Fig. 3 and Fig. 4 are positive, which preliminarily verifies the research hypothesis of this paper. However, it is worth noting that since the scatter plot does not exclude the influence of any confounding factors, and can only reveal the correlation between the two variables, the research hypothesis needs to be further empirically tested.

Baseline regression

Table 3 shows the benchmark regression results of this paper. The results show that after control variables and fixed effects are added successively, the estimated regression coefficients of Dgt for EI and DI gradually decrease, while the goodness of fit R2 gradually increases. From column (5), the regression coefficient of Dgt on EI is 5.9764***, which proves that digital transformation significantly improves enterprise exploratory innovation, and thus hypothesis H1a can be verified. From the perspective of economic significance, when the degree of digital transformation increases by 1 unit, the enterprise exploratory innovation increases by 19.08% on average; From column (6), the regression coefficient of Dgt on DI is 4.1855***, indicating that digital transformation significantly improves exploitative innovation, and hypothesis H1b can be verified.

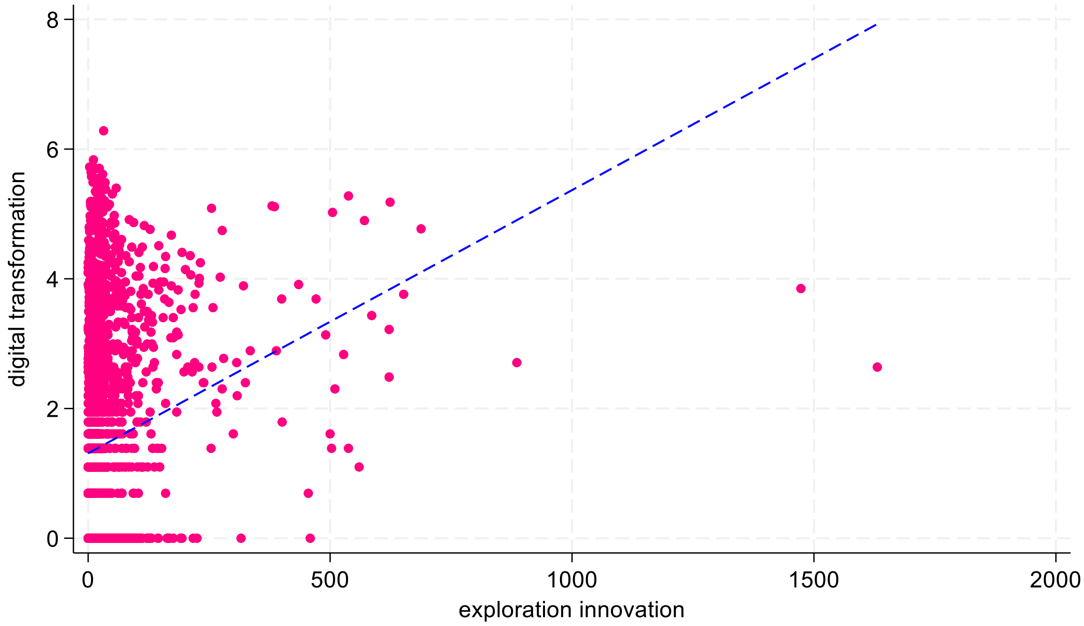

Figure 3. Correlation between digital transformation and exploratory innovation

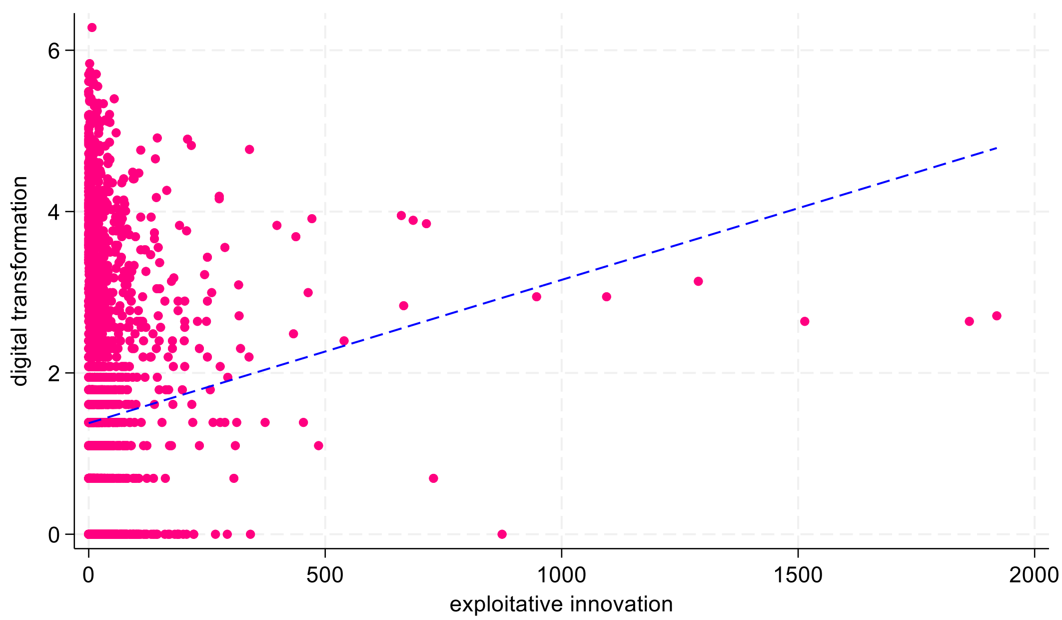

Figure 4. Correlation between digital transformation and exploitative innovation

From the perspective of economic significance, when the degree of digital transformation increases by 1 unit, the average increase of enterprise exploitative innovation is 12.69%, which is less than the increase of exploratory innovation, indicating that digital transformation has a greater effect on the improvement of enterprise exploratory innovation, and hypothesis H1c can be verified.

Table 3 Baseline regression results

Variable	EI (1)	DI (2)	EI (3)	DI (4)	EI (5)	DI (6)
Dgt	10.8677***	6.6676***	7.6560***	5.2040***	5.9764***	4.1855***
	(1.310)	(1.195)	(0.991)	(1.066)	(1.080)	(1.062)
Age			-10.7175***	-1.5241	-10.6826***	-0.7621
			(2.200)	(1.947)	(2.742)	(2.530)
Size			34.5618***	20.8594***	39.8434***	25.7830***
			(3.359)	(2.569)	(3.720)	(2.870)
Lev			-8.9410	32.3089***	-8.5371	16.0237
			(13.518)	(9.369)	(13.894)	(10.542)
Roa			-15.2682	63.8992**	-19.1312	59.2214***
			(13.685)	(26.757)	(13.994)	(21.028)
TQ			3.1264*	-1.8391	2.7278*	-2.6702**
			(1.640)	(1.175)	(1.589)	(1.144)
MB			-45.1579***	-44.1771***	-49.6196***	-47.5441**
			(11.962)	(14.366)	(13.957)	(18.963)
Z			-0.5277***	-0.3617**	-0.4392***	-0.1881
			(0.146)	(0.148)	(0.147)	(0.126)
Constant	15.7139***	23.3941***	-688.1169***	-406.6892***	-835.0996***	-568.0761***
	(1.268)	(1.335)	(69.255)	(50.114)	(80.593)	(60.605)
R^2	0.044	0.012	0.186	0.080	0.248	0.159
Year	No	No	No	No	Yes	Yes
Ind	No	No	No	No	Yes	Yes
Obs	2,580	2,580	2,580	2,580	2,580	2,580

Note: In brackets is robust standard error, ***, ** and * respectively indicate significant at the significance level of 1%, 5% and 10%, as shown in the following table.

Robustness test

Considering that the binary innovation is a counting variable, the results estimated by OLS may be biased. In this paper, Poisson regression model is used for robustness test, and the test results are listed in Table 4. In the Poisson regression model, the regression coefficients are all positive and significant, so the baseline regression conclusion is robust.

Table 4 Regression results of robustness test

Variable	EI (1)	DI (2)	EI (3)	DI (4)	EI (5)	DI (6)
Dgt	0.3015***	0.1838***	0.2281***	0.1592***	0.1456***	0.1170***
	(0.025)	(0.025)	(0.021)	(0.025)	(0.023)	(0.025)
Control	No	No	Yes	Yes	Yes	Yes
Year	No	No	No	No	Yes	Yes
Ind	No	No	No	No	Yes	Yes
Obs	2,580	2,580	2,580	2,580	2,580	2,580

Note: Limited by space, the control variables are the same as in Table 3 and the following table.

Mechanism test and heterogeneity test

Mechanism test

Financing constraint mechanism

In this paper, SA index is calculated according to Hadlock & Pierce's measurement method (Hadlock & Pierce, 2010)[1],The absolute value of SA is taken to measure financing constraint FC, and the test results of financing constraint mechanism are shown in Table 5.

Table 5 Test results of financing constraint mechanism

Variable	FC (1)	EI (2)	DI (3)
FC		-75.3380***	-45.6388***
		(24.090)	(15.689)
Dgt	-0.0047**		
	(0.002)		
C	Yes	Yes	Yes
Year	Yes	Yes	Yes
Ind	Yes	Yes	Yes
R^2	0.857	0.250	0.159
Obs	2,580	2,580	2,580

The regression coefficient of Dgt to FC is -0.0047**, indicating that digital transformation can significantly

[1] $SA=-0.737*Size_1+0.043*Size_1$^2-0.040*Age, where $Size_1$=ln(total assets at the end of the period (unit: million yuan),Age is the company's listed years.

reduce financing constraints. Meanwhile, the regression coefficients of financing constraints on dual innovation are -75.3380*** and -45.6388***, respectively, indicating that easing financing constraints can significantly promote dual innovation. In summary, financing constraint is one of the mechanisms for digital transformation to enhance enterprise dual innovation.

Human capital structure

Referring to the study of Tusheng Xiao et al. (Xiao, Sun, Yuan & Sun, 2022), the human capital structure was quantified by using Educ_ratio as a substitute variable. The test results of human capital structure mechanism are shown in Table 6. The regression coefficient of Dgt to Educ_ratio is 0.0356***, indicating that the improvement of the degree of digital transformation will significantly improve the human capital structure of enterprises. At the same time, Educ_ratio regression coefficients for dual innovation are 57.5268*** and 33.5227*, respectively, indicating that human capital structure is positively correlated with dual innovation. To sum up, human capital structure is one of the mechanisms for digital transformation to promote dual innovation.

Table 6 Test results of human capital structure mechanism

Variable	Educ_ratio (1)	EI (2)	DI (3)
Educ_ratio		57.5268***	33.5227*
		(10.607)	(17.885)
Dgt	0.0356***		
	(0.004)		
Control	Yes	Yes	Yes
Year	Yes	Yes	Yes
Ind	Yes	Yes	Yes
R^2	0.544	0.302	0.171
Obs	1,701	1,701	1,701

Heterogeneity test

Heterogeneity of operational efficiency

Business efficiency is measured by total factor productivity (TFP). With reference to the studies of Blundell and Bond (Blundell & Bond, 1998) and Xiaodong Lu and Yujun Lian (Lu & Lian, 2012), this paper uses GMM method to measure the total factor productivity [2]. Meanwhile, define that enterprises with total factor productivity greater than or equal to the mean are high operating efficiency, otherwise low operating efficiency. The heterogeneity test results of operating efficiency are shown in Table 7. For enterprises with high operating efficiency, the regression coefficient of Dgt on EI is 5.5792***, and the regression coefficient of Dgt on DI is 3.8603**. For enterprises with low operating efficiency, the regression coefficient of Dgt on EI is only 1.7919**, and the correlation between Dgt and DI is not significant. Therefore, the digital transformation of enterprises with higher operating efficiency has a more significant effect on the improvement of enterprises' dual innovation. The hypothesis H2a and H2b were verified. Therefore, it is necessary to optimize the business environment, reduce taxes and fees, and improve the operation efficiency of enterprises.

Table 7 Test results of operating efficiency heterogeneity

Variable	EI		DI	
	High operating efficiency	Low operating efficiency	High operating efficiency	Low operating efficiency
	(1)	(2)	(3)	(4)
Dgt	5.5792***	1.7919**	3.8603**	0.5949
	(1.980)	(0.898)	(1.833)	(0.943)
Control	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes
Ind	Yes	Yes	Yes	Yes
R^2	0.423	0.308	0.368	0.192
Obs	903	1,107	903	1,107

Regional heterogeneity

To test regional heterogeneity, the study samples were divided into three groups according to the region, and each group was returned separately. Table 8 shows the results of regional heterogeneity test. In the eastern samples, the regression coefficient of Dgt for EI was 6.1815***, and the regression coefficient of Dgt for DI was 3.1879***. In the samples from central and western regions, Dgt had no significant effect on dual innovation. Thus, hypotheses H3a and H3b can be tested. Therefore, digital policy support should be given to the central and western regions to improve the digital ecological environment; We will promote cross-regional

2 $y_{it} = \varpi_t(1-\rho) + \rho y_{it-1} + \beta l_{it} + \gamma k_{it} - \rho\beta l_{it-1} - \rho\gamma k_{it-1} + \eta_{it}$

Where y_{it} represents the logarithmic form of output; l_{it} represents the logarithmic form of labor input; k_{it} represents the logarithmic form of capital input; ϖ_{it} is part of the residual.

talent flow, strengthen digital infrastructure, and accelerate the development of the digital economy.

Table 8 Results of regional heterogeneity test

Variable	EI east (1)	Middle (2)	west (3)	DI east (4)	Middle (5)	west (6)
Dgt	6.1815***	3.1604	7.1745	3.1879***	1.8922	9.3142
	(1.133)	(2.864)	(7.015)	(1.097)	(2.388)	(5.858)
Control	Yes	Yes	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes	Yes	Yes
Ind	Yes	Yes	Yes	Yes	Yes	Yes
R^2	0.242	0.403	0.408	0.164	0.373	0.371
Obs	1,960	377	238	1,960	377	238

Conclusion and Revelation

Conclusion

Transformation is the way for enterprises to explore new value creation models, which is conducive to enterprises to innovate. Based on the sample of Chinese listed enterprises from 2007 to 2022, this paper selects relevant word frequency to quantize digital transformation, theoretically analyzes and empirically examines the impact of digital transformation on enterprises' dual innovation. Conclusions are drawn: (1) Digital transformation significantly improves the level of dual innovation, and has a greater impact on the establishment of old and new enterprises. Improving employee structure and easing financing constraints are two mechanisms of action. The synergistic effect of digital transformation, talent and capital stimulates the dual innovation vitality of enterprises. (2) The effect of digital transformation is reflected in the higher operating efficiency of enterprises in the eastern region, which makes the comprehensive innovation of enterprises enter a virtuous circle.

Enlightenment

Based on the above conclusions, the following policy implications are proposed: First, enterprises should clarify transformation goals and promote enterprise digitalization. The essence of digital transformation is an innovation process using digital technology, which has the characteristics of long-term and directional, and belongs to strategic decision-making. First of all, business executives must fully realize the importance of digital transformation to the high-quality development of enterprises, and understand and grasp how to transform from the height of enterprise development strategy. Secondly, the relevant knowledge of digital technology is the key premise, and business executives must fully learn the relevant knowledge, fully grasp the current situation of enterprise development, and combine their own resources, capabilities and industry characteristics in a timely manner to combine digital technology with their own management process. Finally, the goal of enterprise digital transformation should be subdivided into specific functional departments to form a specific implementation plan to promote enterprise digital reform from top to bottom. Second, strengthen the construction of digital infrastructure to facilitate the digital transformation process of enterprises. First of all, as a government investment, infrastructure construction has the characteristics of diminishing marginal returns, so infrastructure construction can not be "one-size-fits-all", there must be a master and a secondary, the government's infrastructure construction can be moderately inclined to the central and western regions. Secondly, we can further optimize the business environment, reduce taxes and fees, and effectively increase the tax burden of enterprises, so as to fully develop the positive effect of digital transformation of enterprises and improve the operation efficiency of enterprises. Third, improve the market supervision system. On the one hand, relevant government departments should give policy support to digital transformation enterprises, encourage enterprise transformation, and strengthen supervision to ensure the timeliness and effectiveness of financial subsidies and preferential policies given by the government. On the other hand, in order to more fully stimulate the enthusiasm of enterprises to implement digital strategies, practical policy support can be provided by sharing the cost of enterprise transformation with the government. Led by the government, the government and enterprises jointly contribute to the establishment of a special fund to reward those enterprises that have made achievements in digital transformation. Fourth, promote the agglomeration of dual innovation factors at multiple levels to promote the improvement of regional dual innovation capability. Promoting the integrated development of production, university and research, and establishing a multi-dimensional long-term mechanism of talent cultivation and introduction are conducive to promoting talent agglomeration, leading to factor agglomeration, and promoting the improvement of regional dual innovation ability. First of all, we should respect talents and promote the free and full flow of talents throughout the country by reducing the obstructing effect of policy barriers on the flow of talents. Secondly, strengthen the linkage of elements in the eastern and central regions through the flow of talents, and finally achieve the joint improvement of the national innovation ability in the agglomeration.

Limitations and prospects

The limitation of this paper is that it is limited to the availability of data and does not discuss the impact of digital platform construction on two-way innovation, which is the direction of further research.

Declaration

Acknowledgment: First of all, I would like to thank my school, which regularly invites well-known researchers to give lectures at our school, so that I can understand the academic frontier and related research progress.

Secondly, I would like to thank my supervisor for providing me with the valuable opportunity to conduct research at the Institute of Innovation and Development of Hunan University of Science and Technology, allowing me to be guided and inspired. Finally, I would like to thank the reviewers for their constructive suggestions for this article, which has greatly improved the quality of the article. Without the support of these people, this work would not have been possible. I would like to express my sincere gratitude to all the scholars and staff who contributed to this article.

Funding: The research presented in this work was supported by two sources:
Self-funded: Most of the funding for the study comes from self-funding, including data processing, material costs, and travel costs.
Hunan University of Science and Technology: Thanks to the database resources subscribed by Hunan University of Science and Technology, the literature resources and data sources of the articles are guaranteed, which greatly promotes the research process.

Conflict of interest: The authors declare no conflicts of interest.

Authors contribution: Research topic: I am responsible for determining the topic of the article. Research Framework: I am responsible for developing the research framework, including the development of research content and the selection of research methods. Research data: I am responsible for the collection, processing, export, analysis and storage of data, and ensure the rigor of the research in a quantitative way. Essay Writing: I wrote the main body of the dissertation, including the various parts of the essay. Thesis revision: I have made significant contributions to the editing and revision of papers. Overall, my contribution to this dissertation covers all stages of the research process.

Data availability: The datasets used and analyzed during the current study are publicly available.

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Journal of Environmental Science and Economics
https://doi.org/10.56556/jescae.v3i2.940
ISSN: 2832-6032

RESEARCH ARTICLE

Carbon Sequestration Potentials for Conservation of Sheikh Russel Aviary and Eco-Park, Rangunia, Chittagong

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Received: 02 May, 2024, Accepted: 23 June, 2024, Published: 27 June, 2024

Abstract

The study investigates the carbon sequestration potential of tree species in the Sheikh Russel Aviary and Eco-Park, situated in diverse natural settings. Utilizing quadrate sampling, the study selected plot sizes of 26*26 m based on tree species diversity. Employing a Randomized Block design with nine blocks, three plots were laid out for each block, categorized as Top, Middle, and Bottom according to hill altitude. Soil samples were collected at depths of (0-15cm) and (15-35cm) for calculating soil organic carbon and moisture content through the loss of ignition method. Enumerating 781 trees from 27 families within 27 quadrates, the survey revealed total volume, basal area, biomass, and carbon sequestration potential, with *Acacia auriculiformis* displaying the highest Importance Value Index (IVI). Notably, *Acacia auriculiformis*, *Tectona grandis* and *Gmelina arborea* exhibited the highest carbon sequestration potentials, contributing significantly within specific diameter and height classes. The study further assessed soil organic carbon content and moisture levels, providing a comprehensive overview of the ecological contributions of the studied area.

Keywords: Carbon Sequestration; Sheikh Russel Aviary; Eco-Park; Allometric Model; Importance Value Index

Introduction

The ongoing industrial revolution and escalating urbanization in the modern world are contributing to the heightened concentration of greenhouse gases (GHGs), notably methane (CH_4) and carbon dioxide (CO_2), in the atmosphere (Hangarge et al., 2012 and Nowak & Crane, 2002). The escalating carbon emissions stand as a paramount concern in today's context, a concern that was comprehensively addressed in the Kyoto Protocol, recognizing it as a primary causal factor for global warming (Ullah & Al-Amin, 2012). Forest ecosystems, encompassing 62% to 78% of the total terrestrial carbon, play a pivotal role in influencing the response to rising atmospheric CO_2 concentrations, thereby impacting the global carbon cycle (Hagedorn et al., 2002). International studies (Aryal et.al, 2020), particularly by the Intergovernmental Panel on Climate Change (IPCC, 2007), extensively document evidence linking climate change to human-induced increases in GHG concentrations. In this context, the role of green trees becomes imperative, given their high potential for tapping atmospheric carbon through photosynthesis (Hangarge L.M et al., 2012). The sequestered carbon, stored in plant tissues(Siddique et al., 2024), facilitates growth (Grogan & Matthews, 2002). Forests are accredited as natural brakes on climate change due to their ability to sequester and store carbon (Islam et al., 2016). Global estimates from the Forest Resources Assessment indicate that the world's forests alone store 289 Gigatons of carbon in their biomass.

Recognizing the crucial role of forests in mitigating climate change(M.S. et.al, 2020, Nelson. et al.,2008;NOAA,2008), many countries have initiated assessments to enhance and maintain carbon sequestration in their forest resources (Kaul et al., 2010).The Food and Agriculture Organization (FAO, 2001) proposes three strategies for forest carbon management(Nowak et. al.,2002; Ram Oren et al.,2001; Ravindranath et. al.,2007):creating carbon sinks, (Miah et al., 2011; Mignone et al.,2008) minimizing carbon release rates, and reducing fossil fuel demand. The Kyoto Protocol involves Bangladesh in an atmospheric greenhouse gas reduction regime through its Clean Development Mechanism (CDM) concept (Schlesinger et al., 2001; Schnell.et.al, 2014; Scotcher, 2005). This allows for the generation of carbon credits from natural forests and afforestation/reforestation activities in developing countries(Yong Shin et al., 2007;Simon et al.,2018; Chowdhury et al., 2023, 2024).However, challenges exist in Bangladesh, where a significant portion of forest land lacks satisfactory tree cover (Talukdar et al., 2020). Hilly forests face severe degradation due to overpopulation, shifting cultivation, and agricultural expansion, leading to a substantial loss of natural forest (Yong Shin et al., 2007).Despite these challenges, Bangladesh, with its substantial pool of existing bare hills, has the potential to play a major role in mitigating global warming and earning carbon credits (Simiele et al., 2022).Additionally, communities can derive various benefits from forests, such as adapting to climate change, conserving natural resources (Srinivasan et. al.,2008; US EPA,2015), and promoting sustainable development. Integrating existing forest management strategies with climate change through carbon sequestration becomes crucial at this juncture (Islam et al., 2016; Yong Shin et.al, 2007).

Biomass holds a pivotal position in forest stand productivity, and understanding the relationship between biomass carbon and biodiversity parallels that of biodiversity and ecosystem function. Amid global efforts to reduce global warming(K. N. Islam et al., 2020), strategies aimed at absorbing CO_2 from the atmosphere and sequestering it in terrestrial ecosystems gain significant attention. Developing countries, facing challenges in supporting forest conservation and afforestation, can potentially benefit from ecotourism, which offers a sustainable approach to tourism accommodations(Ghale et al., 2022). Harnessing tourism to generate national and regional revenue, while simultaneously contributing to global warming mitigation, introduces new perspectives to various business sectors associated with tourism, such as transportation, entertainment, and accommodation(Mamun et al., 2022). Initiatives promoting tourism's contribution to global warming mitigation have been developed with the aim of establishing a mutually beneficial relationship between tourism and climate change (Bookbinder et al., 1998 and Kiper, 2013).

While discussions often focus on minimizing carbon emissions from tourism activities, few address the positive contribution of tourism activities to absorbing and storing carbon (Wabnitz et al., 2018). The overarching objective of this project paper is to quantify sequestered carbon, assess people's opinions, and evaluate the potential of eco-tourism at Sheikh Russel Aviary and Eco-park. The study aims to measure the total carbon sequestration of tree species and explore the relationship between carbon sequestration potential and tree species diversity.

Materials and methods

Experimental design for quantitative enumeration of tree species

"Sheikh Russel Aviary and Eco-Park, Rangunia" is situated at Nischintapur Mouza of Kudala beat in Rangunia Range, Chittagong district, under the jurisdiction of Chittagong South Forest Division, near the border of the hill tracts. Covering an area of 210.0 ha, it is positioned between 22°18' and 22°37' north latitudes and 91°58' and 92°08' east longitudes. The project is approximately 35.0 km east of Chittagong city, close to the Chittagong-Kaptai Highway, neighboring Chandraghona town, and the well-known Karnafuly paper mill and Kaptai hydroelectricity project (Rahman et.al. 2022). Data collection followed a Randomized Block design, as illustrated in (Figure 1). The study area was divided into 9 blocks (Mamun et.al.,2020), and three plots were established for each block, categorized as Top, Middle, and Bottom based on the altitude of hills(Hossain et al., 2020,2015; I. Islam et al., 2022; Uddin et al., 2020).Plot size determination utilized the quadrate sampling method, with a sampling plot size estimated at 26m * 26m (Figure 1).

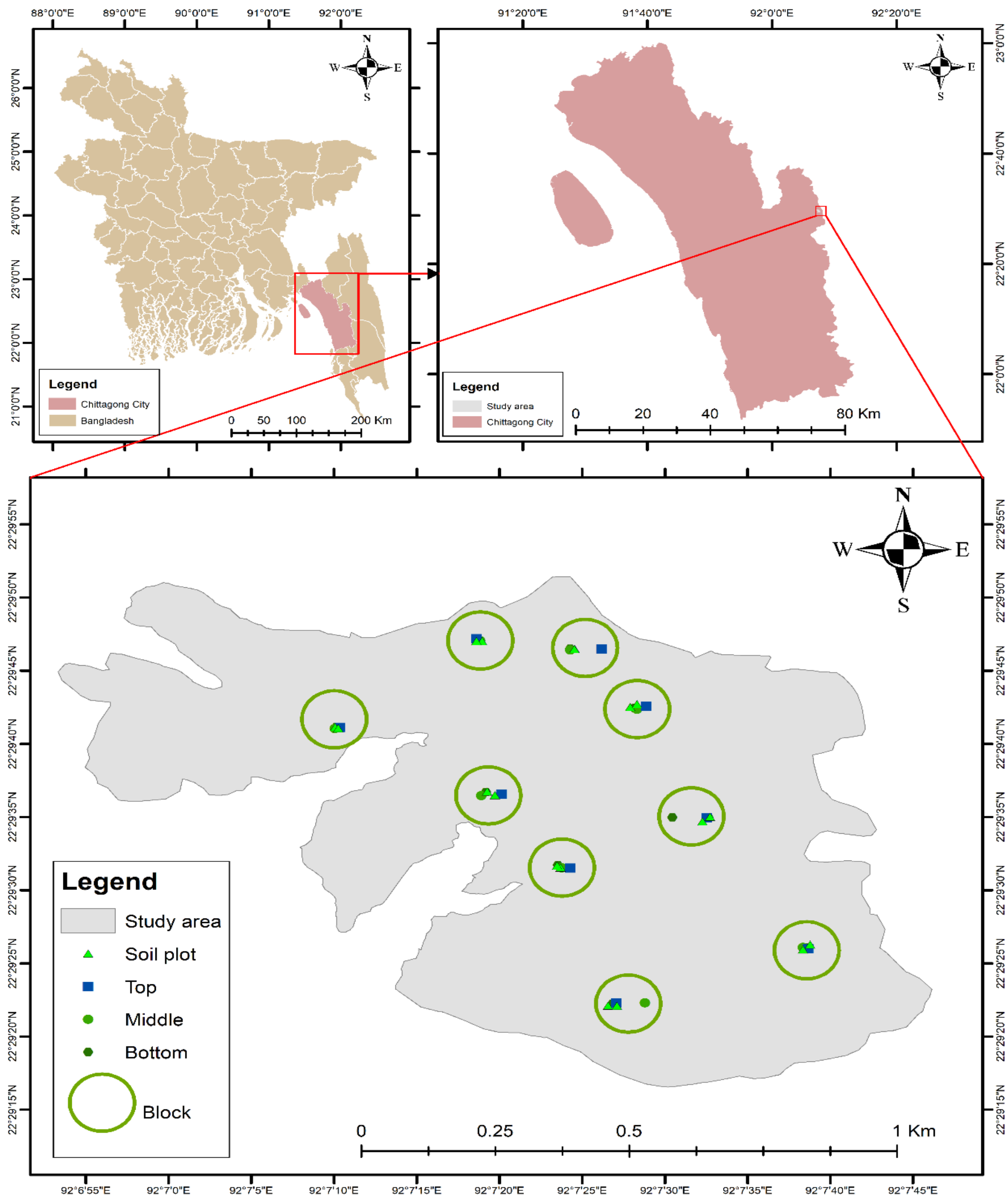

Figure 1: Map of blocks of Sheikh Russel Aviary and Eco-Park.

Soil data collection

Figure 01, From the 9 blocks, 18 plots were selected, and two soil samples were collected from each plot at depths of (0-15 cm) and (15-35 cm) from the top and bottom of the hills. Soil organic carbon was determined using washed silica crucibles, which were dried in an oven at 105°C for 20 minutes. Oven-dried soil was ground, and 5g of the ground soil was placed in silica crucibles and weighed using an electric balance (Mamun et.al.,2020). The crucibles with soil were then transferred to an electric furnace, ignited at 850°C for 3 hours, cooled in a desiccator, and reweighed to determine the percentage loss of ignition (%LOI). LOI was expressed relative to the weight of oven-dry soil, and the percentage of moisture was relative to the weight of field-moist soil, calculated according to the formula (Wang et al., 2013 and Ullah & Al-Amin, 2012).

Results and discussion

Phytosociological characters of tree species

The study conducted at Sheikh Russel Aviary and Eco-Park in Bangladesh recorded a total of 50 tree species, highlighting a diverse range of flora within the area. Among these, *Acacia auriculiformis* exhibited the highest Importance Value Index (IVI) of 62.14, indicating its dominance in the ecosystem. This species was followed by *Tectona grandis* with an IVI of 44.01 and *Gmelina arborea* with an IVI of 30.54(Figure 2), underscoring their significant presence and ecological roles. The study also detailed the distribution of species among various botanical families. Families such as Verbenaceae (223 individuals), Mimosaceae (183), Combretaceae(62), Moraceae(83), Euphorbiaceae(28), Myrtaceae(40), and Tiliaceae (22) were particularly well-represented in the park. These families are noted for their adaptability to the local environment and their ability to sequester substantial amounts of carbon, contributing to the park's overall carbon sequestration capacity. A significant portion of the tree species (381 individuals) were found in the diameter at breast height (DBH) range of 5-15 cm, comprising approximately 48.8% of the total tree species recorded. This DBH class is crucial as it includes young to mature trees that play a vital role in carbon storage and the ecological stability of the area (Islam et al., 2016). The prevalence of trees in this DBH range suggests a relatively young forest structure, which is often indicative of active growth and dynamic ecological processes. In terms of height distribution, the majority of the tree species fell within the height class of 7.1 to 17 meters (Talukdar et al., 2020).

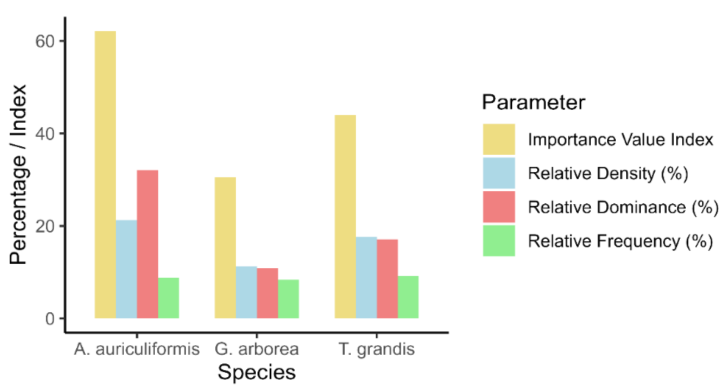

Figure 2: Importance value index (IVI) of the top three tree species in Sheikh Russel Aviary and Eco-park

This height class included 44 individual tree species and a total of 346 tree species, making up around 44.3% of the total tree population in the study area. The dominance of trees in this height range further emphasizes the park's role in carbon sequestration, as taller trees generally have a larger biomass and thus a greater capacity for carbon storage(Siddique et al., 2024). The study's findings underscore the ecological importance of Sheikh Russel Aviary and Eco-Park in terms of biodiversity and carbon sequestration. The presence of diverse species and significant numbers of trees in various DBH and height classes highlights the park's potential as a carbon sink, contributing to climate change mitigation efforts(Wang et al., 2013 and Ullah & Al-Amin, 2012). The data on IVI, DBH, and height distribution provide valuable insights into the structure and composition of the forest, which can inform conservation and management strategies aimed at enhancing the park's ecological functions. In addition to its role in carbon sequestration, the diversity of tree species and families within the park supports a wide range of ecological processes and services. These include habitat provision for various wildlife species, soil stabilization, water regulation, and nutrient cycling. The presence of species from different families also indicates a resilient ecosystem capable of withstanding environmental changes and disturbances (Talukdar et al., 2020). However, the study also points to the need for ongoing monitoring and management to maintain and enhance the ecological health of the park (Table 1). This includes efforts to protect and promote the growth of young trees, manage invasive species, and ensure sustainable tourism practices (Wang et al., 2013 and Ullah & Al-Amin, 2012). The high IVI values of certain species suggest that they are particularly well-suited to the local conditions and may be prioritized in future afforestation and conservation efforts(Siddique et al., 2024). Overall, the study provides a comprehensive overview of the tree species composition and structure within Sheikh Russel Aviary and Eco-Park, highlighting its significant role in carbon sequestration and biodiversity conservation. The detailed analysis of IVI, DBH, and height distribution offers a foundation for further research and management initiatives aimed at preserving and enhancing the ecological value of this important natural area.

Table 1: Relative frequency (RF), relative density (RD), basal area/ha (BA in m^2), relative dominance (RDo) and importance value index (IVI) of trees at Sheikh Russel Aviary and Eco-park, Bangladesh.

Species Name	RD (%)	RF (%)	RDo (%)	IVI
Acacia auriculiformis A. Cunn.	21.25	8.79	32.09	62.14
Tectona grandis L.f.	17.67	9.21	17.14	44.01
Gmelina arborea Roxb.	11.27	8.37	10.90	30.54
Artocarpus heterophyllusLam	7.04	2.93	5.57	15.54
Terminalia arjuna (Roxb.ex DC.)	4.74	2.93	3.72	11.39
Artocarpus chama Buch.-Ham.	3.33	5.02	2.84	11.19
Syzygium cumini (L.) Skeels	3.46	5.02	1.81	10.29
Terminalia bellerica (Gaertn.)	2.94	3.35	2.81	9.10
Grewia nervosa (Lour.) Panigr.	2.56	3.77	2.70	9.03
Protium serratum (Wall. Ex Coelbr.) Engl.	2.30	2.93	1.71	6.95

Biomass and carbon sequestration potentials and relation with tree species diversity

A total of 781 trees were observed to estimate biomass and carbon sequestration potentials, with measurements of 102.774 (t/ha) for biomass and 51.387 (t/ha) for carbon sequestration (Table 02 and 03) in the surveyed area. The study delved into the relationship between carbon sequestration potentials within height and DBH classes of all tree species, identifying *A. auriculiformis* and Teak as dominant species in carbon sequestration (Table 2). An allometric model was utilized to calculate the biomass of individual tree species, ensuring a non-destructive and accurate method for biomass estimation (Talukdar et al., 2020). Carbon sequestration potential varied across DBH and height classes, with larger DBH and height classes demonstrating higher carbon sequestration potentials. The study also highlighted the dominance of *A. auriculiformis* and Teak in sequestering the highest carbon within specific DBH and height classes (Wang et al., 2013 and Ullah & Al-Amin, 2012).

Table 2: Total biomass and carbon sequestration potential for top 9 tree species at Sheikh Russel Aviary and Eco-park, bangladesh

Species	Biomass(kg)	TAGB(t/ha)	BGTB(t/ha)	TTB(t/ha)	CSP(t/ha)
Acacia auriculiformis A. Cunn.	166	28.49	7.41	35.89	17.95
Tectona grandis L.f.	138	16.05	4.17	20.23	10.11
Gmelina arborea Roxb.	88	7.41	1.93	9.33	4.67
Artocarpus heterophyllusLam	55	3.48	0.90	4.38	2.19
Terminalia arjuna (Roxb.ex DC.)	37	2.78	0.72	3.50	1.75
Artocarpus chama Buch.-Ham.	23	2.57	0.67	3.23	1.62
Syzygium cumini (L.) Skeels	26	2.15	0.56	2.71	1.35
Terminalia bellerica (Gaertn.)	13	1.85	0.48	2.34	1.17
Grewia nervosa (Lour.) Panigr.	20	1.78	0.46	2.24	1.12
Protium serratum (Wall. Ex Coelbr.) Engl.	18	1.57	0.41	1.98	0.99

Note: Tree above ground biomass calculated as following below formula (Mahmood et al., 2020), Ln (TAGB) = -6.6937+ 0.809*Ln (D2 *H*W). The below ground tree biomass (BGTB) was calculated by multiplying the above ground biomass (AGTB) by root-to-shoot ratio of 0.26 (Hangarge et al., 2012); (Islam et al., 2016): BGTB = AGB × 0.26. TTB) = AGTB + BGTB(Sheikh et al., 2011) and CSP = TTB × 50%(Pearson et al., 2005) and Islam et al., 2016)

Soil carbon sequestration, moisture, and organic carbon variability

In this study, we analyzed the carbon sequestration potential (CSP), soil moisture content (SMC), and soil organic carbon (OC) across various blocks, with measurements taken at different soil depths (Top, Middle, and Bottom). CSP, quantified in metric tons per hectare (t/ha), serves as an indicator of the soil's ability to sequester carbon dioxide (CO_2), thus contributing to climate change mitigation. SMC, expressed as a percentage, reflects the water content within the soil (Chowdhury et.al. 2007), which is critical for supporting plant growth and influencing both biological and chemical processes. OC, also expressed as a percentage, represents the concentration of carbon in the soil's organic matter, an essential component for maintaining soil fertility and overall soil health (Islam et al., 2016).Soil samples were systematically collected from 18 plots, with two samples taken from each plot at specified depths: Top (0-15 cm) and Bottom (15-35 cm). The determination of OC was carried out following a standard protocol: washed silica crucibles were initially dried at 105°C for 20 minutes, cooled in desiccators, and weighed (Talukdar et al., 2020). Oven-dried soil samples were then ground, and exactly 5 grams of the ground soil were placed in the crucibles (Barna, 2011), which were subsequently weighed (Islam et al., 2016). The crucibles containing the soil samples were transferred to an electric furnace, where they were ignited at 850°C for 3 hours(Siddique et al., 2024). After cooling (Table 3), the crucibles were weighed again to calculate the percentage loss of ignition (LOI). The OC was then calculated using the formula OC = 0.476 * (%LOI - 108), as referenced in studies by Wang et al. (2013) and Ullah & Al-Amin (2012).The results indicated significant variability in CSP, SMC, and OC across the different blocks and soil depths. CSP values ranged from 1.03 to 4.55 t/ha, highlighting differences in carbon storage capacity across the study area. SMC varied significantly between the Top and Bottom soil layers, reflecting differing moisture retention capabilities(Siddique et al., 2024). OC levels also showed considerable variation both within and between blocks, indicating differences in the soil's organic matter content. These findings underscore the importance of spatial and vertical variability in soil properties, which are critical for understanding and managing the potential for carbon sequestration and overall soil health in the study region.

Table 3: Carbon sequestration potential, Soil moisture content (%) and soil organic carbon (%) as Block wise

	CSP(t/ha)			SMC (%)		OC (%)	
	Top	Middle	Bottom	Top	Bottom	Top	Bottom
Block 1	1.11	1.17	2.74	16.39	19.57	0.57	1.67
Block 2	1.72	4.55	2.47	21.45	14.97	1.57	1.81
Block 3	2.68	1.51	2.82	16.94	18.12	1.71	1.71
Block 4	2.33	1.03	1.51	16.83	15.45	1.24	0.62
Block 5	1.09	1.60	1.54	17.08	20.37	2.05	1.95
Block 6	1.49	1.05	1.77	17.71	36.92	1.57	1.67
Block 7	1.61	1.89	1.94	19.97	19.71	1.48	2.05
Block 8	2.24	1.37	1.43	18.27	14.19	1.09	1.09
Block 9	1.99	2.06	2.70	17.28	15.98	1.19	1.38

Note: Carbon sequestration potential(CSP),Soil moisture content(SMC),Organic carbon(OC), For determine soil organic carbon, washed silica crucibles were dried in oven dry at 105◦ C for 20 minutes, cooled in desiccators and then weight were taken. Oven dry soil were grind by pistol and then exactly 5g of grind soil were kept in silica crucibles and weighted by electric balance. The crucibles with soil were then transferred to an electric furnace for igniting at 850◦C for 3 hours. Then crucibles with soil were cooled in a desiccators and reweight to determine the percent loss of ignition (%), Organic carbon=0.476*(%LOI-108) (Wang et al., 2013 and Ullah & Al-Amin, 2012). 18 Plots were selected for collection of soil sample. From each plots 2 soil samples were collected according to soil depth such as Top (0-15 cm) and Bottom (15-35 cm) to determine soil organic carbon.

Conclusion

The study identifies *Acacia auriculiformis*, *Tectona grandis*, *Gmelina arborea*, *Artocarpus heterophyllus*, *Terminalia arjuna*, and *A. heterophyllus* as key tree species in Sheikh Russel Aviary and Eco-Park, Bangladesh, for carbon sequestration, with rates ranging from 17.946 to 1.354 t/ha. These species are notably dominant in height classes of 12.1-17m and DBH classes of 15.1-25cm, playing a critical role in carbon storage and overall ecosystem health. With average soil organic carbon at 1.46% and moisture content at 18.73%, the study highlights the park's significant contribution to mitigating carbon emissions through afforestation and underscores the value of species diversity in enhancing carbon sequestration. It also suggests broadening research to include understory vegetation and soil carbon for a comprehensive understanding of the park's carbon storage potential, emphasizing the need for sustainable management that balances conservation with tourism. The selection of these species is strategic, considering their growth characteristics and adaptability to the local climate. *Acacia auriculiformis* and *Tectona grandis* are fast-growing species with high carbon sequestration potential, ideal for rapid afforestation. *Gmelina arborea* and *Artocarpus heterophyllus* not only store carbon but also support local biodiversity. The inclusion of *Terminalia arjuna*, known for its medicinal properties, adds ecological value by promoting a diverse habitat for various wildlife species.

The study's findings on soil organic carbon and moisture content are critical for understanding the broader ecosystem dynamics within the park. High levels of soil organic carbon indicate healthy soil, essential for sustaining plant growth and enhancing the forest's overall carbon sequestration capacity. The relatively high moisture content suggests favorable conditions for tree growth, supporting a dense and diverse canopy that enhances carbon sequestration. However, the study acknowledges several limitations that may affect the generalizability and completeness of its findings. One significant limitation is the exclusion of understory vegetation and soil carbon measurements. These components are crucial for understanding the total carbon sequestration potential, as they play significant roles in carbon cycling and nutrient turnover within forest ecosystems. Another limitation is the focus on specific tree species, potentially overlooking the contributions of less dominant species, which are important for maintaining ecosystem diversity and resilience. Additionally, the use of allometric equations for estimating carbon sequestration may introduce uncertainties, as these generalized models may not fully capture species-specific growth patterns and biomass accumulation. The study's emphasis on the park's carbon sequestration potential as a climate change mitigation strategy may also overlook other important ecosystem services, such as biodiversity conservation, water regulation, and soil protection. This focus could lead to management practices that prioritize certain species or approaches at the expense of overall ecological health. Future research should address these limitations to provide a more holistic understanding of the park's ecological contributions and to inform balanced conservation strategies.

Declaration

Acknowledgment: The Divisional Forest Officer, Cox’s Bazar Forest Division, Bangladesh provided necessary support during the field works.

Funding: Self-financed

Conflict of interest: No conflict of Interest

Ethics approval/declaration: This study did not involve human participants or animals, and ethical approval was not required. The research focused on plant carbon sequestration and was conducted in compliance with institutional guidelines for ecological and environmental research. All necessary permits for plant sampling and data collection were obtained from the relevant authorities where applicable.

Consent to participate: Not applicable. This research did not involve human participants, so no consent to participate was required.

Consent for publication: Not applicable. This study did not involve any individuals or identifiable data that would require consent for publication.

Data availability: Data sharing is not applicable to this article as no new data were created or analyzed in this study. The data that support the findings of this study are available from the author, [Mohd Imran Hossain Chowdhury], upon reasonable request.

Author’s contribution: Mohd Imran Hossain Chowdhury: Designed the study, performed data analysis, wrote the initial draft, and contributed to the final manuscript revision. Chinmoy Das: Conducted the experiments, contributed to data analysis, and reviewed the manuscript.

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Journal of Environmental Science and Economics
https://doi.org/10.56556/jescae.v3i2.981
ISSN: 2832-6032

RESEARCH ARTICLE

Assessing the Impact of AI Innovation, Financial Development, and the Digital Economy on Load Capacity Factor in the BRICS Region

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Received: 22 May, 2024, Accepted: 25 June, 2024, Published: 28 June, 2024

Abstract

This study explores the impact of AI innovation, financial development, and the digital economy on the Load Capacity Factor (LCF) in BRICS nations from 2000 to 2019. Cross-sectional dependence and slope homogeneity tests reveal that the variables exhibit both dependence and heterogeneity. Panel unit root tests confirm stationarity, and a cointegration analysis establishes long-term relationships among the variables. The Panel ARDL method identifies a U-shaped relationship between income and LCF, supporting the LCC hypothesis. AI innovation and the digital economy positively influence LCF, promoting environmental sustainability. Conversely, financial development significantly reduces the LCF in both the short and long terms. To validate these findings, robustness checks using DKSE (Driscoll Kraay Standard Error), AMG (Augmented Mean Group), and CCEMG (Common Correlated Effects Mean Group) estimation techniques yield consistent results with the Panel ARDL analysis. Furthermore, the D-H causality test reveals unidirectional causal relationships from income, financial development, and the digital economy to LCF. It also identifies a bidirectional causal relationship between LCF and AI innovation. These findings highlight the dual role of AI and the digital economy in enhancing environmental sustainability while addressing the challenges posed by financial development in the BRICS nations.

Keywords: AI Innovation; Financial Development; Digital Economy; LCC Hypothesis; BRICS

Introduction

A growing emphasis on sustainable growth can be credited to the decline in the environment caused by corporate operations, industrialization, and the utilization of fossil fuels for energy (Dong et al., 2024). Since the SDGs were endorsed by the UN in 2015, nations in transition have faced numerous obstacles in accomplishing the objectives placed by the organization (Feng et al., 2024). To combat global ecological issues, the UN has designated "green energy" as the 7 sustainable development objectives (Chen,2022). Moreover, to keep temperature level to 1.5°C, Beck and Mahony (2018) predict that GHG emissions must be reduced by 45% until 2030 compared to 2010 levels, achieving net-zero status around 2050. A recent IPCC estimate states that by 2029, energy-related CO2 emissions should rise by 40%–107% (Liu et al., 2023).We made use of the BRICS emerging economies to illustrate the need for appropriate resilience policies based on frameworks that take the link between the natural world, technological advances, and financial stability into consideration. We selected BRICS area for our empirical investigation concerning multiple scenarios. This countries are among the rapidly emerging nations that seek economic progress through misuse of resources, which exacerbates ecological degradation (Mahalik et al.,2024; Ahmad et al.,2024b). In 2020, the economy accounted for 23.5% of the world's total (Jafari et al. 2022). This development paradigm will deplete energy supplies, degrade the state of the economy, and increase the release of GHG's (Ameyaw et al. 2019; Nepal et al. 2021). As a result, they have pledged to reduce carbon emissions and broaden their energy investments, especially by adding renewable energies to their conventional power holdings (Ullah et al. 2023), to minimize global warming (Hassan et al. 2020). Regrettably, especially in emerging economies like the BRICS, economic expansion frequently takes priority over resilience and ecological health (Ghosh et al., 2023; Caglar et al., 2022). The LCF is a measure of ecological condition, is determined by calculating biocapacity from the EFP (Raihan et al., 2023b).

In the long run, GDP growth promotes the adoption of green technology, which lowers EF and improves LCF, even though it may initially hinder biocapacity (Voumik et al., 2024). The BRICS nations concentrate about 25% of the world's surface area, 40% of its population, and 25% of its economy. The contribution of BRICS to worldwide financial expansion has exceeded 40%. Forecasts commonly predict that BRICS will maintain its position as a major global power until 2050 (Tutar et al., 2024). Renewable energy technology adoption and innovation can be accelerated by financial development, which provides the funding needed, risk reduction, and incentive for investment (Premeph,2023; Sohail et al.,2019). Development in monetary field might promote advances in technology and cause the use of energy to fall, both of which could cut CO2 (Ridwan, 2023; Onwe et al.,2024). However, the depletion of ecosystems and an upsurge in CO2 can also be attributed to the expansion of the finance industry (Mngumi et al., 2024). The correlation between financial development (FD) and pollution is of utmost importance when pursuing responsible prosperity, especially in the economies of the BRICS countries. These nations are challenged by balancing their rapid growth with the increasing energy demands (Yadav et al., 2024; Faruk et al.,2023). Moreover, few works illustrated that the digital economy (DGE), symbolized by digital financial services, could present a previously rare chance to discover a resolution. Zhou et al. (2022) argue that it is possible to advance the decarbonization process without jeopardizing economic expansion or the well-being of individuals. Moreover, effective financial management stimulates the digital economy, environmental efforts, and a drop in CO2 emissions from companies (Zhang et al., 2023; Sohail et al.,2018a). By utilizing cutting-edge technologies like Big Data and the Internet of Things, DGE can maximize the use of resources and achieve swift economic growth without compromising the environment (Baloch et al., 2024). Growing DGE is a good way to increase ecological efficiency, reduce resource and environmental strain, and raise national GDPs (Qin et al., 2022). AI has the potential to be a strong tool to boost productivity, efficiency, and imaginative thinking due to its potential for use in areas including robotics, data processing, and decision-making (Makridakis, 2017). Furthermore, artificial intelligence (AI), in particular machine learning models, are growing in popularity for optimizing systems in some fields, most notably CO2 collection and emission reduction from human actions (Delanoe et al., 2023).

The EF measures the globe's capacity to replenish its resources and the amount of productive land required to replace the assets consumed by global populations (Sonu et al., 2011). However, prior studies have not sufficiently explored the supply side of the ecology. According to Sieche et al. (2010), a value of "1" signals the sustainability threshold, but results below "1" indicate the current ecological condition is unsustainable. These reasons make it clear that the LCF is a better indicator than CO2 emissions and EFP because it shows the supply and demand of ecological resources (Pata and Balsalobre-Lorente, 2022). This study's goal is to examine, utilizing data from 1980 to 2017, how the digital economy, financial development, economic growth, and AI innovation affect the LCF. It achieves this by combining the ARDL approach with the LCC hypothesis. The following are the research's main adds to the ecological literature: (i) this is the first attempt to investigate how AI innovation and the digital economy affect LCF in the context of rising economies, particularly those of the BRICS nations. (ii) A few studies have used LCF as a metric to examine how financial development affects environmental damage. (iii) Within the context of the BRICS, this research explores the practicality of the Load Capacity Curve (LCC) theory. (iv) Our work made use of innovative techniques such as DKSE, AMG, and CCEMG, along with the D-H causality test, to establish causal relationships between the LCC hypothesis and its determinants, ensuring its robustness. The major findings of the study show that GDP squared, AI innovation, and the DGE have a positive impact on the ecosystem in the BRICS region, whereas GDP growth and financial expansion lead to ecosystem unsustainability. Therefore, policymakers can use these findings to support green growth, implement AI, and foster sustainable monetary growth within and outside of the BRICS community.

The interplay of AI, financial development, and the digital economy is crucial in advancing global sustainability goals, particularly the United Nations Sustainable Development Goals (SDGs). AI, with its ability to analyze complex data, optimize resource use, and enhance efficiency, plays a pivotal role in supporting sustainable industrialization (SDG 9) by streamlining manufacturing processes and reducing waste. Financial development, on the other hand, provides the necessary investment and resources to foster innovation and infrastructure, enabling industries to adopt cleaner and more sustainable technologies. The digital economy accelerates these advancements by connecting stakeholders, facilitating access to markets, and enabling the widespread adoption of green technologies. Together, these factors also drive progress in climate action (SDG 13) by improving predictive analytics for environmental changes, promoting green financing for climate projects, and enabling the shift toward low-carbon industries. Moreover, they support affordable and clean energy (SDG 7) by enhancing energy management systems, improving renewable energy integration, and expanding access to clean energy technologies in underserved regions.

There are five sections in this analysis. The second part, which follows the introduction, is a review of the literature that spotlights specific results and brings up areas for additional study. The third section describes the research variables, methods, and data sources. The fourth segment offers a comprehensive evaluation and discussion of the outcomes. The sixth and seventh sections, respectively, provide the conclusions and policy implications.

Literature Review

Numerous scholarly investigations explore the complex links between financial development, technical innovation, economic growth, and LCF across various geographic contexts. Furthermore, after thoroughly analyzing the corpus of prior research and providing new insights into the intricate relationships between creative variables, such as AI innovation and the digital economy. Our goal in going beyond conventional evaluation is to bring a unique perspective to this quickly evolving field of research.Multiple investigations in the body of literature have analyzed the link between monetary development and ecological systems, each using separate methods and in different areas; they discovered varying degrees of accomplishment. From 1992 to 2020, Gu et al. (2024) focused on how economic expansion altered the BRICST economies' EFP. Using found that there is a link between GDP rise and a spike in ecological difficulties by utilizing the DOLS, FE-OLS, and MMQR methodologies. Latif et al. (2023) investigated how GDP affected LCF in 48 Asian nations between 1996 and

2020. The analysis revealed that environmental damage is caused by GDP growth. Similarly, Pattak et al. (2023) considered Italy adopting the STIRPAT and ARDL framework from 1972 to 2021. The analysis deployed that an additional 1% in GDP causes 8.08% spike in CO2 pollutions. From 1990 to 2018, Yang et al. (2023) evaluate the LCC hypothesis's applicability using the MMQR technique. They demonstrate that GDP has detrimental consequences on ecological quality. A substantial amount of research also found similar outcomes, such as Voumik et al. (2023b) in Kenya; Hassan et al. (2024) in BRIC countries; Raihan et al. (2023c) in Malaysia; and Ridwan et al. (2023) in France. However, Raihan et al. (2024a) used the ARDL model to conduct a study and discovered that economic growth was somewhat responsible for India's emissions reduction. Similar to this, Raihan et al. (2023a) observed that rising GDP growth may eventually result in lower levels of emissions in China based on the PHH hypothesis. However, Muhammad et al. (2020) employed two-stage least squares regression techniques and found a U-shaped connection between GDP and emissions.

The impact of artificial intelligence (AI) innovation on low-carbon footprints (LCF) remains insufficiently understood. Some researchers have highlighted the potential ecological consequences of AI as relevant studies continue to emerge (Al-Sharafi et al., 2023; Ridwan et al., 2024e; Rahman et al., 2024). With the advancement of digital technologies, the rising demand for energy intensifies environmental degradation, as noted in various studies. Industrial digitalization has led to increased energy consumption and exacerbated environmental harm compared to historical levels (Li et al., 2020; Ridzuan et al., 2023; Hossain et al., 2023; Sohail et al., 2018b; Shiam et al., 2024a). On a positive note, advancements in technology have been found to enhance China's ecological conditions (Raihan et al., 2022a). Alpan et al. (2022) and Arif et al. (2024) observed that AI's capabilities in learning, relationship-building, and decision-making for specific contexts, when combined with the effective integration of the Internet of Things (IoT), could accelerate efforts to reduce CO2 emissions. Wang et al. (2023) assessed AI's global impact on ecological footprints from 2010 to 2019, concluding that AI significantly reduces ecological footprints and advocating for increased government investment in AI research and deployment. Conversely, Liang et al. (2022), using data from China and an interactive three-stage network DEA model, found that the manufacturing sector has substantial room for improvement in leveraging AI to reduce pollutants. Additional research by Chan and Huang (2003), Rasheed et al. (2024), Rana et al. (2023), Ferdous et al. (2023), and Masood and Ahmad (2021) has further suggested that AI innovation contributes to ecological sustainability.

Several researchers have examined the influence of financial development (FD) on the advancement of a sustainable ecology. Scholars argue that FD benefits the ecosystem by attracting foreign investment (Eskeland and Harrison 2003; Raihan et al.,2024h; Islam et al.,2023), promoting the adoption of greener technologies (Frankel and Rose 2002; Tanchangya et al.,2024), and providing low-interest funding for ecologically sound projects (Tamazian and Rao 2010; Shiam et al.,2024b). All of these factors help to create more sustainable and clean surroundings. Rahman et al. (2023) examine the implications of FD on the environment in the BRICS countries. The study used FMOLS and DOLS panel estimation techniques, and it found that financial development significantly increases environmental sustainability. Similarly, financial development also improves natural health in the member states of the Asia-Pacific Economic Cooperation by reducing CO2 pollution (Zafar et al., 2021). Conversely, from 1990 to 2018, Li et al. (2024) explored how the BRICS economies' financial expansion affected ecological well-being. Using the CS-ARDL approach, they discovered that FD harms environmental quality. According to Saqib et al. (2024), financial development degrades environmental quality. They examined the effects of these developments on the environment and equitable development in the ten countries with the highest EF. Ali et al. (2023) used several techniques, including OLS, PQR, and CCEMG, and found comparable results, indicating that financial development was the cause of biodiversity loss in the E-7 region. However, Zhao et al. (2021) discovered unexpected results, indicating that FD has a direct and probably mild impact on ecological damage. This further emphasizes the fact that financial inclusion has distinct effects on emissions.

According to Kuntsman and Rattle (2019), the development, upkeep, and disposal of digital equipment have all harmed the environment. By connecting all aspects of business over the Internet, Moriset and Malecki (2009) contend that the DGE reduces physical location. An increasing body of research (Wang et al., 2021; Ma et al., 2022) has examined how the digitalized economy affects CO2 emissions; nevertheless, there exits deficiency of analysis comparing DGE and LCF. Raihan et al. (2024c) examine the effect of the DGE on CO2 emissions in the G-7 region between 1990 and 2019. The paper utilized the ARDL model, revealing a significant mitigation in carbon footprint due to the digital economy. In a similar vein, Jiang et al. (2024) found that in 30 Chinese regions, carbon emissions decrease by 0.082–0.092% for a 1% surge in the DGE. The use of spatial econometric approaches achieved this. Moreover, researchers have found that the improvement of the DGE also reduces the emissions of the closest provinces. Li et al. (2023) apply the ARDL technique to explain how the next eleven economies enhanced their LCF between 1990 and 2018. Over time, the results show that reliance on DGE reduces LCF. On the other hand, Xu et al. (2024) report that the relationship between CO2 emissions and the digital economy is inverted U-shaped, with the effects of quality of life on CO2 emissions decreasing as the DGE progresses. Furthermore, Li et al. (2021) recommend hedging practices to mitigate early-stage CO2 emissions associated with the DGE.

Despite the existence of analyses on the association among GDP, financial development, urbanization, and ecological damage, there is still a need for further research in this field, particularly in the BRICS countries. Furthermore, less research has been done on how AI innovation and the digital economy impact LCF, particularly in the selected area. To bridge such gaps, this research investigates the associations between the BRICS region's GDP, DGE, AI innovation, FDI, and LCF. By examining these neglected areas, the analysis provides a fresh viewpoint on the complex processes influencing the ecosystem level in those targeted areas. The study adds a tremendous deal of value to the field by offering insights that stakeholders and policymakers dealing with ecological concerns in the bloc of BRICS nations require.

Methodology

Data and Variables

This work used data to explore the implications of several independent variables on the LCF of the BRICS countries between 1990 and 2019. We collected the LCF as a dependent factor from the reliable Global Footprint Network (GFN) for this analysis. We gather information about the digital economy, AI innovation, and financial development from WDI, Our World in Data, and the IMF, which aligns with the policy variable in our research. Furthermore, the WDI provides information about the GDP variable. A key component of the study is Table 1, which offers a full description of all of the factors examined along with helpful information regarding their background, definitions, and units of measurement.

Theoretical Framework

We utilized the LCC hypothesis, which claims that there prevails a U-shaped link between GDP and environmental condition (Pata & Kartal, 2023). This connection underscores the importance of understanding how resource consumption rises in tandem with GDP growth and increases in individual assets, highlighting it as a critical element of ecological sustainability (Degirmenci & Aydin, 2022). Several research studies, including (Huang et al., 2023; Atasoy et al.,2022a; Shahzad et al., 2024; Islam et al.,2024; Hossain et al.,2024; Ridwan et al.,2024d), used the LCF as an endogenous factor in their analysis. We include AI innovation as a new component in our analysis in addition to financial development as examined by Destek and Sarkodie (2019). We also take into account the digital economy, which Zhang et al. (2022) have identified as a major environmental driver.

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
AI	AI Innovation	LAI	Annual patent applications related to AI	Our World in Data
FD	Financial Development	LFD	Financial Development Index	IMF
DGE	Digital Economy	LDGE	Imports of ICT goods (% of total imports)	WDI

In our current analysis, we have created the following equation (1) for LCC theory:

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

Here, the variables for income in equation (1) are GDP and GDP squared, while the variable for additional factors impacting the LCF is Zt. The purpose of incorporating more noteworthy factors such as financial development, digital economy, and innovation into AI Equation (2) is to enhance the understanding of the aspects that impact the LCF.

$$LCF = f(GDP, GDP^2, AI, FD, DGE) \qquad (2)$$

In equation (2) innovation in AI is denoted by AI, development in finances is symbolized by FD, and digital economy is represented by DGE. Equation (3) is used for economic modification:

$$LCF_{it} = \alpha_0 + \alpha_1 GDP_{it} + \alpha_2 GDP_{it}^2 + \alpha_3 AI_{it} + \alpha_4 FD_{it} + \alpha_5 DGE_{it} \quad (3)$$

The logarithmic values of the variables are shown in equation (4). It simplifies complex relationships into simpler linear forms, which improves understanding and makes it possible to draw conclusions based on statistics.

$$LLCF_{it} = \alpha_0 + \alpha_1 LGDP_{it} + \alpha_2 LGDP_{it}^2 + \alpha_3 LAI_{it} + \alpha_4 LFD_{it} + \alpha_5 LDGE_{it} \quad (4)$$

Empirical Methodology

This inquiry's evaluation process is divided into seven stages. We initially utilize the Pesaran CSD test to gauge the dependencies across the countries. We then implement the slope homogeneity test. Third, we employ the first and second-generation unit root analyses (IPS, CIPS, and CADF) to confirm stationarity. The panel cointegration evaluation is the fourth step. We implement the ARDL framework in the fifth step to determine both short-term and long-term associations. Then, we conducted the DKSE, AMG, and CCEMG to verify the consistency of the long-run estimation. Ultimately, we performed the D-H causality examination to measure the correlation between the chosen parameters.

CSD Test

To assure the validity of estimates and the accuracy of conclusions, it is imperative that we tackle the CSD difficulty (Grossman and Krueger, 1991). The incidence of CSD is due to various factors, such as externalities, implicit variation, economic and geographical interaction, and unseen correlated variables. To solve this problem, we used a CSD assessment proposed by Pesaran (2004). For this particular situation, the equation below is applicable:

$$\text{CSD} = \sqrt{\frac{2}{N(N-1)}}\left(\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\sqrt{T_{ij}}\ \hat{\rho}_{ij}\right) \tag{5}$$

Slope Homogeneity Test

When analyzing panel data, we must address slope heterogeneity due to the variation in weight across different countries. We utilized Pesaran and Yamagata (2008), SH testing in this investigation. We applied the following equations to the SH test:

$$\breve{\Delta}= \sqrt{N\left(\frac{N^{-1}S\%-k}{\sqrt{2k}}\right)} \text{ and } \breve{\Delta}_{adj}= \sqrt{N\left(\frac{N^{-1}S\%-k}{\sqrt{\frac{2k(T-k-1)}{T+1}}}\right)} \ldots\ldots\ldots\ldots(6)$$

Panel Unit Root Test

Our initial investigation deployed the first generation IPS test developed by Im et al. (2003). Then, we used Pesaran's CIPS and CADF, which are second-generation unit root analyses that take into account slope heterogeneity and CSD. The purpose of these examinations was to validate the efficacy of ARDL as a substitute for typical cointegration methods. Equation (7) marks the results of the IPS test.

$$\Delta y_{it} = \delta_i + \alpha_i t + \beta y_{it-1} + \rho_i \Delta y_{it-1} + \varepsilon_{it} \ldots\ldots\ldots\ldots (7)$$

The CIPS test equation takes the following form:

$$CIPS = \frac{1}{N}\sum_{i=1}^{N} t_i\,(N,T) \ldots\ldots (8)$$

Here 'N' represents a cross-sectional dimension, and 'T' represents a time series dimension. The CADF method is presented by equation (9):

$$\Delta Y_{it} = \beta_i + \rho_i Y_{i,t-1} + \vartheta_i \bar{Y}_{t-1} + \sum_{j=1}^{p} \gamma_{ij} \Delta Y_{i,t-1} + \varepsilon_{it} \ldots\ldots (9)$$

Where, $\bar{Y}_{t-1}$ and $\Delta Y_{i,t-1}$ are average for lagged and first difference of each cross-sectional series.

Panel Cointegration Test

This work measured panel cointegration using a second-generation method created by Westerlund (2007). This method provides consistent and dependable results even when CSD is present (Kapetanios et al., 2011). The conventional structure of this test is illustrated by the following four equations:

$$G_a = \frac{1}{n}\sum_{i=1}^{N} \frac{\acute{a}_i}{SE(\acute{a}_i)} \ldots\ldots (10)$$

$$G_t = \frac{1}{n}\sum_{i=1}^{N} \frac{T\acute{a}_i}{a_i(1)} \ldots\ldots (11)$$

$$P_t = \frac{\acute{a}}{SE(\acute{a})} \ldots\ldots (12)$$

$$P_a = T\acute{a} \ldots\ldots (13)$$

Here, mean group statistics are indicated by Gt and Ga, and cointegration is symbolized by Pt and Pa.

Panel ARDL Model

This study utilizes the ARDL technique, first introduced by Pesaran et al. (2001), as an efficient method to assess the short- and long-term connection among the model's factors. It can outperform the OLS, VECM, and VAR models in both term estimations as a result of its independent latency length framework (Voumik and Ridwan, 2023). Furthermore, by accounted for the delayed period of variables, we can implement this model to investigate endogeneity (Voumik et al., 2023c; Polcyn et al.2023). Unlike the traditional approach, this model enables the researcher to use a variety of variables with various lag times (Hasan et al., 2023; Voumik et al.,2023a). Researchers can separately investigate the long- and short-run period of this method (Rehman et al., 2021; Ridwan & Hossain, 2024). Equation (14) displays the ARDL long-run estimation.

$$\begin{aligned} lnLCF_t = {} & \partial_0 + \partial_1 \mathrm{lnLCF_{t-1}} + \partial_2 lnGDP_{t-1} + \partial_3 lnGDP^2{}_{t-1} + \partial_4 lnAI_{t-1} + \partial_4 lnFD_{t-1} + \partial_7 lnDGE_{t-1} \\ & + \sum_{i=1}^{w} \vartheta_1\, \Delta lnLCF_{\mathrm{t-i}} + \sum_{i=1}^{w} \vartheta_2\, \Delta \mathrm{lnGDP_{t-i}} + \sum_{i=1}^{w} \vartheta_3 \Delta lnGDP^2{}_{t-1} + \sum_{i=1}^{w} \vartheta_4\, \Delta\, lnAI_{t-i} \\ & + \sum_{i=1}^{w} \vartheta_5 \Delta \mathrm{lnFD_{t-i}} + \sum_{i=1}^{w} \vartheta_6 \Delta \mathrm{lnDGE_{t-i}} + \epsilon_t \qquad (11) \end{aligned}$$

We compare the information supporting cointegration to the null hypothesis, which suggests the absence of cointegration. If the F-statistic exceeds both the lower and upper limits values, the null hypothesis is rejected. The following two possibilities are presented:

$$H_0 = \vartheta_1 = \vartheta_2 = \vartheta_3 = \vartheta_4 = \vartheta_5 = \vartheta_6 \quad (15)$$

$$H_1 = \vartheta_1 \neq \vartheta_2 \neq \vartheta_3 \neq \vartheta_4 \neq \vartheta_5 \neq \vartheta_6 \quad (16)$$

Our research adopts the ECM model (Engle & Granger, 1987) to analyze both short- and long-term connections. Equation (17) reveals the short-term link by utilizing the ARDL estimates.

$$lnLCF_t = \vartheta_0 + \sum_{i=1}^{w} \vartheta_1 \Delta \mathrm{lnLCF_{t-i}} + \sum_{i=1}^{w} \vartheta_2 \Delta \mathrm{lnGDP_{t-i}} + \sum_{i=1}^{w} \vartheta_3 \Delta \mathrm{ln} GDP^2{}_{\mathrm{t-i}} + \sum_{i=1}^{w} \vartheta_4 \Delta\, lnAI_{t-i} + \sum_{i=1}^{w} \vartheta_5 \Delta \mathrm{lnFD_{t-i}} + \sum_{i=1}^{w} \vartheta_6 \Delta \mathrm{lnDGE_{t-i}} + \ell ECT_{t-i} + \epsilon_t \quad (17)$$

Robustness Check

We utilized the Driscoll and Kraay (1998) developed DKSE test, a commonly used method for addressing CSD. Unlike traditional standard errors, DKSE reduces the risk of biases and errors during parameter estimation by accounting for potential correlated data errors (Ridwan et al., 2024a). Alternatively, we can establish CDs using the highly resilient AMG estimator (Eberhardt and Bond 2009). In the end, we used Pesaran (2006) CCEMG, which can handle structural cracks that can't be seen and common features that don't stay in place (Kapetianos et al., 2011).

D-H causality Test

This work used the causality method (Dumitrescu & Hurlin, 2012) to illustrate the causal relationship between the variables. We prefer this test over the panel Granger causality test because it incorporates cross-sectional dependence. This technique allows for the estimate of both N > T and T > N samples, which gives it plenty of versatility and is useful for providing consistent findings during CD (Ahmed and Le, 2021). We can express the D-H panel's causality as follows:

$$\mathrm{y_{it}} = \theta_\mathrm{i} + \sum_{\mathrm{j-1}}^{\mathrm{j}} \lambda_\mathrm{i}^\mathrm{j} \mathrm{y_{i(t-j)}} + \sum_{\mathrm{j-1}}^{\mathrm{j}} \beta_\mathrm{i}^\mathrm{j} \mathrm{x_{i(t-j)}} + \varepsilon_{\mathrm{it}} \quad (14)$$

Results and Discussion

Table 2 is the descriptive statistics, which is the first step towards examining variables and fully grasping their properties, including mean, standard deviation, minimum and maximum values, etc. Out of all the variables, LGDP2 has the greatest mean (76.62), whereas LFD has the lowest mean. While LLCF has the lowest value, LGDP2 also has the largest value. Moreover, positive skewness in LLCF and LDGE indicates a concentration of values to the right of the mean, while negative skewness in LGDP, LGDP2, LAI, LRSP, and LFD indicates a leftward skew. In these distributions, all variables, except LGDP and LGDP2, have kurtosis values less than 3, indicating modest platykurticity. The findings of the Jarque-Bera test show that none of the parameter data sets had a normal distribution.

Table 2. Summary statistics of variables

Statistic	LLCF	LGDP	LGDP2	LAI	LFD	LDGE
Mean	-0.099205	8.744605	76.6202	3.054113	-0.508423	2.303808
Median	-0.170368	8.808211	77.5848	3.113269	-0.507575	2.165588
Maximum	1.972074	9.22577	85.11483	3.89182	-0.226608	3.260742
Minimum	-1.562449	7.693433	59.18891	1.791759	-0.950286	1.302204
Std. Dev.	1.055331	0.391927	6.688636	0.500842	0.214967	0.451703
Skewness	0.12615	-1.100278	-1.010352	-0.405564	-0.200829	0.691474
Kurtosis	1.644066	3.526287	3.32096	2.437028	1.657579	2.807014
Jarque-Bera	7.925885	21.33094	17.44276	4.061935	8.180928	8.124125
Probability	0.019007	0.000023	0.000163	0.131209	0.016731	0.017213
Sum	-9.920473	874.4605	7662.02	305.4113	-50.8423	230.3808
Sum Sq. Dev.	110.2586	15.20711	4429.048	24.83345	4.574878	20.1995
Observations	100	100	100	100	100	100

Table 3 demonstrates the Pesaran CSD test outcomes. The p value for all variables is 0.000, indicating that all CSD statistics values are highly significant at the 1% significance threshold. The null hypothesis, which posits that there is no CSD across nations, is denied for all of the factors, as shown by the results. This implies that a change in one of the sample countries may also affect the remaining nations.

Table 3. Cross sectional Dependence test

Variables	CD-Statistics	P-Value
LLCF	9.73***	0.000
LGDP	13.26***	0.000
$LGDP^2$	13.20***	0.000
LAI	5.63***	0.000
LFD	8.53***	0.000
LDGE	7.58***	0.000

The slope heterogeneity examination results in Table 4 demonstrate that the existence of slope heterogeneity is well-supported. Based on the P-values of 0.022 and 0.004, this implies the rejection of the null hypothesis that no slope heterogeneity exists.

Table 4. Results of SH test

SH tests	Δ statistic	P-value
$\breve{\Delta}$ test	2.292**	0.022
$\breve{\Delta}_{adj}$ test	2.843***	0.004

"Null Hypothesis: Slope of the coefficients are homogenous"

Table 05 illustrates the unit root evaluations' conclusions. The IPS test outcomes suggest that all other variables become stationary after the initial difference, keeping only LGDP and LGDP2 stationary at the level form. The CIPS and CADF assessments indicate that the remaining factors (LLCF, LAI, LFD, and LDGE) are stationary at I(1). Additionally, evaluations indicate that LGDP and LGDP2 are stationary at the I(0) level. In summary, the other elements are stationary in their level form I(0), while LLCF, LAI, LFD, and LDGE are stationary at the first difference I(1).

Table 5. Results of panel Unit root test

	IPS		CIPS		CADF		Decision
	I(0)	I(1)	I(0)	I(1)	I(0)	I(1)	
LLCF	-1.606	-4.704***	-1.635	-3.680***	-1.922	-3.630***	I(1)
LGDP	-3.045***	-4.256***	-3.180***	-4.570***	-3.174***	-4.890***	I(0)
$LGDP^2$	-3.031***	-4.381***	-3.105***	-4.089***	-3.012***	-4.075***	I(0)
LAI	-1.854	-7.130***	-1.107	-5.381***	-1.677	-5.022***	I(1)
LFD	-1.902	-5.465***	-1.184	-5.866***	-1.985	-4.091***	I(1)
LDGE	-2.054	-4.498***	-2.081	-4.814***	-1.067	-3.618***	I(1)

In Table 06, using four test statistics, the Westerlund (2007) cointegration test assesses long-term correlations between variables. P-values less than 0.05 for the Gt and Pt test statistic support the rejection of the null hypothesis. It indicates the presence of cointegration and a steady, long-term association between the factors in the panel dataset.

Table 6. Results of Panel Cointegration test

Statistics	G_t	G_a	P_t	P_a
Value	-4.821***	-5.680**	-4.231**	-3.413***
Z-Value	-1.891	1.975	2.671	1.407
P-Value	0.001	0.021	0.039	0.001

The Panel ARDL model's results, presented in Table 07, demonstrate the intricate dynamics influencing the BRICS region's carbon pollution. In terms of LGDP, the short-term coefficient is 0.3017 while the long-run coefficient is -0.4131, and both are statistically significant at conventional levels. This suggests that economic expansion alone contributes to environmental degradation in this setting. Our results support the encouraging link between GDP and environmental damages found by Alotaibi and Alajlan (2021), Raihan et al.(2024b), Kongkuah (2021), Raihan et al.(2022b), Rahman et al.(2022), Ahmad et al.(2024a) and Sun et al. (2024). However, this result defies previous observations made in West Africa (Halliru et al., 2020). Similarly, LGPR has a positive association with LCO2 in both periods. In the short run, the coefficient has a positive value of 0.0206, and in the long run, the value is 0.1362. The variable is significant because its p value is less than the conventional level for both periods. This conclusion highlights that long-term green growth cause's betterment for the natural world. Furthermore, there is a beneficial connection between AI innovation and LCF across both short and long periods. Specifically, a 1% expansion of LAI in the long and short term will boost LLCF by 0.0216% and in 0.040%. These results imply that utilization of modern AI technology could boost ecological conditions in both terms, and the results are significant in both terms. It aligns with the outcome of Raihan et al.(2024g), Atasoy et al.(2022a), Shiam et al.(2024c); Ridwan et al.(2024b), Ridwan et al.(2024c). For real-time hazardous material monitoring in-ground and plant matter, there are several benefits to utilizing AI-powered sensors and equipment (Singh and Kaur, 2022). The study by Pachot and Patissier (2022), Abir (2024), Mithun et al.(2023) and Yadav and Singh (2023) demonstrate the potential of AI to enhance ecological sustainability. Conversely, these destructive relations between LFD and LLCF persist in both the long and short term. In both the long and short term, an additional 1% increase in LFD is responsible for a fall of LLCF by 0.017% and 0.023%, respectively. This result is significant at conventional thresholds and indicates that financial development is not good for the BRICS region's ecosystem. However, because financial growth has a beneficial impact on CO2 pollutions, Al-Mulali et al. (2025) stated that it can improve ecosystem level both in the short and long term. The conclusions observed by Khan et al. (2021) in 184 nations and Yasin et al. (2021) in 59 less developed economies, Akther et al.(2024) in USA, Bala et al.(2024) in G-7 areas, Abir et al.(2024) within USA and Raihan et al.(2024d) within Indonesia are consistent with our analysis. In both the short and long term, the table demonstrates a positive relationship between LDGE and LLCF in both short and long terms. The long-term results indicate statistical significance with a p value of 0.015, while the short-term results demonstrate insignificance with a p value of 0.015 and the short-term results with a p value of 0.065. For every 1% increase in LDGE, there will be a 0.244% and 0.117% spike in LLCF in the long run and short run, respectively. In particular, the effect suggests that the digital economy raises the ecosystem's level. Our results concur with Dai et al. (2023) in emerging territories. However, Zhao et al. (2024) don't agree with us and claim that the digital economy harms the environment.

Table 7. Results of Panel ARDL model

Variable	Coefficient	Std. Error	t-Statistic	Prob.*
Long-run Estimation				
LGDP	-0.744	0.5343	-4.7975	0.000
LGDP2	0.874	0.5380	4.8730	0.000
LAI	0.216	0.0381	5.6685	0.000
LFD	-0.017	0.1070	-5.1666	0.048
LDGE	0.244	0.0983	2.4839	0.015
Short-run Estimation				
COINTEQ01	-0.454	0.3233	-4.4051	0.005
D(LLCF(-1))	-0.108	0.3081	-4.3524	0.025
D(LGDP)	-0.226	0.2331	5.1260	0.000
D(LGDP2)	0.343	0.8553	-4.1255	0.000
D(LAI)	0.040	0.0310	6.3065	0.000
D(LFD)	-0.023	0.2622	-3.0903	0.028
D(LDGE)	0.117	0.2441	0.4797	0.065
C	10.494	2.6559	10.399	0.000

Table 8 uses three distinct estimating strategies to detect the validity of ARDL results. With values of -0.243 in DKSE, -0.781 in AMG, and -0.530 in CCEMG estimates, the predicted coefficients for LGDP reveal a negative connection with LCF across all approaches. The short- and long-term results of the ARDL model align with the negative influence of the LGDP variable on LCF in the BRICS zones, a finding that every scenario supports at the 1% significance level. Conversely, the encouraging connection between LLCF and LGDP2 suggests that sustained, substantial increases in GDP do not negatively impact the BRICS ecosystem. In the DKSE estimation, at the 1% level, in AMG, at the 5% level, and in CCEMG, at the 10% level, the LGDP2 variable is significant. In a similar vein, all approaches demonstrate favorable relationships between the LAI coefficient and LLCF. To be more specific, for every 1% improvement in AI innovation, the LLCF grows by 0.229% in the DKSE, 0.036% in the AMG, and 0.029% in the CCEMG. In DKSE, AMG, and CCEMG, the LAI factor is statistically significant at a level of 1%, supporting the conclusions of the ARDL model and emphasizing the beneficial effects of AI innovation on the ecological systems of the BRICS territories. All three analyses failed to identify any beneficial connection between LLCF and LFD. In DKSE, AMG, and CCEMG, the LFD coefficient is significant at the 1%, 5%, and 10% thresholds, consequently. According to these results, for every 1% increase in LFD, there is a corresponding decline in LLCF of 0.127%, 0.129%, and 0.516%. This suggests a connection between biodiversity loss and increased financial development in the BRICS region. Conversely, the upward trend between LDGE and LLCF confirms that more digitalized economy promotes biodiversity in the area under study. Across all estimations, the LDGE variable is significant at the 1% threshold. These results bolster the study's conclusions and the ARDL model, which served as the main estimating technique.

Table 8. Results of Robustness Check

VARIABLES	(1) DKSE	(2) AMG	(3) CCEMG
LGDP	-0.243***	-0.781***	-0.530
	(0.947)	(0.368)	(0.148)
LGDP2	0.650***	0.328**	0.691*
	(0.353)	(0.402)	(0.185)
LAI	0.229***	0.036***	0.029***
	(0.145)	(0.013)	(0.114)
LFD	-0.127***	-0.129**	-0.516*
	(0.360)	(0.0991)	(0.523)
LDGE	0.583***	0.073***	0.069**
	(0.0982)	(0.0991)	(0.206)
Constant	15.876***	12.575***	14.890***
	(4.845)	(6.283)	(4.680)
Observations	100	100	100
Number of groups	5	5	5
R-squared	0.977	0.891	0.985

Note: Standard errors in parentheses, *** p<0.01, ** p<0.05, * p<0.1

Table 9 presents the outcomes of the D-H causality test. The analysis reveals a unidirectional causal connection between LLCF and LGDP, LGDP2, and LFD, as evidenced by the p-value of less than 0.05 for each instance.

This allows us to reject the null hypothesis that there exists no causal connection and establish that LGDP, LGDP2, and LFD are Granger causes of LLCF. Additionally, there is evidence that LAI and LLCF have a bidirectional causal relationship. However, we have not found any causal link between LDGE and LLCF, nor within LGDP2, LFD, or LDGE. Given that the corresponding p-values in these instances are greater than 0.05, we cannot reject the null hypothesis that there is no causality. As a result, it is possible to assert that neither LDGE nor LLCF are Granger-caused by one another.

Table 9. Results of D-H causality test

Null Hypothesis	W-Stat	Zbar-Stat	Prob.
LGDP ≠ LLCF	7.99979	4.43646	0.006
LLCF ≠ LGDP	2.60139	0.18715	0.851
LGDP2 ≠ LLCF	7.78583	4.26804	0.054
LLCF ≠ LGDP2	2.61761	0.19991	0.841
LAI ≠ LLCF	4.54821	1.71957	0.015
LLCF ≠ LAI	6.6585	3.38067	0.004
LFD ≠ LLCF	3.84299	1.16446	0.044
LLCF ≠ LFD	2.49106	0.1003	0.920
LDGE ≠ LLCF	2.55677	0.15203	0.079
LLCF ≠ LDGE	7.39168	3.95779	0.574

Conclusion and Policy Recommendation

The study looked closely at the complex links between GDP, financial development, AI innovation, and the digital economy on LCF in the BRICS nations between 1995 and 2022. Sophisticated econometric techniques analyzed the LCC hypothesis, identifying key factors affecting regional load capacity. This investigation verified that the dataset was free of unit root issues by performing analyses for CSD and slope homogeneity, as well as using both first- and second-generation unit root tests to address potential methodological challenges. Additional panel tests for cointegration highlighted the interrelated nature of the variables by demonstrating long-term interactions between them. The study employed the ARDL framework to capture the short- and long-term interactions among the selected factors. The ARDL findings revealed that, in the BRICS region, AI innovation, the squared GDP term, and the digital economy had encouraging consequences for LCF. Conversely, we found that both GDP growth and financial expansion had negatively impacted the ecosystem. We utilized techniques such as DKSE, AMG, and CCEMG to ensure the resilience of the conclusions. We also investigated the possible causal links between each variable using the Dumitrescu-Hurlin (D-H) causality test. Findings suggested a one-way causal association between LCF, FD, and GDP. Additionally, there was proof of a reciprocal causal relationship between LCF and AI innovation. However, we found no clear causal relationships between LCF and DGE, nor between LCF and GDP, FD, or GDP squared. Furthermore, this work emphasizes how crucial it is to give sustainable development proper consideration in finance and pursue balanced growth to mitigate its detrimental impact on biodiversity. Finally, it provides policymakers and stakeholders with meaningful knowledge and a comprehensive understanding of all factors affecting environment sustainability in BRICS area. The findings of this research carry substantial policy frameworks for the BRICS nations, particularly in the realms of monetary expansion, sustainable ecosystem, and advances in technology. Given the beneficial influence of AI innovation and the digital economy on the LCF, lawmakers might encourage the integration of advanced technologies into their economic frameworks to foster sustainable growth. Investment in AI and digital infrastructure could not only foster productivity but also contribute to green environment by optimizing resource usage and reducing carbon footprints. Conversely, the study's revelation that financial development lowers the LCF suggests that unregulated financial expansion might responsible for unsustainable resource use and environmental degradation. The U-shaped relationship between income and the LCF indicates that as economies grow, initial increases in income may strain environmental resources, but further growth, coupled with technological advancements, can reverse this trend. Thus, it is crucial for BRICS countries to focus on achieving balanced economic growth that leverages technological innovations to mitigate environmental impacts. Furthermore, the study's findings of causal relationships suggest that targeted interventions in AI and the digital economy could lead to better environmental sustainability. However, it is important to be careful with financial development to avoid bad outcomes. Policymakers should also consider the bidirectional relationship between AI innovation and the load capacity factor, suggesting that as AI advances, it can further enhance environmental sustainability, which in turn can create a favorable environment for more AI-driven solutions. Overall, a comprehensive approach that integrates technological advancement, financial regulation, and environmental sustainability is essential for the BRICS countries to gain long-term green growth.

Declaration

Acknowledgment: N/A

Funding: N/A

Conflict of interest: N/A

Ethics approval/declaration: N/A

Consent to participate: N/A

Consent for publication: N/A

Data availability: Available on request

Author's contribution: Sarder Abdulla Al Shiam led the conceptualization, methodology, and manuscript preparation. Shake Ibna Abir was involved in data collection, analysis, and drafting sections of the manuscript, while Dipankar Saha handled data curation, visualization, and statistical analysis. Shaharina Shoha contributed to the literature review and manuscript drafting. Hemel Hossain assisted with experimental work and data validation. Md Shah Ali Dolon and Hasibur Rahman supported data interpretation and critical revisions of the manuscript. Md Tanvir Ahsan provided technical oversight and guidance, and Afsana Akhter contributed to final editing and proofreading. Mohammad Ridwan supervised the research, ensured the integrity of the work, and finalized the manuscript for submission.

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