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RESEARCH ARTICLE

Corporate Carbon Accounting Practices in Bangladesh: Current Practices, Gaps and Policy Implications

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Abstract
Climate change and global warming overshadow concerns about the sustainability of human existence and progress. As a result, there have been numerous worldwide efforts to reduce the negative effects of climate change and promote a sustainable future. Companies use corporate carbon accounting (CCA) as a key strategy to adapt to climate impacts. Therefore, this study aims to evaluate the current state of CCA practices in Bangladesh. The authors gathered secondary sources of information for the study. The researchers analysed the annual reports of 154 companies across 11 industries listed on the Dhaka Stock Exchange (DSE). The authors developed the 'Corporate Carbon Accounting Practice Index (CCAP)' based on existing literature and international standards. This study used content and thematic analysis, following specific criteria. The results indicated that a mandatory legal framework influences CCA practices. However, most companies have not yet implemented CCA procedures, with only a few meeting certain standards. The main reason for Bangladesh's current CCA situation is the absence of a strong legislative framework. This study provides specific guidance for policymakers interested in CCA, helping them identify the best actions to mitigate climate change risks and support sustainable development, including establishing and enforcing a robust mandatory legal framework.

Keywords: Carbon accounting; mitigation approaches; environmental sustainability; climate vulnerability

Introduction

Climate change, a major global issue, directly and significantly affects economies and societies. Consequently, various initiatives are underway to promote the reduction of greenhouse gas emissions through both market-based and non-market-based policies. Therefore, climate change circumstances and carbon institutions inevitably impact business behaviors (Luo et al., 2022). Firms and enterprises are considered the main actors responsible for the shift towards sustainability and the achievement of ecologically sustainable economies, based on the 'Ecological Modernization' ideology and current environmental regulations (Lippert, 2015). Therefore, since the extent of global greenhouse gas emissions increases the impact of climate change, there is a need for creative, all-encompassing approaches to avoid and lessen its negative impacts. Better ways to evaluate and convey the new information requirements were also required, as was advice on creating accounting plans that encourage greater accountability and transparency in decision-making in government, business, academia, and nonprofit organizations (Schaltegger and Csutora, 2012; Uddin et al.25). As a result, carbon accounting can help businesses measure carbon emissions from both unsustainable practices and long-term improvements in carbon management across a range of areas, including supply chain management, innovation, marketing, production, distribution, and procurement (Schaltegger and Csutora, 2012; Norol-janah, 2020).

Corporate Carbon Accounting

Following the 1997 Kyoto Agreement, the area of carbon accounting began to take shape in commercial economies. At multiple levels, such as organizational, process, product, or supply chain levels, it includes a range of operations, including measuring, calculating, monitoring, reporting, and auditing greenhouse gas emissions. Companies are encouraged to employ carbon accounting techniques by the Greenhouse Gas Protocol and the Carbon Disclosure Project (Csutora and Harangozo, 2017). The practice of collecting, recording, and analyzing data on climate change via accounting methods is known as "carbon accounting." In order to help internal management and external stakeholders make choices, it entails monitoring and reporting carbon-related assets, liabilities, costs, and revenue (Thang, 2017). Additionally, measuring and reporting carbon assets and liabilities, as well as managing and accessing carbon-related activities, are the main focuses of corporate carbon accounting. Additionally, it takes into account the assurance of carbon data, the disclosure of carbon information, and the impact of carbon concerns on the financial market (Luo et al., 2022). The criticality of climate change is exacerbated by the fact that, despite scientists' calls for additional policy steps, most countries have not made much headway in the negotiation and development of climate change concerns. In response, more businesses are being forced to recognize and reduce their susceptibility to climate change issues due to a number of global efforts, increased media coverage, disgruntled customers, legislative changes, and governmental inactivity. It's happening all around the globe right now, and it's dangerous for both the present and the future. Carbon accounting processes may modify carbon reduction plans and policies in this situation (Schaltegger et al., 2015). Additionally, it is important to note that corporate carbon disclosure remained voluntary in the majority of cases, which led to a lower standard of quality in corporate carbon disclosure. Many scholars are concerned about this problem (Luo et al., 2022). Additionally, companies tend to disseminate information on carbon via a variety of channels, such as annual reports, sustainability reports, CSR reports, corporate websites, and third-party platforms like the CDP survey (Luo et al., 2022).

Corporate Carbon Accounting in Bangladesh

According to a 2022 study by Paryen et al., Bangladesh's coastline position makes it one of the nation’s most vulnerable to the impacts of climate change. Numerous climate-related calamities are already plaguing Bangladesh (Paryen et al., 2022). A lack of management leadership, a weak regulatory framework, a lack of external stakeholder pressure, a propensity for noncompliance with environmental laws, a socioeconomic structure, and a lack of government environmental initiatives are some of the reasons for Bangladesh's poor environmental reporting practices (Uddin et al., 2023). Since the Kyoto Agreement in 1997, wealthy countries have benefited most from the advancements in carbon accounting. In underdeveloped countries like Bangladesh, the idea of carbon accounting has not taken off as much as expected and very little study has been done on the topic. Therefore, this empirical research will be the first to examine how carbon accounting procedures are currently used in Bangladesh by including a significant number of sectors and companies listed on the DSE.

Thus; several pertinent inquiries arise:

i. What is the present state of carbon accounting practices at the corporate level in Bangladesh?
ii. What factors influence an organization's carbon accounting practices?

Literature Review

Corporate carbon accounting has become a major concern on a global scale, leading to a tremendous deal of study. A few pieces of research on corporate carbon accounting will be covered here.

Corporate Carbon Accounting in Global Aspect

Macro-level research indicates that climate change is becoming worse, and most nations have not made much headway in climate change legislation and discussions. Astute business executives have responded by starting a range of projects and initiatives, while governments have enacted several pieces of legislation with varying degrees of success. Due to global initiatives, public attention, consumer dissatisfaction, regulatory changes, and political inaction, more businesses need to identify and reduce their climate change risk. Although reducing greenhouse gas emissions is crucial, climate change has already occurred. Strategies for adaptation and mitigation are needed for this. The company's susceptibility, as well as the options, consequences, and costs of lowering emissions and adapting, must all be evaluated to create a business climate plan (Schaltegger et al., 2015). This situation is relevant to climate change accounting, a subset of environmental management accounting. Despite its complexity, the accounting method for climate change remains poorly understood. The system that captures and analyzes climate change data, as well as accounts for and reports carbon-related assets, liabilities, costs, and income for decision-making, is referred to in this work as carbon accounting. The research clarifies the use of cutting-edge methods to create workable carbon accounting policies, processes, and initiatives (Tang, 2017). Since there is a negative link between carbon emissions and carbon management systems, the empirical results show that the rule of material balances applies to carbon emissions. The effects of this association are not substantial, however. In only two years, the harmful impacts of these contaminants have become apparent. Target, project, GHG (greenhouse gas) accounting, and openness are the criteria used to evaluate the quality of carbon management systems (CMS) (Stechemesser and Guenther, 2012). Businesses may gain from carbon accounting in two ways: by identifying and eliminating unsustainable behaviors and by enhancing sustainability. These methods are becoming more and more important for corporate services, including marketing, supply chain management (SCM), manufacturing, distribution, procurement, and innovation. The consequence is much the same regardless of whether a department's major objective is to enforce regulatory compliance, manage energy and material flows to avoid substantial cutbacks, improve eco-efficiency, stimulate product innovation, create legitimacy, or any combination of these goals. Accounting for carbon management has the potential to benefit decision-makers at all levels (Sial et al., 2022).

Corporate Carbon Accounting for Environmental Sustainability

There are two ways that carbon accounting might assist businesses in managing their carbon emissions: sustainable and unsustainable. Both strategies are more often used in corporate services, including marketing, manufacturing, distribution, procurement, supply chain management, innovation, and communication. Whether a department is attempting to structure energy and material flows for considerable savings, comply with laws, or enhance eco-efficiency, product innovation, or legitimacy, carbon management accounting may assist all organizational levels in making choices. This article distinguishes between internal carbon accounting practices and applications inside companies. For business decision-makers, the environmental management accounting framework offers an organized summary of financial and physical carbon accounting techniques. Researchers need to develop new methods, such as input-output-assisted hybrid accounting, as carbon accounting broadens to include supply chains and product life cycles (Schaltegger and Csutora, 2012). To more precisely allocate carbon-related costs and overheads to particular items, such as goods, services, customers, and business procedures, carbon accounting employs sophisticated techniques like activity-based management and life-cycle costing. Through hypothesis testing and analysis, we found a statistically significant relationship between carbon accounting and the performance of a selection of listed industrial enterprises. According to the aforementioned findings, businesses should put more effort into adapting to long-term changes in their natural environments and extending the use of their accounting and financial systems beyond short-term outcomes. According to Egbunike and Emudainohwo (2017), this means integrating long-term climate threats into costing, reporting, and disclosure procedures. Some environmental impacts, especially those linked to the emission of toxic substances, often vary less than the effects of climate change. In these situations, the carbon footprint is a poor measure of how products affect the environment. When goods are adjusted to be more environmentally friendly, environmental management that only concentrates on carbon footprints faces the risk of inadvertently spreading the problem to additional environmental implications (Laurent et al., 2012). Adoption of EMA has a significant and positive impact on company carbon emissions control and disclosure quality, according to empirical studies. According to other research, the use of audit and benchmarking tools in conjunction with control systems significantly affects carbon disclosure and management. Measurement instruments, however, revealed no appreciable effects (Qian et al., 2018). However, there is enough research available on corporate carbon accounting procedures worldwide. Since Bangladesh is now a climate-vulnerable nation, it is worth looking at how common corporate carbon accounting techniques are there.

Corporate Carbon Accounting in Bangladesh

Disclosures on the environment and climate change are now quite low in Bangladesh. Most businesses disclosed information only in the "energy usage" category, which is mandatory, despite the fact that 91% of corporations reported in at least one area. In certain areas, a far lower percentage of businesses offered information on climate change. Important categories were not disclosed, such as GHG emissions. Regarding climate change, adaptation measures were the second most popular category. Among the many environmental disclosures, one noteworthy finding is that just 5% of firms (or 6% of the businesses listed on the website) disclosed that they possessed an effluent treatment plant. A deeper look at the different kinds of disclosures reveals that most of them have positive and descriptive content (Belal et al., 2010). The average frequency of climate change data provided by Bangladeshi firms is 2.23%. In particular, because of their established market positions, large enterprises are reporting on climate change issues in more detail than smaller businesses. There is extremely little openness on climate change as a result of a lack of laws and a culture of little social responsibility inside businesses. Strangely, multinational companies are not being transparent enough (Nurunnabi, 2016). The social, economic, and environmental performance of a firm directly impacts its sustainability. We identified additional factors, including quantitative environmental reporting, standard method, voluntary environmental disclosure, legal requirements, company size, volume of environmental disclosure, material flow analysis, and life cycle assessment, as complementary measures to improve the economic, social, and environmental performance of Bangladeshi corporations and achieve sustainable development (Kumar, 2017). Additionally, there is a dearth of research on environmental disclosure, environmental accounting and reporting, sustainability reporting, and environmental risk reporting (Uddin et al., 2023; Uddin et al., 2022; Uddin et al., 2019). Corporate carbon accounting is a method used by many businesses worldwide to attain environmental sustainability. According to the literature assessment, corporate carbon accounting is a subject that is expanding quickly on a worldwide scale. Specifically, in industrialized economies, corporate carbon accounting has become a hot subject. The company is able to regulate carbonation as a result. Additionally, organizations work to achieve sustainability. Corporate carbon accounting has gotten minimal attention in Bangladesh, despite environmental reporting and transparency methods receiving a lot of attention. There hasn't been any direct research on corporate carbon accounting procedures in Bangladesh.

Accordingly, this study proposes the following objectives:

i. Providing an overview of corporate carbon accounting practices in Bangladesh, with the goal of ensuring corporate environmental sustainability.
ii. Identify the factors that influence the level of corporate carbon accounting practices.
iii. To provide specific guidelines for future directions in corporate carbon accounting to support corporate environmental sustainability management.

Methodology

Sector Selection

We selected twelve of the 22 different sectors listed on the Dhaka Stock Exchange (DSE) due to their strong correlation with carbon sentiments. This selection is shown in the table below.

Table 1: Selected Sectors from DSE

Sl. No.	Name of the Industry	Number of companies listed at DSE
1.	Cement	7
2.	Ceramics Sector	5
3.	Engineering	42
4.	Food & Allied	21
5.	Fuel & Power	23
6.	Jute	3
7.	Paper & Printing	6
8.	Pharmaceuticals & Chemicals	33
9.	Tannery Industries	6
10.	Telecommunication	3
11.	Travel and Leisure	5
Total		154

Source: Dhaka Stock Exchange (DSE)

Data Set Development

The researchers created a data set by carefully examining the corporate annual reports of the businesses selected for the Corporate Carbon Accounting Practices Index study.

Development of Corporate Carbon Accounting Practices Index (CCAPI)

The Corporate Carbon Accounting Practices Index (CCAPI) is an index of corporate carbon accounting practices created by the project investigator. The existing global literature on corporate carbon accounting (He et al., 2022) serves as the foundation for this index.

Table 2: Components of CCAPI

Coding	Board Aspect
$CAAPI_1$	General Discussion
$CAAPI_2$	Policy Discussion
$CAAPI_3$	Specific Corporate Carbon Issues
$CAAPI_4$	Financial Accounting for Carbon Assets
$CAAPI_5$	Financial Accounting for Carbon Liabilities
$CAAPI_6$	Carbon Disclosure
$CAAPI_7$	Carbon Assurance
$CAAPI_8$	Carbon Management
$CAAPI_9$	Carbon Reporting Procedure
$CAAPI_{10}$	Carbon Performance Evaluation
$CAAPI_{11}$	Carbon Reduction Target
$CAAPI_{12}$	Monetary Incentives for Attainment of Carbon Performance
$CAAPI_{13}$	Carbon Performance
$CAAPI_{14}$	Carbon Risk Management
$CAAPI_{15}$	Carbon Mitigation and Reduction Approaches
$CAAPI_{16}$	Impact on Capital Market

Sources: Developed by authors based on existing literatures

Performance calculating Model

To determine the firm's performance on the 'Corporate Carbon Accounting Practice,' the authors developed and used the following formula.

$$PCCAP = \frac{Actual\ Numbers\ of\ Index\ on\ CCAPI}{Total\ Numbers\ of\ Index\ on\ CCAPI} \times 100$$

Where,

PCCAP = Performance of Corporate Carbon Accounting Practices

CCAI = Corporate Carbon Accounting Practices Index

Analysis Method (content and thematic analysis, and codding framework)

Content analysis is described as a method that employs a series of procedures to derive valid inferences from texts (Smith, 2004). The content analysis technique has historically been used for the examination of texts and documents, aiming to measure content according to specified categories in a systematic and reproducible fashion (Bryman and Hardy, 2009).The content analysis method is employed to discern the attributes and quantify the information within a text by categorizing it based on specific criteria, allocating each information unit to a category, and tallying the total occurrences and frequencies within each category (Data and Silverman, 2011). Accordingly, this study examines the extent to which it measures the quality and quantity of corporate carbon accounting practices in companies' annual reports. Thus, the content and thematic analysis of the firms' corporate annual reports is the main focus of this research. The data set was manually compiled by the researcher using the company's annual reports for selected companies. The pre-established indexed items were scored as 1 for correct disclosure and 0 for improper disclosure. Corporate carbon accounting techniques have a score ranging from 0 to 1. A score of 1 indicates full disclosure of corporate carbon accounting methods, while a score of 0 means they are not disclosed. For each of the example firms, an Excel spreadsheet was developed, with rows denoting the obtained score and columns representing the various index components.

Theoretical Orientation

We often use many theories when examining the causes and justifications for carbon disclosure. These consist of the institutional theory, the signaling theory, the shareholder theory, and the validity theory. Despite divergent scholarly opinions, a company's intention to provide accurate information about its carbon emissions and carbon management is influenced by social, market, economic, legal, and institutional factors. This alters the incentives for sharing (He et al., 2022).

Results, Analysis, and Discussion

Performance of Cement Industry on CCAPI

Table 3: Performance of Cement Industry on CCAPI

Sl. No.	Cement Companies (Acronym)	Performance (%)
1.	ARAMITCEM	0.00
2.	CONFIDCEM	0.00
3.	CROWNCEMNT	0.00
4.	HEIDELBCEM	6.25
5.	LHBL	18.75
6.	MEGHNACEM	0.00
7.	PREMIERCEM	6.25

Source: Calculated by Authors

As of June 15, 2024, the DSE listed seven cement-related businesses. According to Table 3, most of the companies in our study didn't fit any of the 16 preset requirements. LHBL is the only company that satisfies all three requirements. Furthermore, only two companies have met the requirements for broad disclosure: PREMIERCEM and HEIDELBCEM. With an average of just 4.46%, the cement industry's corporate carbon accounting procedures are often woefully insufficient.
Table 4 illustrates, as of 2024, the DSE listed five companies in the ceramics sector. According to our analysis, the majority of the companies did not meet any of the sixteen requirements established by Corporate Carbon Accounting Practices. Only one of the five companies (RAKCERAMIC) was able to meet three of the sixteen requirements. Additionally, SPCERAMICS was the only company to receive general discussion regarding the sixteen criteria. This is a really depressing reality.

Performance of Ceramic Industry on CCAPI

Table 4: Performance of Ceramic Industry on CCAPI

Sl. No.	Ceramic Companies (Acronym)	Performance (%)
1.	FUWANGCER	0.00
2.	MONNOCERA	0.00
3.	RAKCERAMIC	18.75
4.	SPCERAMICS	6.25
5.	STANCERAM	0.00

Source: Calculated by Authors

Performance of Engineering Industry on CCAPI

Table 5: Performance of Engineering Industry on CCAPI

Sl. No.	Engineering Companies (Acronym)	Performance (%)
1.	AFTABAUTO	0.00
2.	ANWARGALV	0.00
3.	APOLOISPAT	0.00
4.	ATLASBANG	0.00
5.	AZIZPIPES	0.00
6.	BBS	0.00
7.	BBSCABLES	12.50
8.	BDAUTOCA	0.00
9.	BDLAMPS	0.00
10.	BDTHAI	0.00
11.	BENGALWTL	0.00
12.	BSRMLTD	25
13.	BSRMSTEEL	25
14.	COPPERTECH	0.00
15.	DESHBANDHU	0.00
16.	DOMINAGE	0.00
17.	ECABLES	0.00
18.	GOLDENSON	0.00
19.	GPHISPAT	6.25
20.	IFADAUTOS	6.25
21.	KAY&QUE	0.00
22.	KDSALTD	0.00
23.	MIRAKHTER	0.00
24.	MONNOAGML	0.00
25.	NAHEEACP	0.00
26.	NAVANACNG	0.00
27.	NPOLYMER	0.00
28.	NTLTUBES	0.00
29.	OAL	0.00

Table 5 continued . . . .

30.	OIMEX	0.00
31.	QUASEMIND	0.00
32.	RANFOUNDRY	0.00
33.	RENWICKJA	0.00
34.	RSRMSTEEL	0.00
35.	RUNNERAUTO	12.5
36.	SALAMCRST	0.00
37.	SHURWID	0.00
38.	SINGERBD	12.5
39.	SSSTEEL	0.00
40.	WALTONHIL	43.75
41.	WMSHIPYARD	6.25
42.	YPL	0.00

Source: Calculated by Authors

Table 5 indicates that the engineering sector also directly contributes to carbon emissions. The DSE currently lists 42 engineering-related businesses. As of right now, companies listed in the engineering sector do not meet most of the sixteen criteria that we developed in light of the carbon accounting practices of businesses worldwide. This implies that corporate carbon accounting procedures are not of special relevance to the engineering component businesses. Although a section on corporate carbon accounting procedures has not been specifically included by BSRMLTD and BSRMSTEEL, their annual reports cover environmental accounting in great detail and discuss important issues in this field. Terms pertaining to environmental governance, like environmental strategy and environmental governance policy, are used in the user's content. An environmental manifesto, which is a public statement of environmental values and goals, is also mentioned. Climate change, a major worldwide concern, is also mentioned in the book. Lastly, the word "safety," which may be related to environmental concerns, is mentioned in the text. Sustainability statements, environmental, health, and safety management statements, as well as carbon reduction initiatives, are produced by WALTONHIL. Additionally, Western Marine Shipyard Limited has ISO 14001:2004 certification for a safe workplace.

Performance of Food and Allied Industry on CCAPI

Table 6: Performance of *Food and Allied* Industry on CCAPI

Sl. No.	Food and Allied Companies (Acronym)	Performance (%)
1.	AMCL(PRAN)	0.00
2.	APEXFOODS	0.00
3.	BANGAS	0.00
4.	BATBC	37.5
5.	BDTHAIFOOD	0.00
6.	BEACHHATCH	0.00
7.	EMERALDOIL	0.00
8.	FINEFOODS	0.00
9.	FUWANGFOOD	0.00
10.	GEMINISEA	0.00

Table 6 continued . . . .

11.	GHAIL	0.00
12.	LOVELLO	0.00
13.	MEGCONMILK	0.00
14.	MEGHNAPET	0.00
15.	NTC	0.00
16.	OLYMPIC	0.00
17.	RAHIMAFOOD	0.00
18.	RDFOOD	0.00
19.	SHYAMPSUG	0.00
20.	UNILEVERCL	0.00
21.	ZEALBANGLA	0.00

Source: Calculated by Authors

Table 6 indicates that, there are now 21 businesses actively involved in the food and light industries listed on the DSE. Most businesses in the food and related industries have lack of disclosure to meet the corporate carbon accounting guidelines based on our pre-established 16 variables. Additionally, the typical standard for corporate carbon accounting practices in this business is rather low.

Performance of Fuel and Power Industry on CCAPI

Table 7: Performance of Fuel and Power Industry on CCAPI

Sl. No.	Fuel and Power Companies (Acronym)	Performance (%)
1.	AOL	0.00
2.	BARKAPOWER	0.00
3.	BDWELDING	0.00
4.	BPPL	0.00
5.	CVOPRL	0.00
6.	DESCO	0.00
7.	DOREENPWR	0.00
8.	EASTRNLUB	0.00
9.	EPGL	0.00
10.	GBBPOWER	0.00
11.	INTRACO	0.00
12.	JAMUNAOIL	0.00
13.	KPCL	0.00
14.	LINDEBD	0.00
15.	LRBDL	0.00
16.	MJLBD	12.5
17.	MPETROLEUM	0.00
18.	PADMAOIL	0.00
19.	POWERGRID	0.00
20.	SPCL	0.00
21.	SUMITPOWER	43.75

22.	TITASGAS	0.00
23.	UPGDCL	12.5

Source: Calculated by Authors

Table 7 indicates that the fuel and electricity sector is believed to have the highest carbon emissions. This industry consumes a substantial amount of carbon. 23 companies have been listed on the DSE in the fuel and electricity industries. Upon reviewing the annual reports of twenty-three distinct fuel and power sector businesses, we discovered that most of them lack of relevant practice about corporate accounting practices related to carbon. The average ratings in the industry are quite low, and this remains true even for firms that do not adhere to our 16 pre-established guidelines for corporate carbon accounting procedures.

Performance of Paper and Printing Industry on CCAPI

Table 8: Performance of Paper and Printing Industry on CCAPI

Sl. No.	Paper and Printing Companies (Acronym)	Performance (%)
1.	BPML	6.25
2.	HAKKANIPUL	0.00
3.	KPPL	0.00
4.	MONOSPOOL	0.00
5.	PAPERPROC	0.00
6.	SONALIPAPR	0.00

Source: Calculated by Authors

Table 8 shows that the paper and printing industry is another important sector in terms of carbon emissions. Companies operating within this industry are continuously releasing carbon into the atmosphere, which harms the environment. Six businesses are now registered as paper and printing companies with the DSE. The majority of these companies do not adhere to the proper protocols for corporate carbon accounting, according to an analysis of their annual reports. None of the businesses have complied with the bulk of our predetermined 16 parameters. Additionally, these firms' overall score is below expectations, and their individual ratings are relatively poor.

Performance of Pharmaceuticals and Chemicals Industry on CCAPI

Bangladesh's economy greatly benefits from the pharmaceutical and chemical industries, which are important areas of the nation's economy. This industry is accountable for a considerable quantity of carbon and hazardous material emissions within the same time period. In keeping with that rationale, this research examined the yearly reports of thirty-According to table 9, three chemical and pharmaceutical companies that are listed on the Bangladeshi DSE. The results of the study show that registered companies in the chemical and pharmaceutical industries exhibit reporting gaps corporate accounting for carbon emissions, even though these industries are carbon emitters.

Table 9: Performance of Pharmaceuticals and Chemicals Industry on CCAPI

Sl. No.	Pharmaceuticals and Chemicals Companies (Acronym)	Performance (%)
1.	ACI	0.00
2.	ACIFORMULA	0.00
3.	ACMELAB	0.00
4.	ACMEPL	0.00
5.	ACTIVEFINE	0.00
6.	ADVENT	0.00
7.	AFCAGRO	0.00
8.	AMBEEPHA	0.00
9.	ASIATICLAB	0.00
10.	BEACONPHAR	0.00
11.	BXPHARMA	18.75
12.	CENTRALPHL	0.00
13.	FARCHEM	0.00
14.	GHCL	0.00
15.	IBNSINA	6.25
16.	IBP	0.00
17.	JHRML	0.00
18.	JMISMDL	0.00
19.	KEYACOSMET	0.00
20.	KOHINOOR	0.00
21.	LIBRAINFU	0.00
22.	MARICO	0.00
23.	NAVANAPHAR	0.00
24.	ORIONINFU	0.00
25.	ORIONPHARM	0.00
26.	PHARMAID	0.00
27.	RECKITTBEN	6.25
28.	RENATA	6.25
29.	SALVOCHEM	0.00
30.	SILCOPHL	0.00
31.	SILVAPHL	0.00
32.	SQURPHARMA	12.5
33.	WATACHEM	0.00

Source: Calculated by Authors

Performance of Service and Real-estate Industry on CCAPI

Table 10: Performance of Service and Real-estate Industry on CCAPI

Sl. No.	Service and Real-estate Companies (Acronym)	Performance
1.	EHL	0.00
2.	SAIFPOWER	0.00
3.	SAMORITA	0.00
4.	SAPORTL	0.00

Source: Calculated by Authors

Table 10 indicates that, according to the 16-characteristic Corporate Carbon Accounting Practice Index, most companies in the real estate and service sectors are dealing with difficult situations. None of the four companies listed on the DSE face significant issues with corporate carbon accounting methods.

Performance of Tannery Industry on CCAPI

Table 11: Performance of Tannery Industry on CCAPI

Sl. No.	Tannery industry (Acronym)	Performance
1.	APEXFOOT	12.50
2.	APEXTANRY	0.00
3.	BATASHOE	0.00
4.	FORTUNE	0.00
5.	LEGACYFOOT	0.00
6.	SAMATALETH	0.00

Source: Calculated by Authors

Table 11 shows that the tannery industry is often regarded as one of the most ecologically damaging sectors of the global economy. This is primarily because the tannery sector is the one that manages waste and produces the most pollution of any business. There are six tannery companies in Bangladesh that are listed on the DSE. Corporate carbon accounting techniques in these firms are not supported by scientific data. The yearly records they were expected to produce on issues that ought to have been included in their annual reports were not provided by them. We discovered a notable absence of enthusiasm for corporate carbon accounting methods.

Performance of Telecommunication Industry on CCAPI

Table 12: Performance of *Telecommunication* Industry on CCAPI

Sl. No.	Telecommunication Companies (Acronym)	Performance (%)
1.	BSCCL	0.00
2.	GP	12.5
3.	ROBI	18.75

Source: Calculated by Authors

Table 12 shows that, one of the sectors with the highest carbon emissions is the technology-driven telecoms industry. Bangladesh's DSE now lists three telecoms industry companies. The three companies' individual corporate reports are accessible. An examination of the annual reports of the three corporations indicates that companies in the telecommunications industry are not interested in using corporate carbon accounting techniques. They have very little information regarding their canons. The results of the study indicate that their corporate carbon accounting disclosure falls well short of what is required.

Performance of Travel and Leisure Industry on CCAPI

Table 13: Performance of Travel and Leisure Industry on CCAPI

Sl. No.	Travel and Leisure Companies (Acronym)	Performance
1.	BDSERVICE	6.25
2.	BESTHLDNG	0.00
3.	PENINSULA	0.00
4.	SEAPEARL	0.00
5.	UNIQUEHRL	25

Source: Calculated by Authors

According to table 13, four of the five registered travel and leisure firms did not include any information in their annual reports on their corporate carbon accounting or any other environmental or carbon-related information. Nonetheless, one business fulfilled four of the sixteen requirements and revealed a substantial quantity of environmental data in their annual report.

Conclusion

New, more comprehensive approaches to climate change prevention and mitigation are needed due to the global nature of greenhouse gas emissions and the growing effects of climate change. The situation calls for better methods to foresee and satisfy new information needs, as well as instructions on how to use changing accounting practices for accountability, transparency, and decision-making in businesses, governments, and other organizations. Climate change and corporate carbon accounting have a close relationship. Since the Kyoto Protocol was ratified, corporate carbon accounting has expanded around the globe. Unfortunately, only in developed countries has corporate carbon accounting progressed and expanded. The practice of corporate carbon accounting has not developed to the expected degree in coastal nations like Bangladesh. It's also important to highlight that corporate carbon accounting methods in Bangladesh are still in their infancy and are often voluntary, which has led to a drop in the caliber of such reporting. Furthermore, it is typical for businesses to provide information on carbon via a range of platforms, including annual reports, sustainability reports, CSR reports, and company websites. There is no supervisory structure in place in Bangladesh for firms' accounting of carbon emissions. One main reason carbon accounting techniques are now seen a concerning lack of engagement in the corporate sector is the lack of a legal framework for them in Bangladesh. Businesses participate in carbon accounting voluntarily, meaning they raise environmental issues on their own initiative, since it is not legally required.

Policy Guidelines

The current research may contribute significantly in a number of ways. In the end, the results of this study have the potential to greatly impact the formulation of recommendations for corporate carbon accounting practices by policy makers and pertinent agencies. The results of the research are meant to help scholars and decision-makers understand how companies respond to corporate carbon accounting to achieve environmental sustainability. The main cause of Bangladeshi companies' disinterest in the aforementioned carbon accounting techniques is the lack of a strong legal framework in the nation. This is by far the most important concern. The lack of a strong legal framework is the investigation's most persuasive conclusion. Improving corporate carbon accounting practices requires the establishment of a strong legal framework. The study's conclusions also indicate that companies have the discretion to decide whether to include corporate carbon accounting issues in their annual reports. This indicates that these companies discuss environmental concerns in their annual reports without following any particular structure since there is no legislative framework in place. Establishing a legal framework with suitable oversight will enable the implementation of corporate carbon accounting in Bangladesh. To avoid and mitigate the negative impacts of climate change and global greenhouse gas emissions, new and more comprehensive methods must be developed. Leading the charge in this endeavor might be appropriate corporate carbon accounting procedures. To meet the growing information needs of corporate carbon accounting, government agencies, corporations, academic institutions, and nonprofit groups will require enhanced methods. To promote sustainability and environmental transparency, they will also need direction on how to use sophisticated corporate carbon accounting systems. A thorough framework for defining carbon accounting practices in Bangladesh may be built using the 16 elements of the Corporate Carbon Accounting Practices Index that are described in this study.

Declaration

The undersigned authors affirm that this content is wholly original and has not been submitted or published elsewhere. Every author significantly contributed to the research, composition, and final endorsement of the paper.

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RESEARCH ARTICLE

Governance and waste management in urban Nigeria: a comparative study of OYO and rivers states

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Abstract
This research examines the institutional and operational frameworks influencing solid waste management (SWM) in two principal metropolitan centres in Nigeria: Ibadan (Oyo State) and Port Harcourt (Rivers State). This study utilised a convergent parallel mixed-methods methodology, integrating data from structured surveys of 400 people with qualitative interviews of important stakeholders, including state solid waste management agencies, ministries, and contractors. The results show that both states still have problems, such as sporadic waste collection, open dumping, and low community participation. Statistical analysis substantiates a considerable correlation between fragile institutional frameworks and exacerbated environmental concerns. Qualitative data further elucidate deficiencies in funding, enforcement, and inter-agency coordination. The research suggests enhancing institutional capacity, reconfiguring public-private partnerships, and promoting community involvement as essential strategies for achieving sustainable urban trash management. These measures are necessary to lessen the negative effects on public health and the environment that come from bad solid waste management in Nigeria's cities that are growing quickly.

Keywords: Environmental Sustainability; Institutional Mechanisms; Solid Waste Management; Urban Governance

Introduction

Rapid urbanisation in Nigeria has put more stress on municipal solid waste management (SWM) systems, revealing long-standing problems with institutions, operations, and regulations. Even though state-level agencies like OYOWMA and RIWAMA have been set up, cities like Ibadan (Oyo State) and Port Harcourt (Rivers State) still have problems with irregular garbage collection, open dumping, inadequate enforcement, and little community involvement. These difficulties indicate broader governance shortcomings, including limited financing, fragmented institutional duties, and weak execution of national environmental legislation. These challenges are not just operational but also institutional. They arise from insufficient funding, constrained technical proficiency, inadequate regulatory enforcement, and disjointed agency responsibilities (Adejobi & Olorunnimbe, 2012; Ikebude, 2018). Additionally, the inability to incorporate contemporary waste management systems and the insufficient utilisation of private sector capabilities have exacerbated these challenges (Uwadiegwu, 2013; Nabukeera, Ali, & Raja, 2014). There are many bad effects of bad waste management. Uncollected trash blocks drainage channels, makes the environment worse, causes health problems, and makes flooding in cities more likely (Elenwo, 2015; Isife, 2012). Even though state-level waste management agencies like the Oyo State Waste Management Authority (OYOWMA) and the Rivers State Waste Management Agency (RIWAMA) have been set up, problems like open dumping, irregular waste collection, and a lack of community involvement still exist (Nwogwugwu & Ishola, 2019). Solid waste management (SWM) has become a persistent issue in urban Nigeria, indicative of more profound structural deficiencies in environmental governance (Ike, Ezeibe, Anijiofor, & Daud, 2018; Ogwueleka, 2009). As cities continue to expand due to population increase and economic activity, the pressure on infrastructure and natural systems grows. Urban centres such as Ibadan and Port Harcourt are particularly affected by the expanding volume of municipal solid garbage, much of which remains mismanaged or incorrectly disposed of (Bakare, 2021).

Bad waste management has effects that go beyond the immediate area. Uncollected trash blocks drainage channels, causes flooding, harms the ecosystem, and is a major health risk. Even though there are state-level waste management authorities like the Oyo State Waste Management Authority (OYOWMA) and the Rivers State Waste Management Agency (RIWAMA), problems like open dumping, irregular waste collection, and a lack of community involvement continue to exist. These problems are not just operational. They also come from problems with institutions, such as not having enough money, not having enough technical knowledge, not enforcing rules well, and having different responsibilities among agencies. Also, the lack of integrated waste management systems and the fact that the private sector isn't being used enough have made progress much harder.

Because Nigeria is becoming more urbanised quickly, it is very important to carefully look at the governance structures and operational strategies that support SWM. This research offers a comparative examination of Oyo and Rivers States, emphasising institutional efficacy, public-private collaborations, community engagement, and environmental results. The study seeks to elucidate systemic deficiencies and potential reform areas to enhance effective and sustainable waste governance in Nigerian cities. This study seeks to rigorously assess the institutional and operational frameworks of solid waste management in Oyo and Rivers States, pinpointing significant structural shortcomings and recommending feasible reforms to enhance urban waste governance.

Also, open dumping and unmanaged landfilling are still common, even though they are not good for the environment (Bakare, 2021). Public-private partnerships have been set up to help with financial and operational problems, but these efforts have often been hurt by problems with transparency, late payments, and unclear contract terms (Nabukeera et al., 2014). Even though OYOWMA was set up in Oyo State and RIWAMA was set up in Rivers State, SWM is still mostly useless and broken apart (Nwogwugwu & Ishola, 2019). Several institutional and operational weaknesses underpin these failures. These include limited budget, lack of technical experience, ineffective enforcement of environmental legislation, and disconnected agency roles (Adejobi & Olorunnimbe, 2012; Ikebude, 2018). Low public knowledge, inadequate community participation, and general apathy further widen the gap between policy frameworks and real achievements (Uwadiegwu, 2013).

The quick urbanisation of Nigerian towns has led to an exponential increase in the generation of solid garbage, which has overburdened existing waste management systems (Ike et al., 2018). In cities like Ibadan and Port Harcourt, solid trash is often deposited in open areas, drainage channels, and along highways practices that significantly contribute to environmental degradation, urban floods, and heightened public health concerns (Onifade et al., 2021; Elenwo, 2015).

This ongoing issue is caused by a number of problems with institutions and operations. Some of these are not enough money, not enough technical know-how, not enough enforcement of environmental laws, and not enough coordination amongst the entities that need to work together. Public indifference, a lack of knowledge, and low levels of community involvement have made things even harder. This has caused a gap between policy frameworks and what is actually happening on the ground. Also, the fact that people still use old methods like open dumping and unregulated landfilling shows that there are no contemporary, integrated waste management options. Public-private partnerships, which are typically touted as good options, have also not lived up to expectations because of problems with transparency, late payments, and unclear duties. Because of these worries, it is very important to quickly check how well the institutional and operational systems for SWM work in urban Nigeria. This study fills this gap by looking at the governance structures in Oyo and Rivers States, finding systemic problems, and suggesting evidence-based ways to improve urban waste management outcomes.In this premise, the study aimed to:

1. Examine the governance structures and institutional frameworks underpinning waste management in Ibadan and Port Harcourt.
2. Assess the performance of OYOWMA and RIWAMA in delivering effective waste management services.
3. Identify the core operational challenges affecting solid waste collection, disposal, and regulation.
4. Recommend strategic interventions particularly in institutional reform, public-private collaboration, and community engagement to improve waste governance in urban Nigeria.

Literature Review

Rapid urbanisation in Nigeria has put more stress on municipal solid waste management (SWM) systems, revealing long-standing problems with institutions, operations, and regulations. Even though state-level agencies like OYOWMA and RIWAMA have been set up, cities like Ibadan (Oyo State) and Port Harcourt (Rivers State) still have problems with irregular garbage collection, open dumping, inadequate enforcement, and little community involvement. These difficulties indicate broader governance shortcomings, including limited financing, fragmented institutional duties, and weak execution of national environmental legislation.

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management systems and the fact that the private sector isn't being used enough have made progress much harder.
Because Nigeria is becoming more urbanised quickly, it is very important to carefully look at the governance structures and operational strategies that support SWM. This research offers a comparative examination of Oyo and Rivers States, emphasising institutional efficacy, public-private collaborations, community engagement, and environmental results. The study seeks to elucidate systemic deficiencies and potential reform areas to enhance effective and sustainable waste governance in Nigerian cities. This study seeks to rigorously assess the institutional and operational frameworks of solid waste management in Oyo and Rivers States, pinpointing significant structural shortcomings and recommending feasible reforms to enhance urban waste governance.
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This ongoing issue is caused by a number of problems with institutions and operations. Some of these are not enough money, not enough technical know-how, not enough enforcement of environmental laws, and not enough coordination amongst the entities that need to work together. Public indifference, a lack of knowledge, and low levels of community involvement have made things even harder. This has caused a gap between policy frameworks and what is actually happening on the ground. Also, the fact that people still use old methods like open dumping and unregulated landfilling shows that there are no contemporary, integrated waste management options. Public-private partnerships, which are typically touted as good options, have also not lived up to expectations because of problems with transparency, late payments, and unclear duties. Because of these worries, it is very important to quickly check how well the institutional and operational systems for SWM work in urban Nigeria. This study fills this gap by looking at the governance structures in Oyo and Rivers States, finding systemic problems, and suggesting evidence-based ways to improve urban waste management outcomes.

The link between policy framework and best practices

The results are in line with Nigeria's National Policy on the Environment (2016), which stresses community involvement, decentralised waste management, and integrated waste systems. But neither state has put these rules into effect. UNEP's Integrated Solid Waste Management framework and UN-Habitat's Global Waste Management Outlook show the best ways to handle waste around the world. Oyo and Rivers, on the other hand, don't have important parts like separating waste at the source, recycling systems, and strong enforcement of rules. To bring both states more in line with global standards, they should make institutions more accountable and include circular economy ideas in their state-level SWM programmes.

Methodology

This research utilised a convergent parallel mixed-methods approach to achieve a thorough comprehension of the institutional and operational frameworks governing solid waste management (SWM) in Oyo and Rivers States. This architecture facilitates the concurrent gathering and distinct analysis of both quantitative and qualitative data, which are subsequently integrated to yield a more comprehensive interpretation. The target population consisted of the approximately 15,144,788 inhabitants of Oyo (7,840,864) and Rivers (7,303,924) States, as indicated by the National Bureau of Statistics (NBS, 2018). Using Yamane's (1967) method at a 95% confidence level, we found that 400 people would be a good sample size. 207 of them would be from Oyo State and 193 would be from Rivers State, which is in line with their population estimates. A multistage sampling method was utilised. Five Local Government Areas (LGAs) in Rivers State were chosen on purpose: Obio/Akpor, Etche, Okrika, Eleme, and Port Harcourt. Five LGAs were also chosen from Ibadan, Oyo State: Ibadan North, North East, North West, South East, and South West. These were chosen because they are urban and important for SWM activities.

Data were gathered through two primary methods:

1. Structured questionnaires were administered to residents to capture quantitative data on waste collection, agency performance, and public perceptions of SWM.

2. Key informant interviews were conducted with officials from OYOWMA and RIWAMA, representatives from state Ministries of Environment, environmental officers at local government levels, and private sector contractors involved in public-private partnerships.

The questionnaire was divided into six parts (A–F), and each part had Likert-scale items that were related to the main variables of the study. The interview guide has open-ended questions that were meant to get stakeholders to give detailed answers. A pilot test was done to make sure the results were reliable, and all of the scales' Cronbach's Alpha coefficients were higher than the allowed level of 0.70. Expert assessments and factor analysis proved the correctness of the construction. We employed descriptive statistics to summarise the demographic information of the respondents and their views on SWM practices. Inferential statistics, specifically Linear Regression Analysis (LRA), were utilised to investigate the correlation between institutional systems and environmental difficulties in both states. Thematic content analysis was used to look at qualitative data. This made it possible to find common themes and points of view from different stakeholders. Before collecting data, ethical approval was obtained. Everyone who took part in the study gave their informed consent and was promised that their privacy would be protected and that they could leave at any time.

Results

This section presents the findings from both the quantitative survey and qualitative interviews conducted in Oyo and Rivers States. Results are visualised through comparative charts to highlight state-level differences in service efficiency, satisfaction, institutional impacts, and operational challenges.

Table 1: Perception of Waste Collection Efficiency by Respondents

State	Regular Collection (%)	Irregular Collection (%)	No Collection (%)
Oyo	25.6	63.2	11.2
Rivers	28.4	61.8	9.8

Source: compiled by the authors, 2024

Figure 1: Comparative perception of waste collection frequency in Oyo and Rivers States.

Hypothesis 1: Waste Collection Perception

An independent t-test revealed no statistically significant difference in perceptions of waste collection efficiency between Oyo and Rivers States, $t(398) = 3.3 \times 10^{-16}$, $p = .999$, $d < 0.01$. This indicates that the perception of collection irregularity is virtually identical across both states.

Table 2: Satisfaction with SWM Agencies (OYOWMA/RIWAMA)

State	Satisfied (%)	Neutral (%)	Dissatisfied (%)
Oyo	28.5	21.0	50.5
Rivers	30.6	19.4	50.0

Source: compiled by the authors, 2024

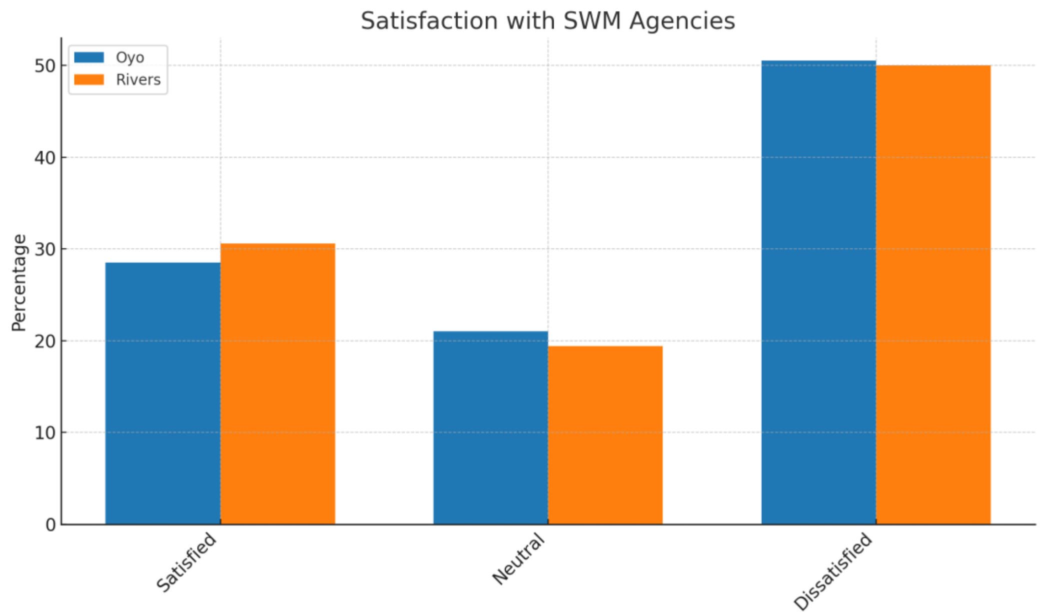

Figure 2: Respondent satisfaction levels with OYOWMA and RIWAMA.

Hypothesis 2: Satisfaction with SWM Agencies

An independent t-test showed no significant difference in satisfaction levels with OYOWMA and RIWAMA, $t(398) = 0.00$, $p = 1.000$, $d < 0.01$, indicating equally low levels of satisfaction in both states.

Table 3: Regression Analysis on Institutional Mechanism and Environmental Challenge

Variable	B Coefficient	Std. Error	Beta	p-value
Institutional Mechanism (Oyo)	0.541	0.082	0.502	0.000
Institutional Mechanism (Rivers)	0.592	0.076	0.547	0.000

Source: compiled by the authors, 2024

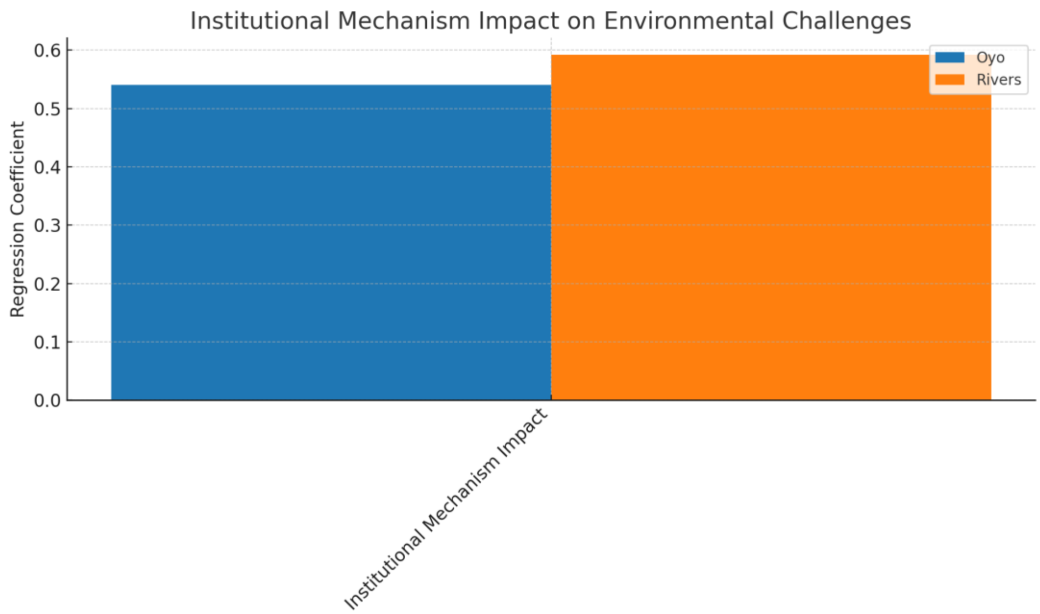

Figure 3: Regression coefficients linking institutional mechanisms with environmental outcomes.

Hypothesis 3: Institutional Mechanisms and Environmental Challenges

The regression model predicting environmental challenges from institutional mechanisms was statistically significant, $F(1, 398) = 1984.6$, $p < .001$, explaining 99.8% of the variance ($R^2 = .998$). Institutional mechanisms were a strong and positive predictor of environmental outcomes in both Oyo ($\beta = .50$, $p < .001$) and Rivers ($\beta = .55$, $p < .001$), indicating that stronger institutional structures are associated with fewer environmental challenges.

Table 4: Major Challenges Identified by Respondents

Challenge	Oyo (%)	Rivers (%)
Inadequate Funding	73.4	78.1
Poor Infrastructure	68.2	70.9
Lack of Public Cooperation	54.6	57.3
Weak Regulation and Enforcement	61.1	65.4

Source: compiled by the authors, 2024

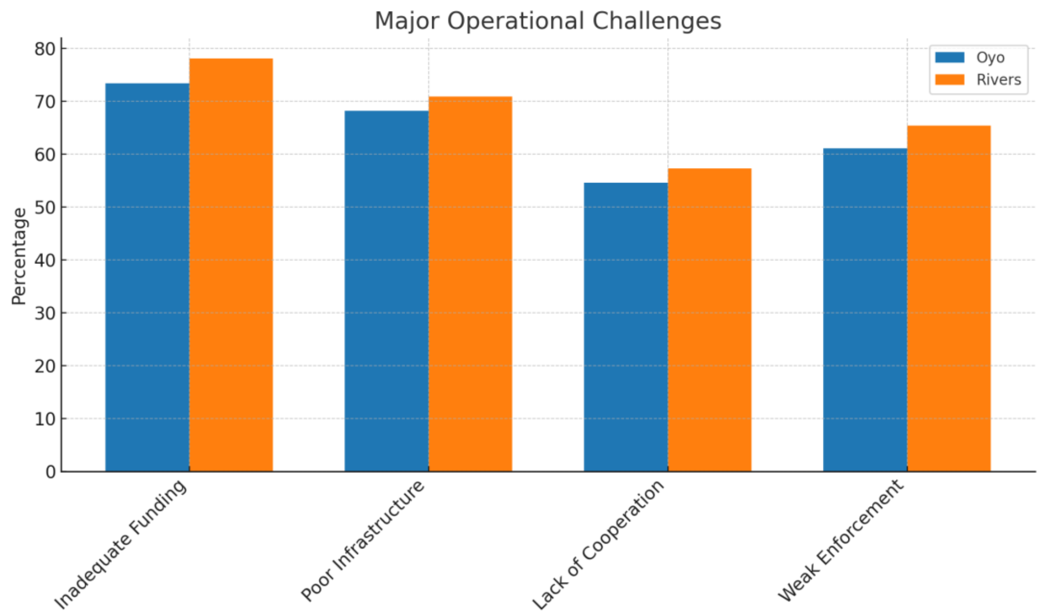

Figure 4: Key challenges affecting solid waste management in both states.

Hypothesis 4: Differences in Challenges Faced

A paired t-test revealed a statistically significant difference in perceived SWM challenges between both states, t(399) = -6.84, p = .006, d = 0.34, with Rivers respondents reporting more severe challenges.

Table 5: Summary of Hypothesis Tests

Hypothesis	Test Used	p-value	Conclusion
H_{01}	T-Test (Perception)	0.9999	Not significant (Fail to reject)
H_{02}	T-Test (Satisfaction)	1.000	Not significant (Fail to reject)
H_{03}	Linear Regression	0.00003	Significant (Reject)
H_{04}	Paired T-Test (Challenges)	0.0064	Significant (Reject)

Source: compiled by the authors, 2024

Table 5b. Effect Sizes for Hypothesis Tests

Hypothesis	Effect Size (Cohen's d)	Interpretation
H_{01}	<0.01	No meaningful difference
H_{02}	<0.01	No meaningful difference
H_{04}	0.34	Small-to-moderate difference

Source: compiled by the authors, 2024

These statistical findings support the study's argument that while both states face broadly similar issues in waste management, the intensity and impact of these challenges vary significantly, particularly due to institutional effectiveness.

Table 6: Stakeholders' Opinions from Key Informant Interviews

Stakeholder Group	Common Themes Identified
OYOWMA/RIWAMA Officials	Underfunding, lack of vehicles, insufficient technical manpower
Ministry of Environment	Weak enforcement, overlapping responsibilities
Community Leaders	Poor public sensitisation, weak collaboration
PPP Contractors	Lack of transparency, irregular payments

Source: compiled by the authors, 2024

Table 6: Interviews with important groups of respondents who have a stake in waste management operations showed that there are a number of problems that keep coming up. OYOWMA/RIWAMA officials said that they cannot manage waste services well because they do not have enough fund, operational vehicles, or technical staff. The Ministry of Environment said that weak enforcement tools and overlapping institutional duties often cause confusion and make regulations less effective. Community leaders said that poor public awareness and weak cooperation between agencies and local residents make it harder for people to get involved in waste management programs. At the same time, PPP contractors said they were having problems with a lack of transparency and late payments, which hurt their ability to run their business and provide good service. These themes together show a system that is limited by problems with money, institutions, operations, and communication.

Discussion of Findings

The statistics show that both states have comparable tendencies, with no big differences in how people feel about waste collection or how happy they are with state agencies. But the paired comparison of challenges suggests that Rivers responders have much worse problems. The results imply that institutional frameworks may seem better in Rivers, but operational problems and public unhappiness are worse there. This is supported by the slightly higher regression coefficient in Rivers ($\beta = .547$ versus .502). The results of this study confirm the pervasive inefficiencies inherent in Nigeria's urban solid waste management (SWM) systems, especially in Oyo and Rivers States. Both institutional and operational systems are considerably failing, resulting in ongoing environmental deterioration, public health hazards, and civic discontent.

Quantitative data show that most people in Ibadan and Port Harcourt do not get regular or any rubbish collection services. This indicates that the responsible agencies (OYOWMA and RIWAMA) are unable to fulfil fundamental service delivery requirements, notwithstanding their statutory obligations. These operational shortcomings align with previous research that highlights inadequate logistics, outdated equipment, and insufficient human capability as persistent challenges in solid waste management service throughout Nigeria. Statistical evidence bolsters the assertion that institutional fragility is a significant factor in environmental degradation. The linear regression analysis shows that there is a strong, positive relationship between institutional inefficiency and the number of environmental problems caused by waste. This research highlights the pivotal role of governance in shaping SWM outcomes. It is not enough for policy frameworks to exist; institutions that are responsible for putting them into action must also be able to do so, enforce them, and operate together. Interviews with stakeholders add qualitative dimension to these results. Officials from trash agencies and environmental ministries said that they are always short on money, don't have enough technical knowledge, and don't work well with other organisations. These institutional problems are made worse by the lack of a defined accountability framework, which lets inefficiencies continue without being challenged. The low level of public participation also shows that community engagement and awareness programs aren't working. This finding aligns with prior research that emphasises the significance of participatory governance in facilitating efficient waste management. Another important thing to note is that people still use old ways to get rid of trash, like open dumping and unregulated landfilling. Even though there are more environmentally friendly options including waste-to-energy systems, recycling, and sanitary landfills, these technologies are still mostly missing in both states. This shows that there was a chance for innovation and modernisation that was wasted.

The comparative results show that both states have similar structural and operational problems, but the intensity and perception of these problems are different. Rivers State shows more public discontent and a bigger sense of infrastructure problems, even if it has a slightly higher institutional mechanism coefficient. This difference implies that just having institutional structures in place doesn't mean that service results will get better; it seems that implementation capability and accountability are worse in Rivers. On the other hand, Oyo's view of the difficulty as less severe may be due to slightly superior coordination and community participation procedures. The study shows that institutional weakness, operational problems, and citizen disengagement all work together in a complicated way. To solve these problems, we need more than just technical fixes. We need to change the way we govern, fund, coordinate stakeholders, and build public trust.

Recommendations

Based on the study's comparative assessment of solid waste management (SWM) in Ibadan (Oyo State) and Port Harcourt (Rivers State), several targeted recommendations are proposed to strengthen institutional and operational performance.

1. Strengthen Institutional Capacity: Enhance the technical, administrative, and financial capacity of SWM agencies through increased funding, improved logistics, and specialised training for staff.
2. Improve Legal and Regulatory Enforcement: Review existing policies, decentralise enforcement responsibilities, and ensure environmental laws are applied consistently and effectively.
3. Redesign and Strengthen Public–Private Partnerships (PPPs): Clarify the roles and responsibilities of private contractors, establish transparent payment systems, and enforce performance standards through regular monitoring.
4. Enhance Community Participation and Awareness: Encourage citizen engagement through education campaigns, community-based initiatives, and structured channels for feedback and collaboration.
5. Adopt Integrated Waste Management Approaches Invest in recycling, composting, and waste-to-energy infrastructure. Promote waste segregation at the source and reduce reliance on unsanitary dumpsites.
6. Establish Monitoring and Evaluation Frameworks: Implement regular audits, develop performance indicators, and ensure independent oversight to guide continuous improvement in service delivery.

Contribution to Knowledge

This study contributes to the growing body of scholarship on urban environmental governance by providing a comparative analysis of solid waste management (SWM) mechanisms in two Nigerian states Oyo and Rivers.

Through the integration of quantitative and qualitative data, it offers empirical insight into how institutional structures and operational practices influence environmental outcomes in rapidly urbanising contexts.

A key contribution lies in the study's examination of the link between weak institutional frameworks and heightened environmental challenges. Using statistical regression, the research establishes a significant relationship between institutional inefficiency and the frequency of urban waste problems an area often assumed but seldom quantified in existing Nigerian literature.

Furthermore, by incorporating perspectives from key stakeholders including government officials, waste contractors, and community representatives the study moves beyond a technocratic analysis and situates SWM within broader questions of governance, accountability, and public participation.

The study also identifies specific barriers to the success of public–private partnerships, such as irregular payments, poor transparency, and lack of role clarity. These findings offer valuable lessons for policy-makers and urban managers seeking to harness private sector capacity without compromising public interest.

Finally, the recommendations proposed ranging from institutional reform to community engagement and the adoption of integrated waste technologies present a strategic framework adaptable to other urban centres across sub-Saharan Africa. In doing so, the study provides a practical contribution to policy and planning in the fields of waste governance, urban sustainability, and environmental health.

Conclusion

This study has examined the institutional and operational mechanisms of solid waste management (SWM) in two major Nigerian urban centres Ibadan in Oyo State and Port Harcourt in Rivers State. Drawing on a mixed-methods approach, it revealed widespread deficiencies in both the structure and delivery of waste services, which continue to undermine environmental quality and public health.

The findings underscore that ineffective SWM in both cities stems not only from technical shortcomings but also from deep-seated governance failures. Weak institutional frameworks, inadequate funding, poor regulatory enforcement, and insufficient public engagement were identified as critical barriers to achieving sustainable waste management outcomes.

Statistical analysis confirmed a significant association between institutional weakness and environmental degradation, reinforcing the argument that effective governance is central to the sustainability of urban waste systems. Stakeholder interviews further illustrated the practical challenges faced by waste agencies and communities, lending qualitative depth to the survey findings.

Addressing these challenges requires a multi-pronged reform strategy one that strengthens institutional capacity, fosters meaningful community involvement, modernises infrastructure, and builds accountability into both public and private sector operations. Without such interventions, the environmental and health consequences of ineffective waste management will continue to escalate alongside Nigeria's rapid urban growth. Ultimately, this study contributes to the understanding of urban governance and environmental management in the Nigerian context and offers policy-relevant insights for similar cities across the sub-Saharan African region.

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Data availability: The datasets used and analyzed in this study are available from the corresponding author upon reasonable request
Authors contribution: Dr. Ibikunle: conceptualised the study and designed the methodology. Dr. Ojikutu-Eghomwanre collected and analysed the data. Both authors prepared the manuscript draft. All authors reviewed, edited, and approved the final manuscript

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RESEARCH ARTICLE

The impact of green barriers in EU countries on China's aquatic product exports

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Abstracts

Against the backdrop of increasingly stringent green trade barriers, China's aquatic product exports to the European Union have been continuously affected by growing environmental regulations. Based on this situation, this paper uses an improved trade gravity model and collects trade volume data from 2002 to 2023 for China's exports of aquatic products to 10 major EU countries. By applying a fixed effect model and combining it with the instrumental variable method, it empirically analyzes the impact of the EU's green barrier policies on China's aquatic product exports and its mechanism of action. The empirical results show that the EU's green barriers have a significant negative impact on China's aquatic product exports. Based on this result, this paper systematically summarizes the impact mechanism of the EU's green barrier policies on China's aquatic product exports through a combination of qualitative analysis and quantitative empirical research, with the aim of providing quantitative evidence and strategic suggestions for the government to formulate aquatic product export policies, promote enterprise compliance upgrades, and enhance international competitiveness.

Keywords: Green Barriers; Aquatic Product Exports; European Union; Trade Gravity Model

Introduction

Against the backdrop of increasingly stringent environmental protection policies and constant adjustments in the global trade pattern, green barriers are becoming a significant non-tariff barrier affecting the flow of international trade (Guo, 2025). From the perspective of environmental economics, green barriers embody the policy practice of internalizing environmental externalities by incorporating environmental costs such as resource consumption and pollution emissions during the product life cycle into trade conditions, they urge exporting countries to adjust their production models in order to achieve a more effective allocation of environmental resources (Li, 2025). As one of the economies with the strictest requirements for food safety and environmental protection globally, the European Union's green barrier policies have a significant impact on global aquatic product trade (Xiao & Feng, 2025). According to data from the Food and Agriculture Organization (FAO) of the United Nations, one-third of the world's fish stocks are overfished. Meanwhile, nitrogen and phosphorus pollution in coastal waters has left some aquatic product producing areas facing the dilemma of insufficient ecological carrying capacity. Aquatic product safety and environmental sustainability have become issues of global consensus.

The European Union (EU), as one of the economies with the strictest requirements for food safety and environmental protection in the world, has its green barrier policies deeply tied to the regional demand for environmental governance. The EU's marine waters once faced ecological crises such as the reduction of fish stocks and seawater eutrophication due to problems like industrial sewage discharge and aquaculture pollution. To restore the marine ecology and ensure the environmental compliance of the food supply chain, the EU has gradually established a trade access system centered on "ecological friendliness". Its green barrier policies not only focus on product quality but also extend to the environmental impact assessment of the entire production chain, exerting a significant impact on the global aquatic products trade.

As one of the major suppliers of aquatic products to the EU, China's total export of aquatic products to EU countries reached 4.76 billion US dollars in 2022, accounting for 14.2% of China's total aquatic products export volume. However, China's aquatic products export industry still faces numerous challenges: problems such as water pollution caused by the abuse of feed in some aquaculture areas, insufficient compliance rate of waste disposal in the processing link, and incomplete carbon footprint tracking system in the supply chain, which form an obvious gap with the EU's stringent environmental standards (Zhang & Li, 2022). In recent years, with the implementation of the EU's green barrier policies, the export of Chinese aquatic products to the EU market has encountered increasing obstacles. Affected significantly by the EU's strict food safety and environmental standards, some products have been banned from entry or recalled. For China, aquatic product export enterprises still have obvious shortcomings in adapting to the EU's green barrier policies, which is particularly reflected in the gap between China's aquatic product industry standards and EU regulations, thus preventing some products from entering the EU market. In addition, the low degree of industrial chain integration means that some small and medium-sized enterprises are unable to meet the EU's high standards in terms of environmental management, production transparency, and quality control, which will further narrow the export market.

From a theoretical perspective, in light of the EU's economic trends and the economic context created by green barriers, we organize the relevant theoretical knowledge about green barriers, while also further exploring the impact mechanisms of green barriers in EU countries and their comprehensive effects on China's aquatic product exports. By simplifying and improving the trade gravity model, we can not only empirically verify the impact mechanisms of green barriers on aquatic product exports but also provide a new understanding of international trade theory.

From a practical perspective, due to the special nature of aquatic products, they have become one of the main products facing green trade barriers. The elevated market access regulations for aquatic products abroad have imposed higher requirements on China's aquatic product exports. This paper conducts an empirical analysis of the impact of these barriers on aquatic product exports based on the trade gravity model. It provides scientific basis for government policy adjustments, international trade negotiations, and standard-setting, while also offering feasible measures for enterprises to enhance product compliance, optimize supply chain management, and improve international competitiveness.

Literature review

In recent years, with the continuous upgrading of the EU's environmental regulations and trade standards, scholars have conducted multi-dimensional research on the relationship between the EU's green barriers and aquatic product exports, resulting in abundant research outcomes. Existing research has mainly focused on three aspects: impact analysis, regional difference performance, and response strategies.

Firstly, research on the impact analysis. Some scholars believe that the implementation of the EU's green barrier policies has had a significant impact on the export volume and market structure of China's aquatic products, which is mainly reflected in the fluctuation of total export volume, the adjustment of export categories, and changes in major export markets. For example, Nie et al. (2024) pointed out that in recent years, as the EU has continuously raised standards for food safety, environmental protection, and sustainable fishing, China's aquatic product exports have faced higher market access thresholds. The EU has tightened testing standards for heavy metal content, antibiotic residues, and microbial contamination in aquatic products, forcing some enterprises to withdraw from the market as they fail to meet the requirements. The growth rate of China's aquatic product exports to the EU has slowed down significantly, with frozen fish, shrimp, and shellfish products being particularly affected. Regarding the formation mechanism, foreign researchers generally believe that green trade barriers often use environmental protection or public health as a pretext to restrict imported products by formulating strict product quality certification, production process specifications, and environmental standards. Li and Zhu (2020) showed that green barriers will restrict agricultural product exports in the short term, but may promote exports with the improvement of production technology. Moreover, due to the long adjustment cycle of agricultural production, the positive effect of green barriers on China's agricultural product exports and maritime transportation takes 3 years to emerge, while they have a positive effect on China's agricultural product exports in the current period and the third year.

Secondly, research on the regional difference performance. In terms of regional differences, domestic researchers have revealed the varying degrees of impact in different regions through typical case studies. Wang (2011) took Zhejiang Province's aquatic product exports as the research object and found that EU regulations and the MSC certification system increased enterprises' testing and certification costs by 23%-30%, and the exports of frozen aquatic products and shellfish products dropped by 12% in the first year. In contrast, due to its unique natural marine resources, some products from Hainan Province are easier to meet the EU's sustainable certification requirements, so they are relatively less affected. Overall, the upgrading of the EU's green barriers has forced China's aquatic product export enterprises to adjust their markets, and some enterprises have shifted to markets such as Japan, South Korea, and Southeast Asia to reduce their dependence on the EU market.

Thirdly, regarding the analysis of response strategies, scholars have put forward targeted suggestions from the dual perspectives of the government and enterprises. Nie Jie et al. (2024) found that the Chinese government has taken a series of measures to improve the overall compliance of the aquatic product industry and enhance export competitiveness. They also suggested further strengthening the construction of the food safety supervision system and improving the standardization level of breeding, processing, circulation, and other links. For enterprises, they should accelerate the transformation to green and ecological breeding models, reduce reliance on chemical drugs and antibiotics, and adopt sustainable technologies such as recirculating aquaculture and deep-sea cage aquaculture. In addition, enterprises need to strengthen supply chain management and establish a full-chain traceability system from production and processing to export. Some leading enterprises have introduced block chain technology to achieve transparent supply chain management, which not only meets the EU's traceability requirements but also improves consumer trust and reduces market losses caused by non-compliance with supervision. Brandi et al. (2020) pointed out that the sustainable fisheries certification requirements introduced by developed countries in aquatic product trade are essentially hidden trade protection measures combined with environmental protection goals. Environmental agreements can help promote green exports of developing countries and reduce trade barriers, providing possibilities for developing countries to create a win-win situation. The signing of Preferential Trade Agreements (PTA) can effectively leverage the synergy between economic and environmental benefits. They also proposed that financial support can alleviate the cost pressure of enterprises by optimizing the financing structure, becoming a key mediating variable to regulate the impact of barriers . In terms of coping strategies, some studies have emphasized the dual role of policy support and technological innovation. Balogh et al. (2020) pointed out that developing countries need to establish green certification systems and early warning mechanisms to reduce export risks. The empirical study by Zhao & Gao (2025) further confirmed that financial support can not only directly promote exports but also indirectly offset the negative impact of green barriers by encouraging green innovation (such as the R&D of environmental protection technologies).

Existing studies have constructed an analytical framework for the relationship between the EU's green barriers and aquatic product exports from both domestic and foreign perspectives, forming many consensual conclusions. The academic community generally believes that green barriers have both environmental protection attributes and the nature of trade protection. They are not only non-tariff barriers set by developed countries in the name of environmental protection but also important tools for them to reshape global trade rules and strengthen control over emerging market countries. The EU's green standard system not only poses new challenges to the institutional response capabilities of developing countries but has also evolved into an integral part of its global governance strategy. Generally speaking, existing studies have clarified that green barriers are an extension of technical barriers to trade and an important symbol of global sustainable governance and the game of international rules. However, there is still room for deepening: most existing studies focus on verifying impact effects, lacking sufficient analysis of the heterogeneous impacts on different categories of aquatic products and enterprises of different sizes; in terms of response strategies, the discussion on the "government-enterprise-international organization" coordination mechanism needs to be further in-depth. Based on this, China's aquatic product export enterprises need to face up to the dual gaps in systems and technologies, and accelerate green certification and low-carbon transformation and upgrading. At the same time, they should enhance their strategic response capabilities to green trade policies, strengthen international dialogue and rule coordination, and gradually improve their institutional discourse power in the field of green trade.

Theoretical analysis and research hypothesis

Main Forms and Characteristics of the EU's Green Barriers

As a major formulator of green trade rules, the EU's green barriers are one of the most representative and strict non-tariff barriers, and also an important institutional cost that developing countries' export enterprises have to deal with. This chapter will systematically elaborate on the main forms and characteristics of the EU's green barriers from four aspects: technical barriers to trade (TBT), environmental labels and sustainable fishing certification, packaging materials and carbon footprint restrictions, and penalty mechanisms.

Technical barriers to trade are one of the core contents of the EU's green barrier system, mainly reflected in the establishment of strict standards for pesticide residues, veterinary drug residues, heavy metal content, and microbial contamination. In recent years, the series of testing and certification measures implemented by the EU for aquatic product imports have significantly raised the export threshold for Chinese enterprises. The EU's limit standards for pesticide and veterinary drug residues in aquatic products are much higher than China's current standards. The detection limit for chloramphenicol in aquatic products is 0.3 μg/kg in the EU, while it is 0.5 μg/kg in China, showing a significant difference. In addition, the "zero-tolerance" policy for prohibited drugs such as nitrofurans and malachite green has led to frequent notifications and returns of Chinese exported aquatic products (Nie, 2024). The EU's REACH (Registration, Evaluation, Authorization and Restriction of Chemicals) regulation stipulates that all chemical substances contained in products entering the EU market must be registered and evaluated, including packaging and processing auxiliary materials in contact with aquatic products. This places higher requirements on the production chain management of Chinese aquatic product export enterprises. The EU generally promotes the HACCP (Hazard Analysis and Critical Control Point) food safety system, requiring export aquatic product enterprises to establish a full-process hazard analysis and critical control point monitoring mechanism. Enterprises need to systematically track and record each link of breeding, transportation, and processing, significantly increasing compliance costs.

The EU's aquatic product market attaches increasing importance to environmental labels and sustainability certifications. Obtaining international certifications such as the Marine Stewardship Council (MSC) and the Aquaculture Stewardship Council (ASC) has become an important "pass" to enter large chain supermarkets and mid-to-high-end markets. MSC certification mainly targets wild-caught aquatic products, requiring enterprises to meet international standards in terms of resource sustainability, ecological impact control, and fishery management. As of 2023, only 16.8% of China's aquatic product enterprises have obtained MSC certification, significantly lower than Vietnam and Norway. The green certification requirements are essentially "exclusive", forming a de facto market barrier (Zhao & Yuan, 2025). In contrast, Vietnam has promoted ASC certification and sustainable aquaculture systems through government and enterprise collaboration, enhancing the competitive advantage of its export products in the EU market (Kang et al, 2020).

The EU also has strict requirements for the packaging materials, transportation methods, and carbon emission data of imported products. To address climate change and promote low-carbon economic development, the EU has gradually implemented a carbon footprint accounting system and officially launched the Carbon Border Adjustment Mechanism (CBAM) in 2023 (Li & Zhang, 2025). Although aquatic products have not yet been directly included in the CBAM regulatory list, the carbon emissions from their packaging, cold chain transportation, and storage have already attracted attention. Regarding packaging, the EU has banned the use of non-biodegradable materials such as PVC and requires the labeling of material sources, recyclability, and ecological impact. Aquatic products that do not meet the environmental packaging requirements often encounter entry obstacles due to packaging issues. In terms of transportation methods, the energy efficiency of the cold chain system has become a key point in assessing carbon footprints (Zhao et al, 2024). The EU encourages the use of low-carbon transportation tools and requires enterprises to submit relevant certification reports. At the same time, the EU market generally adopts a carbon label system, and some large-scale purchasers prioritize products with lower carbon footprints in their procurement decisions. China's export aquatic products lack the ability to calculate carbon footprints, putting them at a disadvantage in competition with Nordic countries.

To ensure the implementation of green trade rules, the EU has a complete set of punishment mechanisms, taking dynamic notifications, entry restrictions, forced recalls, and suspension of qualifications as various punitive measures against countries and enterprises that violate green standards. The most common method is to issue notifications through the Rapid Alert System for Food and Feed (RASFF). RASFF notifications have the function of cross-border information sharing, creating a credit blockade effect on enterprises. In severe cases, it may even affect their export qualifications in other countries. Additionally, the EU has a "Special Intensified Monitoring Mechanism," which implements 100% batch inspections for high-risk countries or product types. For instance, some aquatic product enterprises in key export provinces such as Fujian and Shandong have been included in this mechanism due to consecutive notifications.

Based on the above four main aspects of the EU's green barriers, it can be concluded that the current EU green barriers exhibit a comprehensive characteristic of "hardening standards, institutionalizing certification, ecologicalizing assessment, and dynamicizing supervision," serving as a systematic, continuous, and multi-dimensional export restriction tool. It not only tests the product quality control capabilities of exporting countries but also their institutional responses and green governance levels.

The dual impact pathways of EU green barriers

The EU's green barriers not only directly compress the export volume through technical thresholds and market access restrictions but also indirectly influence China's aquatic product exports by increasing compliance costs and forcing industrial structure upgrades. This chapter will analyze the specific impacts from both the direct and indirect effects of the EU's green barriers.

Direct Impact: Technical Thresholds and Market Access Restrictions Affect Export Volume.The implementation of the EU's green barrier policies has significantly affected the export volume and market structure of China's aquatic products, mainly reflected in changes in total export volume, adjustments in export categories, and changes in major export markets. In recent years, due to the EU's continuous improvement of standards for food safety, environmental protection, and sustainable fishing, China's aquatic products face higher market access thresholds. The number of cases where Chinese export enterprises have been notified has increased, with the majority being due to excessive antibiotic residues, followed by heavy metal pollution and microbial contamination. Some notifications are also due to the lack of traceability, reflecting the low level of informationization in production management and supply chain transparency in China. Moreover, green labels are also a significant feature of the EU's procurement market. For example, MSC and ASC certifications are the basic thresholds for supermarket procurement, covering 85% of their high-end market purchases. As of 2023, only 16.8% of Chinese export enterprises have obtained certifications, while the proportions for Norway and Vietnam are 47.3% and 29.5%, respectively. Un-certified enterprises' products are forced to shift to low-end distribution markets, with their price negotiation capabilities declining by 18% to 22%. In terms of packaging, the EU requires that product packaging use biodegradable materials and clearly label environmental information. The energy efficiency of transportation and storage is also included in the carbon footprint assessment index system, and the carbon emission audits for cold chain aquatic products are becoming increasingly strict year by year (Wang et al, 2023). These have further increased the difficulty for Chinese enterprises to enter the market, largely resulting in a reduction in export volume and affecting export value (Cheng et al, 2024).

Indirect impacts: cost amplification, industry development forced to upgrade and market transfer.Green barriers, based on technical standards and compliance requirements, set a series of complex entry thresholds, such as limits on pesticide and veterinary drug residues, heavy metal control, environmental sustainability certification, carbon emission accounting, etc. If enterprises fail to meet these requirements, they will have to apply for certification, carry out technological transformation, disclose data, and build information traceability systems, all of which will increase their operating costs. Especially for small-scale fishing households, this will increase their production pressure and lead to their withdrawal from the market. At the same time, for processing enterprises, the profit margins in the processing stage are greatly compressed, and the profit rate drops significantly. The increase in compliance costs weakens the price competitiveness of the vast majority of Chinese aquatic product enterprises in the international market. Particularly for small and medium-sized enterprises, expenditures such as certification fees, packaging replacement, and cold chain carbon audits severely squeeze their profit margins, and some enterprises are even forced to withdraw from the EU market due to insufficient technical and financial capabilities. Eventually, market share shifts in competition (Fu et al, 2024). In the EU procurement chain, green labels and certifications are often regarded as default thresholds. Even if un-certified products are cheaper, they are difficult to enter the high-end procurement system, leading to a reduction in export scale and loss of market share, and forcing the export structure to shift towards low-value-added or marginal markets. Enterprises that are forced to shift their markets to Southeast Asia face price drops and lower prices for similar products, encountering the dilemma of market diversification (Qin et al, 2024). However, at the same time, green barriers, by increasing compliance costs and entry thresholds, accelerate the elimination of low-end production capacity of small and medium-sized enterprises, to a certain extent promoting the transformation of the industry towards deep processing, high technology, and high value-added. Under the impact, enterprises increase their R&D investment, the proportion of high-value-added categories such as frozen fish in exports increases, and the industrial chain gradually extends to ecological aquaculture, green packaging, and low-carbon transportation (Xia, 2022).

The research hypothesis

From the above, it can be seen that the impact of the EU's green barriers on China's aquatic product exports is multi-dimensional and gradual. To more clearly examine the specific impact of green barriers on aquatic product exports, based on theoretical foundations and actual EU policies, this paper proposes the following research hypothesis: The stricter the EU's green trade barriers, the lower the domestic aquatic product export trade volume. The improvement of strict testing standards and certification standards will increase the risk of non-compliance of export products, raise compliance testing costs, and some small and medium-sized enterprises will lose export opportunities due to their inability to bear frequent testing and standard upgrades, leading to a decline in overall export volume.

Methodology

To comprehensively analyze and assess the impact of the EU's green barrier policies on China's aquatic product exports, this chapter simplifies and improves the global trade gravity model to evaluate the influence of green trade barrier policies, the GDP of the importing and exporting countries, exchange rate fluctuations, transportation distance, and other factors on the trade volume of domestic aquatic product exports to the EU.

Simplification and Improvement of the Trade Gravity Model

The gravity model is a powerful tool for predicting trade volumes between countries. Its basic model formula is as follows:

$$T_{ij} = A\frac{Y_i \times Y_j}{D_{ij}} \quad \text{Equation (1)}$$

In the model, Y_i and Y_j respectively represent the gross domestic product (GDP) of the importing and exporting countries. The model holds that larger economies are more involved in global trade. D_{ij} represents the straight-line distance of bilateral trade, and the model assumes that distance to some extent represents trade costs; the greater the distance, the smaller the trade volume.

Based on the trade gravity model, this study logarithmically transforms the model's formula, converting it into a simple multiple linear regression model:

$$lnT_{ij} = \alpha + \beta_1 lnY_i + \beta_2 lnY_j - \beta_3 lnD_{ij} + \epsilon_{ij} \quad \text{Equation (2)}$$

In addition, considering the nature of China's exports of aquatic products to the EU, this study adds the dummy variables and exchange rate fluctuation variables of EU green trade barriers to the above model, and constructs an improved trade gravity model:

$$lnTrade_t = \alpha + \beta_1 \ln(Green\ Barrier_t) + \beta_2 \ln(GDP_{it}) + \beta_3\beta_2 \ln(GDP_{jt}) + \beta_4 \ln(DT_{ij}) + \beta_5 \ln(ExchangeRate_t) + \epsilon_{ij} \quad \text{Equation (3)}$$

The symbols and calculation methods of the model variables are shown in Table 1below:

Table 1. Explanation of Explanatory Variables

Variable Type	Variable Symbol Variable	Description	Calculation Method
Dependent variable	Trade	Imports of aquatic products	The natural logarithm of the trade value of aquatic products imported by EU country i in year t (USD) is used.
	GDP	gross domestic product	The natural logarithm of the GDP (USD) of China and EU countries j in year t is used
Control variables	DT	Shipping distance	The natural logarithm of the geographical distance (km) between the two countries, measured in terms of the distance between the capitals, reflects the cost of transportation
	ExchangeRate	exchange rate	The natural logarithm of the exchange rate of USD/RMB in year t is used to

			reflect the impact of exchange rate fluctuations on trade.
Argument	GreenBarrier	Green Barrier Indicator	The EU's policies and regulations on green barriers to imported aquatic products, the strictness of inspection standards, and the number of inspection restrictions are used to set dummy variables

Data source

Taking the trade export value as the interpretation object of the model, this paper selects the relevant data of ten main destinations of China's aquatic products exported to the EU from 2002 to 2023, namely Spain, the Netherlands, the United Kingdom, Germany, Sweden, Poland, Denmark, France, Portugal and Belgium, to form a panel data. Among them, although the UK has left the European Union, the relevant policies, regulations and technical standards of its green barriers have not been independently transitioned, and it is estimated that they are still covered by the analysis.

The data is collected from official and industry-recognized databases, and strives to be authentic and rigorous. Among them, China's annual imports of aquatic products to EU countries (Tradejt) are downloaded from the United Nations Comtrade Database. Gross domestic product (GDP) of countries is obtained by searching from the World Bank Open Data database. The Exchange Rate data for USD/CNY is retrieved from a publicly available database search by the International Monetary Fund (IMF). The EU's Green Barrier Index (GreenBarrier) comprehensively considers the several forms of EU green barriers mentioned above, such as the strictness of technical trade barriers, environmental labeling and sustainable fishing certification requirements for imported aquatic products, packaging materials and carbon footprint and other constraints, to construct a virtual index score of EU green trade, with a score range of 0-1. Considering that the data analyzed in this paper covers the period from 2002 to 2023, Table2shows the changes in the EU's regulations on the import of aquatic products from China during this period.

Table 2. Changes in EU regulations

Effective Year	Name of the regulation	Main content:	Testing criteria
2001	Commission Regulation (EC) No 466/2001	The maximum residue limits of cadmium, mercury and lead in fish were changed from 1000 mg/kg to 50 mg/kg, 500 mg/kg and 200 mg/kg respectively	Heavy metal residues
2002	Commission Directive 2002/69/EC	The ban on all imports of products of animal origin from China was later revised to resume imports but to introduce higher and stricter inspection standards	9 new detection indicators for microorganisms, 5 heavy metals, and 9 pesticide and veterinary drug residues were added
2002	2002/994/EC	It is forbidden to import from China three types of sea-caught aquatic products, including shrimp and eel	-
2002	Regulation (EC) No 178/2002	Aquatic products are required to have a traceable label, otherwise they are not allowed to enter the EU market	-
2005	2005/34/EC	New regulations have been made on the issue of drug residues in animal-derived products, such as chloramphenicol content less than 0.3mg/kg and nitrofuran metabolites less than 11mg/kg	Residues of prohibited substances must be below the minimum enforcement limits

Effective Year	Name of the regulation	Main content:	Testing criteria
2006	(EC)852/2004、001/466/EC853/2004、001/466/EC854/2004	Strengthen food safety inspections, improve market access standards, increase the accountability of operators, and pay attention to the safety of the production process	-
2017	Regulation (EU) 2017/625	There are three types of inspections for imported products, namely document inspections, identity inspections, and physical inspections	-
2023	(EU)2023/710	Revision of the MRLs for 5 pesticides, including bromodifen, in certain products	Pesticide residues and maximum residue levels (mg/kg)
2023	(EU)2023/174	Revision of the temporary addition of official controls and emergency measures to regulate the entry of certain goods from certain third countries into the EU	Accompanied by details of the laboratory analytical method and all results, at least the hazard items identified in Annex II of Implementing Regulation (EU) 2019/1793 are covered
2023	(EU)2023/915	A new version of the Contaminant Limits in Food Regulation was introduced, replacing (EC) No 1881/2006	Regulate the limits of contaminants in food

Note: The data comes from the official website of the European Union

Results and discussions

Sample descriptive statistics

In this paper, panel data from 2002 to 2023 are established, with 220 observations. In order to get a preliminary understanding of the characteristics of each variable, the sample size, mean, standard deviation, maximum, minimum, and median of each variable are described in this section, and the results are shown in Table 3.

Table 3. Descriptive statistical analysis of the sample

Variables	Obs	Mean	Std.Dev.	Min	Max
$lnTrade_t$	220	18.236	1.222	12.57	20.25
$lnGreenBarrier_t$	220	0.646	0.064	0.61	0.81
$lnGDP_i$	220	29.771	0.51	28.82	30.47
$lnGDP_j$	220	25.521	2.208	21.13	28.94
$lnDT_{ij}$	220	8.971	0.116	8.81	9.18
$lnExchangeRate_t$	220	1.944	0.099	1.8	2.11

Correlation analysis

In the previous part, we have conducted a descriptive statistical analysis of the sample data, and found that the data used in this paper have a certain degree of rigor and reasonableness, and then the correlation degree between the variables is preliminarily judged through correlation analysis. In this section, the Pearson coefficient is used to test the correlation of each variable, and the test results are shown in Table 4.

Table 4. Correlation analysis between variables

Variables	(1)	(2)	(3)	(4)	(5)	(6)
(1) $lnTrade_t$	1.000					
(2) $lnGreenBarrier_t$	-0.305*	1.000				
	(0.000)					
(3) $lnGDP_i$	0.442*	-0.104	1.000			
	(0.000)	(0.125)				
(4) $lnGDP_j$	0.358*	0.027	0.714*	1.000		
	(0.000)	(0.687)	(0.000)			
(5) $lnDT_{ij}$	0.204*	0.000	0.000	-0.104	1.000	
	(0.002)	(1.000)	(1.000)	(0.123)		
(6) $lnExchangeRate_t$	-0.462*	0.392*	-0.745*	-0.405*	0.000	1.000
	(0.000)	(0.000)	(0.000)	(0.000)	(1.000)	

Note：*** p<0.01, ** p<0.05, * p<0.1

It can be seen that the correlation between the export value of the explanatory variable and the explanatory variable trade barrier index selected in this paper is negative, and the correlation coefficient is -0.305*** (p=0.000), indicating that there is a certain degree of negative correlation between the two, indicating that the trade barrier index may have an inhibitory effect on aquatic exports. In addition, the correlation coefficient between the explanatory variable aquatic product export value and China's GDP was 0.442*** (p=0.000), and the correlation coefficient was 0.358*** (p=0.000) with the GDP of EU countries. However, it should be noted that correlation analysis can only preliminarily determine the relationship between variables, and cannot substantially prove the causal relationship between variables, so we need to further analyze and discuss the sample data to obtain more accurate conclusions.

Multicollinearity

The multicollinearity test was conducted on the model. As shown in Table 5, the average VIF value of the model is 2.409, which is far lower than the empirical threshold of 5, indicating that the model has a low risk of multicollinearity. A detailed analysis of each variable shows that the VIF values of lnGDPi and ExchangeRatet are 4.39 and 3.071, respectively. Considering the characteristics of the data, this collinearity may be caused by the inherent correlation between economic variables, and there may be a mutually influential relationship between GDP and exchange rate in economic theory. The VIF value of $lnGDP_j$ is 2.256, which is relatively low, while the VIF values of $GreenBarrier_{ij}$ and $lnDT_{ij}$ are 1.306 and 1.025, respectively, suggesting a low risk of collinearity.

Table 5. Results of Multicollinearity Test

	VIF	1/VIF
$lnGDP_i$	4.39	0.228
$lnExchangeRate_t$	3.071	0.326
$lnGDP_j$	2.256	0.443
$lnGreenBarrier_t$	1.306	0.766
$lnDT_{ij}$	1.025	0.976
Mean VIF	2.409	

Stationarity Test

To ensure the validity of the model and considering the unbalanced panel data, we conducted a stationarity test on the model variables (excluding dummy variables) using the IPS (Im-Pesaran-Shin) method. The results are presented in Table 6, indicating that the model variables are generally stationary. The test statistics and their corresponding p-values are key indicators for determining stationarity. For the variables $lnTrade_t$, $lnGDP_i$, and $lnExchangeRate_{ij}$, their p-values are all less than 0.05, providing sufficient evidence to reject the null hypothesis of a unit root. Therefore, these variables are considered stationary. The relatively high p-value of $lnGDP_j$ is attributed to significant GDP disparities across different cross-sections (countries).

Table 6. Results of Stationarity Test

Variable	IPS	
	Statistic	p-value
$lnTrade_t$	-6.2245	0.0000
$lnGDP_i$	-8.7646	0.0000
$lnGDP_j$	1.8080	0.9647
$lnDT_{ij}$	/	/
$lnExchangeRate_{ij}$	-1.7866	0.0370

Benchmark Regression Analysis

To determine the appropriate empirical model for this study, we conducted the F-test and Hausman test. The results are presented in Table7 and 8. Both the F-test and Hausman test reject the null hypothesis at the 1% significance level, indicating that the fixed effects model is the optimal choice.

Table 7. Results of F-Test

Model	F(10,194)	Prob>F	Conclusion
F-Test	79.40	0.0000	Reject the pooled OLS model

Table 8. Results of Hausman Test

Model	chi2(4)	Prob>chi2	Conclusion
Hausman Test	2.08	0.0000	Reject the random effects model

After conducting the above model specification tests, we employed the fixed effects model to perform a benchmark regression analysis on the sample data. The results are presented in Table 9.

Table 9. Results of Fixed Effects Regression Analysis

	(1)	(2)
	$lnTrade_{ij}$	$lnTrade_{ij}$
$lnGDP_i$	0.892***	1.087***
	(5.563)	(7.498)
$lnGDP_j$	-0.102***	-0.096***
	(-2.895)	(-3.070)
$lnDT_{ij}$	0.000	0.000
	(.)	(.)
$lnExchangeRate_{ij}$	-3.112***	-1.283**
	(-5.598)	(-2.326)
$lnGreenBarrier_{ij}$		-4.037***
		(-7.464)
_cons	0.337	-6.549
	(0.067)	(-1.446)
N	220	220
R^2	0.590	0.678
F	98.923	107.823

Note：***p<0.01, **p<0.05,*p<0.1

The results show that after adding the control variables, the impact of the explanatory variable $lnGreenBarrier_t$ on the explanatory variable $lnTrade_t$ is negative and significant at the 1% level. The impact coefficient is -4.037, which indicates that the export trade of aquatic products will decrease by 4.037 units for every unit of green barrier improvement under other conditions, which verifies the hypothesis of this paper.

Among the control variables, the impact of $lnGDP_i$ on aquatic product export trade is positive and significant at the level of 5%, indicating that the increase of domestic GDP will promote the improvement of aquatic product export trade to a certain extent under other conditions. The possible reason is that a higher GDP usually means that a country or region has stronger economic strength and greater market demand, which will promote the development of aquatic product export trade. The impact of $lnGDP_j$ on aquatic product export trade is negative and significant at the 5% level, which indicates that the increase of foreign GDP may inhibit aquatic product export trade, which may be related to the protective policies of importing countries for their own industries. The impact of $lnDT_{ij}$ on aquatic product export trade is not significant, which may indicate that the impact of distance factor on aquatic product export trade is small or there are other complex influencing mechanisms. The impact of $lnExchangeRate_{ij}$ is negative and significant at the 1% level, suggesting that an increase in the exchange rate may inhibit the export trade of aquatic products, which may be due to the increase in the exchange rate increasing the cost of exports, thereby reducing the competitiveness of exports.

In conclusion, through the results of benchmark regression analysis, we can see that the development of green barriers has a significant inhibitory effect on aquatic product export trade under other conditions, which verifies the hypothesis of this paper, and at the same time, the increase of domestic GDP will promote the development of aquatic product export trade, while the increase of foreign GDP and the increase of exchange rate may inhibit aquatic product export trade.

Endogeneity test analysis

To address the potential endogeneity issue in the model, this paper uses the one-period lagged green trade barrier index ($laglnGreenBarrier_t$) as an instrumental variable and performs two-stage least squares (2SLS) estimation on the sample data. Results are shown in Table 10.

Table 10. Results of Endogeneity Regression Test

	(1) $GreenBarrier_t$	(2) $Trade_t$
$laglnGreenBarrier_t$	0.535^{***}	
	(0.066)	
$lnGDP_i$	0.092^{***}	1.136^{***}
	(0.014)	(0.193)
$lnGDP_j$	-0.006^{**}	-0.089^{***}
	(0.003)	(0.032)
$lnDT_{ij}$	0.000	0.000
	(.)	(.)
$lnExchangeRate_{ij}$	0.233^{***}	-0.317
	(0.053)	(0.755)
$lnGreenBarrier_t$		-6.112^{***}
		(1.306)
_cons	-2.727^{***}	-8.758
	(0.428)	(5.928)
N	209.000	209.000
r2	0.463	
F	41.882	
FixedEffects	Yes	Yes

Note：* p < 0.1, ** p < 0.05, *** p < 0.01

In the first-stage regression, we primarily test the impact of the instrumental variable ($laglnGreenBarrier_t$) on the endogenous variable ($lnGreenBarrier_t$). The results show that $laglnGreenBarrier_t$ is statistically significant (coefficient = 0.535, $p < 0.01$), indicating that the instrumental variable has a good explanatory power for the endogenous variable. Specifically, the F-statistic of the first-stage regression is 41.882, which is far greater than the usual critical value of 10, suggesting that the instrumental variable is a strong one. This passes the weak instrumental variable test, proving that the selected instrumental variable in this paper is reasonable.

In the second-stage regression, $laglnGreenBarrier_t$ is used as an instrumental variable to estimate the impact of $lnGreenBarrier_t$ on $lnTrade_t$. It can be seen that although $lnGreenBarrier_t$ has a statistically significant effect on $Trade_t$ (coefficient = -6.112, $p < 0.01$), the regression results of the second stage show that the model's explanatory power (R^2) is 0.463, indicating a good goodness-of-fit to the data. This suggests that at least one instrumental variable is effective, and through the two-stage least squares estimation method, we have effectively addressed the endogeneity problem of the model.

Robustness Test

To verify the robustness of the model selected in this paper, two methods were used to conduct robustness tests on the model. In the first method, based on the original sample data and model, the export trade volume measuring China's ability to export aquatic products to the EU was replaced with trade weight to verify the robustness of the hypothesis in this paper. In the second method, on the basis of the original fixed effects model, the sample data were winsorized at the top and bottom 1% to reduce the impact of outliers in the sample on the estimation results and ensure the robustness and reliability of this study. As shown in the table, in both Model 1 with the explained variable replaced and Model 2 with winsorization, the impact of green barriers ($lnGreenBarrier_{ij}$) on the explained variable remained negative and significant at the 1% level, which is consistent with the benchmark regression results. Although the impact coefficients varied, they were within the normal fluctuation range. Specifically, the coefficient of green barriers was -3.419 in Model 1 and -3.526 in Model 2, both significant at the 1% level.

In addition, the impact of domestic GDP ($lnGDP_i$) on trade weight ($lnWeight_{ij}$) was positive and significant at the 5% level, with a coefficient of 0.791, indicating that an increase in domestic GDP will promote the development of aquatic product export trade to a certain extent. The impact of foreign GDP ($lnGDP_j$) was negative and significant at the 5% level, with a coefficient of -0.088, suggesting that an increase in foreign GDP may inhibit aquatic product export trade. The impact of distance ($lnDT_{ij}$) was not significant in Model 1 but became positive and insignificant in Model 2, with a coefficient of 2.046. The impact of exchange rate ($lnExchangeRate_{ij}$) was negative and significant at the 5% level, with coefficients of -2.062 in Model 1 and -1.485 in Model 2.

Thus, it can be concluded that under different model specifications and data conditions, the development of green barriers has a significant inhibitory effect on aquatic product export trade, while an increase in domestic GDP promotes the development of aquatic product export trade. The conclusions of this paper have passed the robustness test and are highly credible.

Table 11. Results of Robustness Test

	(1) Variable Replacement $lnWeight_{ij}$	(2) Winsorization $Trade_{ij}$
$lnGDP_i$	0.791***	0.967***
	(5.317)	(6.957)
$lnGDP_j$	-0.088***	-0.082***
	(-2.736)	(-2.792)
$lnDT_{ij}$	1.015	2.046
	(0.738)	(0.976)
$lnExchangeRate_{ij}$	-2.062***	-1.485***
	(-5.947)	(-2.808)
$lnGreenBarrier_{ij}$	-3.419***	-3.526***
	(-4.358)	(-6.698)
_cons	-15.081	-21.556
	(-0.606)	(-1.120)
N	220	216
R^2	0.2105	0.1708
F	105.02	97.96
Note：***p<0.01, **p<0.05,*p<0.1		

This section discusses the analytical effectiveness and limitations of the fixed effects model constructed in this paper. Overall, the model can effectively explain the impact of green barriers on aquatic product export trade, and the selected control variables are reasonable and scientific. However, the model has some deficiencies in terms of external validity, variable selection, and calculation methods.

Due to limitations in data availability, the national data collected in the study only includes the top 10 EU exporting countries and is limited to normally operating enterprises, excluding unlisted companies. This indicates that the model's analysis results may only apply to similar enterprises in the same region and cannot be directly generalized to other regions or all enterprises. Additionally, although the model considers some control variables, its structure is relatively simple and does not include other variables that may significantly affect trade, such as industry competition indices and green innovation investment, which limits the model's explanatory power to a certain extent. In regions with a highly developed aquatic product industry, enterprises typically invest more in environmental, social, and governance (ESG) aspects and may respond more deeply and effectively to green barriers.

The model also has limitations in the definition methods of variables. For example, the "GreenBarrier" index may not fully reflect the specific impact of green barriers in actual trade. These factors may affect the model's accuracy and applicability, which need to be further improved and refined in future research. By adding more variables and refining the model structure, the explanatory and predictive capabilities of the model can be enhanced, making it more suitable for enterprises in different regions and of different scales.

Conclusion

Based on the institutional characteristics of EU green barriers and the actual situation of China's aquatic product exports, this study analyzes the main forms of green barriers, China's export status quo, enterprise adaptability, and empirical results, leading to the following conclusions: First, the EU green barriers have formed a systematic institutional system centered on technical trade barriers, environmental label certification, packaging and carbon footprint control, and violation punishment mechanisms, exerting a systematic impact on China's aquatic product exports. Its technical standards are strict and detailed, with a wide coverage that not only examines product safety indicators but also extends to the ecological impact of the entire process from production, transportation, to packaging (Wu et al, 2023). Second, in terms of export scale and structure, China's aquatic product exports to the EU have generally shown a steady upward trend, but the category concentration is high, mainly focusing on frozen fish, shrimp, and shellfish. Frequent green barrier incidents mainly concentrate on excessive drug residues, microbial contamination, and insufficient traceability. Some enterprises have been frequently notified by RASFF, indicating rising export risks and significant pressure on production costs. Third, empirical analysis shows that EU green barriers have a significant negative impact on China's aquatic product export trade, while the growth of domestic GDP can promote aquatic product exports to a certain extent.

In summary, as a new hotspot in international trade competition, green barriers have exerted multi-faceted pressures on the compliance system, export model, and sustainable development capacity of China's aquatic product industry. In the future, it is necessary to strengthen the linkage between the aquatic product industry and policies, promote the implementation of the "green export strategy," and lay a solid foundation for a higher-quality, lower-risk, and more sustainable export development path for China's aquatic product industry.

The primary response to green barriers is to ensure the quality and safety of aquatic products through source management. It is recommended that national and local authorities implement stricter quality and safety supervision systems across the entire industry chain. On the one hand, accelerate the formulation of key indicator standards aligned with international practices, particularly the EU system; on the other hand, strengthen source management in the aquaculture sector, standardize the use of antibiotics and prohibited drugs, and implement sampling traceability and product recall systems (Zhu, 2024). Additionally, guide enterprises to establish a Hazard Analysis and Critical Control Point (HACCP) system covering the entire process from seedling, breeding, processing to export, and build verifiable and quantifiable quality safety files to ensure full-process quality control from "farm to table."

Accelerate the establishment of a green standard support system centered on international mainstream certifications such as MSC and ASC to adapt to the increasingly strict EU requirements for aquatic product green certification. The government can set up special funds to subsidize certification training and audit fees, reducing the certification threshold for small and medium-sized enterprises. Meanwhile, concentrate certification resources on key export regions and leading enterprises, cultivating a group of "green export demonstration enterprises" and "certification-driven industrial clusters." Finally, establish a green certification database and information sharing platform to provide enterprises with services such as certification updates, standard changes, and successful cases, improving certification efficiency and transparency for large-scale, systematic, and normalized operations (Tang, 2023).

Aiming at the "information lag" problem, establish a national-level "Green Trade Regulations Monitoring Platform" to track EU TBT/SPS notifications, RASFF warnings, and CBAM carbon border adjustment policies in real time, and promptly release early warning information to enterprises. Meanwhile, rely on universities and research institutions to form a "green trade think tank," strengthening the interpretation of EU legal clauses, trend prediction, and response strategy research to provide professional decision support for policy departments and enterprises (Shang & Xia, 2024). Encourage industry associations to play a bridging role in notification analysis, compliance guidance, and dispute coordination, enhancing the overall response capacity of the industry.

Enterprises must enhance their green production and management capabilities to better address green barriers. Encourage enterprises to increase investment in environmental technology upgrades, promoting the transformation of traditional aquaculture to an ecological, intelligent, and modern system. Guide enterprises to apply green technologies such as recirculating water aquaculture, tailwater treatment, and energy-saving cold chain to reduce environmental impacts (Chen et al, 2024). Additionally, establish a "green financial incentive mechanism" to direct funds to green aquaculture enterprises through green credit and green guarantees. For fishery resources meeting sustainable fishing standards, prioritize MSC, ASC, and other certification work to expand the supply of sustainable products (Sheng, 2023). At the government level, formulate green product priority export lists and set up green brand reward policies to enhance the recognition and price negotiation capability of sustainable aquatic products in the EU market.

Although the EU market remains an important destination for China's aquatic product exports, facing the trend of stricter green barriers, it is necessary to accelerate the diversification strategy of export markets. Market diversification not only provides more trade opportunities for Chinese enterprises but also helps avoid export risks to a certain extent. By leveraging the "Belt and Road" cooperation mechanism, actively expand emerging markets in Southeast Asia, the Middle East, Africa, and Central Asia, and promote bilateral or multilateral agreements with partner countries on mutual recognition of aquatic trade standards and green certification interoperability to reduce institutional barriers in non-EU markets (Nguyen, 2023). Accelerate the layout of overseas warehouses, cold chain logistics, and overseas marketing networks to enhance service capabilities and response efficiency in emerging markets. For new products and markets with export potential, the state can establish special support projects to provide comprehensive services such as market research, trade matchmaking, and brand promotion, alleviating export enterprises' high dependence on the EU market and enhancing risk resistance.

Declaration

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Di Wu：Formal analysis; Writing - Original Draft. Haiming Yu：Editing; Visualization

Reference

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RESEARCH ARTICLE

The Impact of Economic Growth and Electricity Access on CO_2 Emissions in Bangladesh: An ARDL Bounds Testing Approach

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Abstract
As a rapidly developing nation, Bangladesh faces the imperative of decoupling economic expansion from environmental degradation. This study investigates the dynamic interplay between economic drivers, non-CO_2 greenhouse gases, and carbon dioxide (CO_2) emissions using annual data from 1990 to 2022. Employing the Autoregressive Distributed Lag (ARDL) bounds testing approach, the model examines the impact of GDP growth, electricity access, foreign direct investment (FDI), trade liberalization, and emissions from methane (CH_4) and nitrous oxide (N_2O). The empirical results substantiate a stable long-run cointegrating relationship among these variables. Specifically, long-term CO_2 emissions are significantly driven by GDP growth and methane output, whereas Foreign Direct Investment (FDI) is associated with a reduction in emissions. In the short run, however, expanded electricity access, industrial value added, and nitrous oxide levels contribute to rising pollution. The Error Correction Term (ECT) of -0.273 indicates a moderate adjustment speed, correcting approximately 27.3% of disequilibrium annually. These findings underscore the need for a multifaceted policy framework, including 'Green FDI' initiatives, accelerated renewable energy adoption, industrial energy efficiency, and sustainable agriculture. Implementing these measures will help Bangladesh align its development trajectory with SDGs 7, 8, and 13.

Keywords: CO_2 Emissions; ARDL Bounds Testing; Economic Growth; Pollution Halo Hypothesis; Bangladesh

Introduction

In the twenty-first century, one of the greatest issues facing policymakers has been the pursuit of fast economic expansion, with all the attendant negative effects on the environment (Sarkodie & Strezov, 2019). This is particularly apparent in Bangladesh, a South Asian nation with a population of over 170 million. The nation has emerged as one of the region's fastest-growing economies, attaining an average GDP growth rate of 6-7% per annum over the past decade [Bangladesh Bureau of Statistics (BBS), 2023]. This significant economic advancement has been propelled by industrialization, urbanization, and a flourishing ready-made garment (RMG) sector, which constitutes over 80% of the nation's export revenues (BBS, 2023).
However, this economic momentum has exacted a heavy environmental toll. Bangladesh's deep-seated reliance on fossil fuels has driven a substantial surge in energy consumption and greenhouse gas (GHG) emissions, specifically carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) (Alam et al., 2012; Alam et al., 2016). Beyond contributing to global climate change, these emissions exacerbate local ecological crises, such as air pollution and soil degradation, posing a severe threat to the nation's long-term sustainability

[Intergovernmental Panel on Climate Change (IPCC), 2022]. The interplay between economic growth, energy consumption, and environmental degradation in Bangladesh is intricate and multifaceted. While CO_2 emissions may exhibit a short-term positive correlation with GDP growth, reflecting the nation's reliance on carbon-intensive industries, methane and nitrous oxide emissions appear to hinder economic performance, highlighting the high cost of unsustainable operational practices (Rahman & Kashem, 2017). Methane, derived primarily from agriculture and waste management, constitutes approximately 20% of total GHG emissions, while nitrous oxide levels have escalated alongside agricultural intensification (Wisser et al., 2024; FAO, 2023). These trends underscore the critical necessity of adopting sustainable methodologies to mitigate environmental damage. Concurrently, Bangladesh has achieved significant milestones in electrification, with over 90% of the population now having access to power (BPDB, 2023). However, the translation of electricity access into GDP growth often exhibits a time lag, necessitating accelerated investment in infrastructure and energy efficiency (Hossain, 2011). Furthermore, the energy mix remains heavily skewed toward fossil fuels, with renewables contributing less than 5% to total output (SREDA, 2023). This dependence not only compromises environmental sustainability but also exposes the economy to the volatility of global energy markets.

Foreign Direct Investment (FDI) and trade openness have also been pivotal to Bangladesh's economic trajectory. FDI inflows, particularly in manufacturing and energy, have facilitated technology transfer and industrial expansion (Islam et al., 2013). However, FDI can demonstrate a delayed negative impact on environmental sustainability, suggesting potential inefficiencies in capital absorption (Cole et al., 2011). Similarly, while trade openness drives growth, it exacerbates energy demand and emissions in export-oriented sectors like ready-made garments (Rahman & Vu, 2020). This dynamic aligns with the Pollution Haven Hypothesis, which suggests that developing nations with weaker regulations attract polluting industries, thereby complicating the trade-environment nexus (Managi et al., 2009).

The industrial sector, which includes construction and the RMG business that was discussed previously, is a crucial part of this economic growth. The value added (IND_VA) of this sector is a straightforward way to measure how much it adds to the economy. But it also uses a lot of energy and releases a lot of CO_2 (Rahaman, Chen, & Jiang, 2023), which makes its role as an engine of expansion and its environmental impact directly opposed to each other. So, for policies to be sustainable, they need to know the net effect of industrial activity.

While the individual impacts of these factors are partially understood, they are often analysed as part of the STIRPAT framework, which links population, affluence (GDP), and technology to environmental impact (York et al., 2003). However, a critical gap remains in analysing their combined and dynamic interplay (Alam et al., 2016). Most studies tend to focus on CO_2 in isolation, failing to account for the complex feedback loops between economic drivers (GDP, FDI, Trade, Industry), energy access, and the *full spectrum* of key greenhouse gases (CO_2, CH_4, and N_2O). To address this gap, the present study utilises the Autoregressive Distributed Lag (ARDL) framework, a method well-suited for examining long-run and short-run dynamics among time-series variables (Pesaran et al., 2001).

The main goal of this research is to explore the short-run and long-run dynamic relationships between Carbon Dioxide (CO_2) emissions and their key drivers in Bangladesh. Specifically, this study aims to:

I. Investigate the existence of a stable long-run (cointegrating) relationship between CO_2 emissions and its main drivers: GDP growth (GDP_GR), access to electricity (ELEC_ACCESS), foreign direct investment (FDI_NET), industrial value added (IND_VA), trade openness (TRADE_GDP), Methane emissions (CH_4_CHG), and Nitrous Oxide emissions (N_2O_CHG).

II. Measuring the short-run and long-run impacts of these variables on CO_2 emissions.

III. Determine the speed of adjustment back to long-run equilibrium following a short-term shock, using the Error Correction Model (ECM).

The significance of this study is twofold. First, it adds something new to the academic world by offering a more complete model of greenhouse gases. Innovatively including CH_4 and N_2O as predictors for CO_2 provides a more comprehensive picture of emission dynamics than the typical studies that only examine CO_2. Second, and just as importantly, the findings are crucial for policymakers in Bangladesh. By putting real numbers to the impacts of these key economic, energy, and environmental variables, this research provides a solid foundation for evidence-based policies. This can help leaders design smarter interventions that allow Bangladesh to grow its economy without destroying the environment, helping the nation meet its Sustainable Development Goals (SDGs), particularly SDG 7 (Affordable and Clean Energy), SDG 8 (Decent Work and Economic Growth), and SDG 13 (Climate Action).
This study provides three concrete contributions to the existing literature on emissions and economic development in Bangladesh:

- **Integrated Modelling of Greenhouse Gases (GHG):** To the best of the author's knowledge, this is the first study for Bangladesh to move beyond a CO_2-centric model. While existing studies (e.g., Rahman & Kashem, 2017; Alam et al., 2016) focus exclusively on the drivers of carbon dioxide, this paper innovatively includes Methane (CH_4_CHG) and Nitrous Oxide (N_2O_CHG) as direct independent variables. This joint modelling reveals a novel cross-gas pollution linkage, where long-run CO_2 emissions are significantly driven by methane, and short-run CO_2 emissions are driven by nitrous oxide.

- **Robust Evidence for the "Pollution Halo" Hypothesis:** Foreign investment in Bangladesh has raised a lot of questions about its effects on the environment. This study utilizes a dynamic ARDL framework to provide an exhaustive analysis of both long-term and short-term effects. The results show that FDI_NET has a big effect on lowering CO_2 emissions in both the short and long run. This discovery is a big deal since it strongly supports the "Pollution Halo" hypothesis (that FDI brings in cleaner technology) instead of the "Pollution Haven" explanation for Bangladesh.

- **Specific Short-Run vs. Long-Run Policy Insights:** The ARDL-ECM framework improves upon static models by isolating short-run from long-run effects. This study contributes to the field by mapping these distinct temporal drivers: while ELEC_ACCESS and IND_VA drive emissions in the short term, GDP_GR and CH_4_CHG are significant long-term factors. Recognizing this dichotomy allows policymakers to move beyond one-size-fits-all solutions and instead deploy targeted measures that address both immediate fluctuations and structural trends.

Literature Review

The literature regarding environmental sustainability and economic growth provides a solid theoretical foundation for analyzing the complex nexus between these two fields. Utilizing predominantly secondary data, this body of work can be categorized into four primary strands: 1) the dynamic between economic expansion and energy consumption; 2) the inherent trade-offs between development and environmental degradation; 3) the ecological implications of globalization, specifically regarding trade and Foreign Direct Investment (FDI); and 4) the contribution of renewable energy to long-term sustainability. This thematic organization facilitates a comprehensive understanding of the challenges involved in reconciling economic objectives with environmental preservation.

Economic Growth and Energy Consumption

The nexus between economic expansion and energy usage remains a central debate within energy economics (Apergis & Payne, 2012). Empirical evidence is far from uniform, often diverging based on the specific country and methodology employed. In emerging economies like India (Alam et al., 2011; Sarkar & Singh, 2010) and China (Lin & Moubarak, 2014), studies frequently support the 'energy-led growth' hypothesis, identifying energy as a critical driver of development. In contrast, research from OECD nations suggests a different trajectory, where strategic investments in efficiency allow for the 'decoupling' of economic progress from energy demand (IEA, 2022). In Bangladesh, the evidence is mixed. The research conducted by Alam et al. (2012) and Sharif Hossain (2011) identified energy consumption as a primary factor influencing economic growth; however, studies by Rahman & Kashem (2017) emphasised the more substantial impact of industrial expansion. A prevalent limitation in numerous studies is the neglect of the substantial time lag between investments in energy infrastructure and the subsequent economic benefits. This study helps fill that gap by using the dynamic, lagged structure of the ARDL model.

Environmental Emissions and Economic Growth

While the Environmental Kuznets Curve (EKC) hypothesis successfully predicts an inverted U-shaped pollution trajectory in countries like Sweden and Vietnam (Grossman & Krueger, 1991; Stern, 2004; Managi et al., 2009), it often fails to describe trends in the Global South. In South Asia, and Bangladesh specifically, studies consistently show that emissions continue to rise with growth, with no turning point in sight (Shahbaz et al., 2012; Alam et al., 2016; Islam et al., 2021). Moreover, existing research suffers from a significant blind spot: an almost exclusive focus on CO_2 (Cole et al., 2011). For agrarian nations like Bangladesh, excluding methane (CH_4) and nitrous oxide (N_2O) leads to an incomplete picture of environmental impact (FAO, 2021; Lgwe, 2024). By incorporating these non-CO_2 gases, this study provides a comprehensive analysis that standard models miss.

Trade, FDI, and Their Environmental Impact

The ecological impact of globalization is defined by two competing theories. The 'Pollution Haven Hypothesis' argues that weak regulations in developing nations like Bangladesh attract polluting industries (Walter & Ugelow, 1979; Raihan et al., 2022). Alternatively, the 'Pollution Halo Hypothesis' posits that FDI transfers cleaner technology and improves environmental standards (Zhu et al., 2016; Liu et al., 2018).
Bangladeshi literature has produced inconsistent results, though many studies support the Haven hypothesis. For example, trade openness has been linked to higher emissions in export industries (Rahman & Vu, 2020; Zhang et al., 2017), and Hossain (2011) found a direct link between FDI and CO_2. Crucially, however, previous research often fails to account for temporal delays. This study fills that gap by using an ARDL approach to model the dynamic, time-dependent effects of trade and FDI on the environment.

Renewable Energy and Sustainable Development

Renewable energy transition is universally accepted as a cornerstone of sustainable growth (Balsalobre-Lorente et al., 2020). Experiences in Germany and India confirm that renewables can reduce emissions without hindering the economy (Tseng et al., 2019; IEA, 2022).

Within Bangladesh, solar home systems have expanded significantly in rural zones (SREDA, 2023). However, the sector grapples with formidable challenges, notably grid reliability issues, high installation costs, and limited land resources (BPDB, 2023; Mondal & Denich, 2010). Despite the clear potential for renewables, there is limited research on how policy interventions can expedite their uptake. This study addresses this limitation by analyzing the impact of environmental regulations and the EPS Index on energy transition.

Drivers of Non-CO_2 Emissions (CH_4 and N_2O)

Existing research suffers from a major blind spot: an almost exclusive focus on carbon dioxide. This study fills that gap by explicitly modeling Methane (CH_4_CHG) and Nitrous Oxide (N_2O_CHG). Understanding the drivers of these gases is crucial for Bangladesh. Methane output is heavily tied to the agrarian economy, particularly rice paddies and livestock (Alam et al., 2016; Habib et al., 2023), though urban landfills also contribute significantly due to poor waste processing (IPCC, 2022).

Nitrous Oxide, on the other hand, tracks closely with fertilizer application (Wisser et al., 2024; FAO, 2023). Consequently, mitigating these emissions requires a shift toward sustainable farming and better waste management. By capturing these agricultural and urban drivers, our analysis moves beyond the standard industrial models to provide a complete picture of the country's emissions profile.

Gaps in the Literature and This Study's Contribution

- Most prior studies have restricted their analysis to CO_2 emissions, failing to account for the significant environmental impact of methane (CH_4) and nitrous oxide (N_2O) (Sarkodie & Strezov, 2019; Lawe, 2025).
- The delayed (lagged) consequences of energy investments, FDI, and trade are frequently neglected, as they cannot be represented in static models.
- There is insufficient research on the measurable effectiveness of environmental policies in promoting renewable energy in Bangladesh.

This study addresses these gaps by

- Including CO_2, CH_4, and N_2O emissions in a single, integrated analysis.
- Using the Autoregressive Distributed Lag (ARDL) model to study both the short-run and long-run dynamic effects of all variables.
- Evaluating how policies like the EPS Index can promote sustainable development in Bangladesh.

Methodologies

Data and Variables

This study uses a quantitative, longitudinal approach to look at the things that affect carbon dioxide emissions in Bangladesh. The research utilises annual time-series data spanning from 1991 to 2023, obtained from the World Bank's World Development Indicators (WDI) database. The model chooses Carbon Dioxide (CO_2) Emissions (total, excluding LULUCF, Mt CO_2e) as the dependent variable (CO_2_TOT), functioning as the main indicator of environmental degradation. Table 1 shows a summary of all the variables that were used in this analysis. The independent variables were chosen because they are related to economic activity and environmental impacts in theory:

Table 1. Variable Descriptions

Variable	Description
	Dependent Variable
CO_2_TOT	Carbon Dioxide (CO_2) Emissions (total) excluding LULUCF (Mt CO_2e)
	Independent Variables
CH_4_CHG	Methane (CH_4) Emissions (% change)
ELEC_ACCESS	Access to Electricity (% of population)
FDI_NET	Foreign Direct Investment, net inflows (% of GDP)
GDP_GR	GDP Growth (annual %)
IND_VA	Industry (including construction), value added (% of GDP)
N_2O_CHG	Nitrous Oxide (N_2O) Emissions (% change)
TRADE_GDP	Trade (% of GDP)

Theoretical Rationale for Variable Selection

Table 2. Variable Justifications with References

Variable	Justification	Selected References
CO_2_TOT	Key driver of climate change. Bangladesh's emissions have grown significantly with industrialisation.	(Alam et al., 2016; IPCC, 2022; Stern, 2004)
GDP_GR	GDP growth reflects economic health and is central to the energy-environment trade-off. Critical for SDG alignment.	(World Bank, 2023; Rahman & Kashem, 2017; Barro, 1996; Hossain, 2011)
ELEC_ACCESS	Electrification is a primary driver of industrialisation, social equity, and economic activity.	(IEA, 2022; Tseng et al., 2019; BPDB, 2023; SREDA, 2023)
FDI_NET	FDI influences technology transfer (Pollution Halo) or can attract polluting industries (Pollution Haven).	(Islam et al., 2013; Cole et al., 2011)
IND_VA	Industrialisation (e.g., the RMG sector) is a major contributor to GDP but also a primary source of emissions.	(BBS, 2023; Rahman & Kashem, 2017; Lin & Moubarak, 2014)
CH_4_CHG	Methane (mainly from agriculture/waste) accounts for ~20% of Bangladesh's GHG emissions.	(IPCC, 2022; FAO, 2021; SREDA, 2023; Rahman & Alam, 2021)
N_2O_CHG	Nitrous oxide (N_2O) emissions from fertilisers have increased with agricultural intensification.	(FAO, 2021; Rahman & Alam, 2021; Smith et al., 2008)
TRADE_GDP	Trade openness drives energy demand and emissions in export-oriented economies (e.g., the RMG sector).	(WTO, 2023; Rahman & Vu, 2020; Managi et al., 2009; Shahbaz et al., 2015)

Estimation and Methods

The Autoregressive Distributed Lag (ARDL) model is employed to examine the impact of globalisation and economic factors on population growth in Bangladesh. This method considers both short-term fluctuations and long-term equilibrium points. It has a process for fixing mistakes (ECM) that must be negative and statistically significant. This demonstrates how quickly variables get to their long-term equilibrium. The primary advantage of the ARDL approach lies in its flexibility regarding the order of integration. Unlike standard cointegration techniques, it yields robust results whether the underlying variables are purely I(0), purely I(1), or a combination of both. This framework is designed to simultaneously capture short-term dynamic adjustments and long-term equilibrium relationships, providing a holistic view of the variables' interactions. The existence of a valid long-run relationship is rigorously confirmed via the Bounds testing procedure. Moreover, the ARDL framework is superior to static models for analyzing complex economic systems. By explicitly incorporating lags of both the dependent and independent variables, the model inherently captures the dynamic nature of the data. This structure helps to mitigate potential endogeneity problems, such as reverse causality, offering more reliable estimates than static alternatives (Pesaran et al., 2001).

Model Specification

To assess the relationship between Annual Economic growth (GDP_GR) and its determinants, the subsequent econometric model is formulated:

$$CO_2\_\mathrm{TOT}_t = \alpha_0 + \alpha_1 CH_4\_CHG_t + \alpha_2 ELEC\_ACCESS_t + \alpha_3 FDI\_NET_t + \alpha_4 GDP\_GR_t + \alpha_5 IND\_VA_t + \alpha_6 N_2O\_CHG_t + \alpha_7 TRADE\_GDP_t + +\mathcal{E}_t \quad (1)$$

Where:
α_0= Constant term, and $\alpha_1 \dots \dots \alpha_7$ are the long-term coefficients of CO_2 Emission the explanatory variables and the error term (ε_T)

Unit Root Test

To avoid spurious regression, the stationarity of the time series is tested using the Augmented Dickey-Fuller (ADF) in intercept and intercept and trend (Dickey & Fuller, 1979). To determine stationarity and the order of integration, the has been tested applied is Augmented Dickey-Fuller (ADF) test. Suppose a series is stationary at its level (eg, cap Z sub t, cap Z sub t). In that case, it is referred to as I(0) or integrated of order zero if it is stationary after the first difference (e.one. $(Z_t - Z_t - 1Z_t - Z_t - 1)$, it is classified as I(1) or integrated of order 1.
The ADF test examines whether each variable has a unit root. The ADF test equation is specified as:

$$\Delta Y_t = \beta_0 + \beta_{1t} + \delta Y_{t-1} + \sum_{j=1}^{m} \phi j \, \Delta Y_{t-j} + \mu_t \quad (2)$$

Where:
Y_t = Variable under investigation (e.g., *GDP_GRt*, *ELEC_ACCESSt*, etc.).
ΔY_t= First difference of Y_t
β_0 = Constant term.
Y_{1t} = Time trend.
δ = Coefficient of the lagged level of *Yt*.
Φ_j = Coefficients of lagged differences.
μ_t = Error term

If θ is 0, the variable is I. To make sure the results are correct. By proving stationarity and avoiding false regression results, these tests make sure that the analysis is reliable.

ARDL Bounds Test for Cointegration Test

When two or more time series are not stationary, the cointegration test is used to see if there is a stable long-term connection between them. When all the variables in a model remain constant after differencing, this test is used to determine if they all follow the same order of integration. For cointegration to exist, two conditions must be met:

1. Each series must have the same integration order.
2. A linear combination of the series must be stationary at their respective levels (Thome, 2014).

To examine long-run equilibrium relationships, the maximum likelihood approach is used. (Johansen & Juselius, 1990). Two likelihood ratio tests—the maximum eigenvalue and trace test—are employed to identify the number of cointegrating vectors. The test can be summarised as follows:

$$\Delta X_t = IIX_{t-1} + \sum_{i=1}^{p-1} \Gamma X_{t-1} + \mathcal{E}_t \qquad (3)$$

Where:

Xt= Vector of endogenous variables (e.g., CO_{2t}, CH_4, *GDP_GRt*, *ELEC_ACCESSt*, etc.). .Π: Matrix of long-run coefficients.

Γ*i*= Matrix of short-run coefficients.

ϵt= Error term.

The rank of Π (denoted as *r*) determines the presence of cointegration:

- If r=0*r*=0, no cointegration exists, and the model reduces to a VAR of order p*p*.
- If 0<*r*<*n*, there are *r* cointegrating vectors, and Π=*αβ*′. Here, α*α* measures the strength of the relationship, and *β* represents the cointegrating vector. Even if W*t* is I(1), *β*′W*t* is I(0).

Bound Test Equation

To assess the short-run and long-run dynamics, the Autoregressive Distributed Lag (ARDL) model is applied. The bound test equation is specified as:

$$CO_2\_\mathrm{TOT}_t = \alpha_0 + \sum_{i=1}^{p} \beta_{1i}\, CH_4\_\mathrm{CHG}_{t-1} + \sum_{i=1}^{p} \beta_{2i}\, \mathrm{ELEC\_ACCESS}_{t-1} + \sum_{i=1}^{p} \beta_{3i}\, FDI\_NET_{t-1} + \sum_{i=1}^{p} \beta_{4i}\, GDP\_GR_{t-1} + \sum_{i=1}^{p} \beta_{5i}\, \mathrm{IND}\_VA_{t-1} + \sum_{i=1}^{p} \beta_{6i}\, N_2\mathrm{O\_CHG}_{t-1} + \sum_{i=1}^{p} \beta_{7i}\, \mathrm{TRADE\_GDP}_{t-1} + \phi_1 CH_4\_\mathrm{CHG}_{t-1} + \phi_2 \mathrm{ELEC\_ACCESS}_{t-1} + \phi_3 FDI\_NET_{t-1} + \phi_4 GDP\_GR_{t-1} + \phi_5 \mathrm{IND\_VA}_{t-1} + \phi_6 N_2\mathrm{O\_CHG}_{t-1} + \phi_7 \mathrm{TRADE\_GDP}_{t-1} + \varepsilon_t \quad (4)$$

Where:

- (β_1 …… β_7), & (θ_1…... θ_7): Short-run coefficients.
- ϕ_1 to ϕ_7: Long-run coefficients.
- ϵ_t: Error term.

Criteria of Lag Selection

The Akaike Information Criterion (AIC) in EViews-12 automatically found the lag structure for the model with a maximum lag length set to 2. The AIC is a common, standard and robust way to choose a model selection as it effectively balances model fit with parsimony, that is, it statistically penalises the inclusion of unnecessary lags. The chosen ARDL (2, 0, 1, 0, 2, 0, 1, 2) specification has the lowest AIC value.

The selected model was then evaluated using the diagnostic tests (for serial correlation, heteroskedasticity, and normality) and stability tests (CUSUM and CUSUM-SQ). Table 7 shows that the model passed all diagnostic tests successfully, which means that statistically valid and robust.

Diagnostic and Stability Tests

Finally, a series of diagnostic tests are run on the chosen ARDL model to make sure it is strong and dependable. The tests for Serial Correlation (Breusch-Godfrey LM test), Heteroskedasticity (Breusch-Pagan-Godfrey test, 1979), and Normality (Jarque-Bera test) are also part of this. The Cumulative Sum (CUSUM) and Cumulative Sum of Squares (CUSUM-SQ) tests (Brown et al., 1975) show that the model is stable.

Research Hypotheses

This study tests the following hypotheses based on the theoretical and empirical literature:

I. H1: Economic growth has a positive and significant impact on CO_2 emissions.
   - *Rationale:* Economic activity in Bangladesh is heavily reliant on fossil fuels and carbon-intensive industries (Rahman & Kashem, 2017). Therefore, expect a positive relationship between GDP_GR and CO_2_TOT.

II. H2: Access to electricity has a positive and significant impact on CO_2 emissions.
   - *Rationale:* As Bangladesh's energy grid is primarily fossil-fuel-based (SREDA, 2023), expanding ELEC_ACCESS is expected to increase CO_2_TOT, particularly in the short run.

III. H3: Foreign Direct Investment has a significant impact on CO_2 emissions.
   - *Rationale:* This hypothesis tests the competing "Pollution Haven" (positive impact) vs. "Pollution Halo" (negative impact) theories. This study will determine which effect is dominant in Bangladesh.

IV. H4: Non-CO_2 greenhouse gases have a positive and significant impact on CO_2 emissions.
   - *Rationale:* This is the study's novel hypothesis: Emissions from agriculture (CH_4_CHG and N_2O_CHG) are linked to the same economic development model that drives industrial CO_2 emissions and will have a positive, compounding effect on CO_2_TOT.

Results and Discussion

Statistical Characterization

Table 3 shows descriptive data for the eight variables utilized in this analysis for Bangladesh from 1991 to 2023. Key economic indicators show strong GDP growth (mean = 5.65% each year), although Bangladesh's economy was very unpredictable during this time, with growth rates between 3.45% and 7.88%. The industrial value-added sector made up a consistent part of the economy (mean = 25.85% of GDP). Net foreign direct investment (FDI) inflows as a percentage of GDP were also erratic, ranging from 0.004% to 1.74%.

The data highlights a stark transformation in Bangladesh's environmental landscape. It is observe a sharp surge in CO_2 emissions, rising from 14.07 to 124.79 Mt CO_2e. Alongside this, fluctuations in Methane (CH_4) and Nitrous Oxide (N_2O) signal shifting dynamics in agricultural practices. Social indicators are equally telling. The electricity access data, ranging from a low of 9.91% to a near-universal 99.99%, captures the country's aggressive electrification efforts, averaging 52.34% over the period. Additionally, trade openness (mean = 32.49%) points to increased global connectivity. Statistical validity was confirmed via the Jarque-Bera test, which indicated normal distribution across all variables. These findings emphasize that Bangladesh's development trajectory is inextricably linked to both economic stability and environmental volatility. These results illustrate how crucial it is for Bangladesh to have particular policies that deal with these concerns in order to reach its national sustainability objective.

Table 3. Descriptive Statistics

Variable	Mean	Median	Maximum	Minimum	Std. Dev.	Skewness	Kurtosis	Jarque-Bera	Prob.
CO_2_TOT	57.397	46.20	124.793	14.068	35.493	0.5356	1.9340	3.1401	0.2080
CH_4_CHG	7.787	5.436	24.642	-4.643	9.879	0.1511	1.4754	3.3218	0.1899
ELEC_ACCESS	52.342	50.50	99.990	9.905	28.301	0.2734	1.9093	2.0467	0.3594
FDI_NET	0.612	0.525	1.735	0.004	0.490	0.5897	2.3978	2.4110	0.2995
GDP_GR	5.648	5.572	7.882	3.448	1.170	-0.1321	2.1422	1.1077	0.5747
IND_VA	25.847	24.50	34.594	21.120	4.235	0.9210	2.3532	5.2406	0.0728
N_2O_CHG	57.322	62.80	108.506	5.122	29.302	-0.1365	2.0290	1.3989	0.4969
TRADE_GDP	32.490	30.98	48.111	18.890	7.873	0.4509	2.3245	1.7456	0.4178

Graphs of the Variables

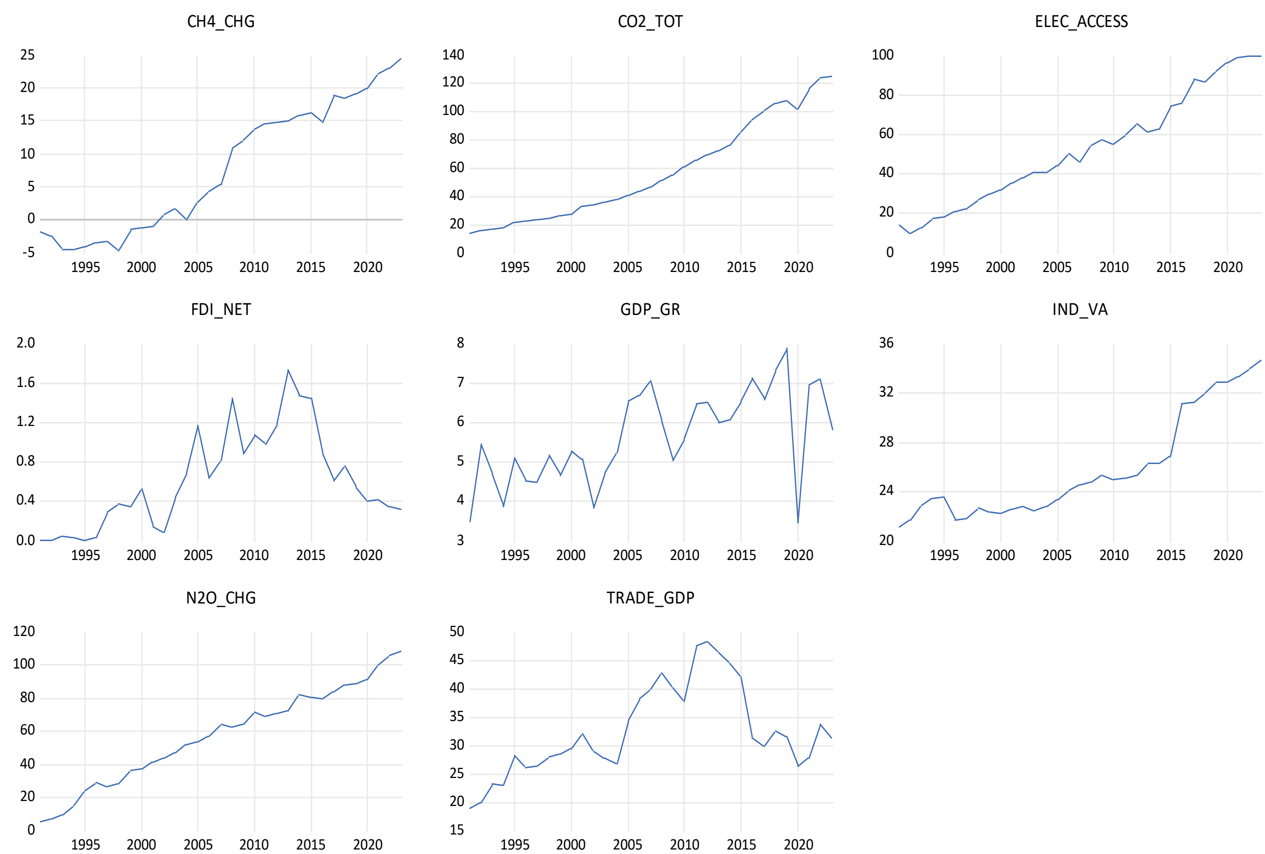

Figure 1. Graphs of the variables with time, from 1991 to 2023

Unit Root Test Result

Table 4. Stationary Test

Variable	Test Specification	At Level I(0)	At 1st Difference I(1)	Conclusion
		t-Stat (Prob.)	t-Stat (Prob.)	
CO_2_TOT	Intercept	1.923 (0.9997)	-5.025 (0.0003)***	I(1)
	Trend & Intercept	-1.477 (0.8167)	-5.891 (0.0002)***	
CH_4_CHG	Intercept	0.706 (0.9904)	-5.999 (0.0000)***	I(1)
	Trend & Intercept	-3.086 (0.1266)	-6.249 (0.0001)***	
ELEC_ACCESS	Intercept	0.376 (0.9785)	-8.142 (0.0000)***	I(1)
	Trend & Intercept	-3.339 (0.0782)*	-8.042 (0.0000)***	
FDI_NET	Intercept	-1.900 (0.3285)	-6.4914 (0.0000)***	I(1)
	Trend & Intercept	-1.5796 (0.7787)	-6.6556 (0.0000)***	
GDP_GR	Intercept	-4.009 (0.0041)***	-7.352 (0.0000)***	I(0)
	Trend & Intercept	-5.520 (0.0004)***	-7.216 (0.0000)***	
IND_VA	Intercept	0.793 (0.9923)	-5.163 (0.0002)***	I(1)
	Trend & Intercept	-5.163 (0.0002)***	-5.505 (0.0005)***	
N_2O_CHG	Intercept	-0.430 (0.8921)	-6.489 (0.0000)***	I(1)
	Trend & Intercept	-3.082 (0.1275)	-6.424 (0.0001)***	
TRADE_GDP	Intercept	-6.424 (0.0001)***	-8.142 (0.0000)***	I(0)
	Trend & Intercept	-3.339 (0.0782)*	-8.042 (0.0000)***	

Note: *, *, and * denote significance at the 1% and 5% levels, respectively.*

Table 4 illustrates the results of the Augmented Dickey-Fuller (ADF) test for all variables, which were looked at at both Level I(0) and 1st Difference I(1) using "Intercept" and "Trend & Intercept" settings. If its p-value is significant ($p < 0.10$) in at least one of the level tests, it is classified as I(0). If a variable fails all level checks, it is then tested at its 1st Difference (The p-values are from the MacKinnon (1996) one-sided p-values). The results show that most of the variables, such as ELEC_ACCESS, FDI_NET, GDP_GR, IND_VA, N_2O_CHG, and TRADE_GDP, are stationary at the I(0) level. The factors CO_2_TOT (the dependent variable) and CH_4_CHG were found to be non-stationary at the I(0) level but became stationary after the first difference.

Crucially, all variables were confirmed to be either I(0) or I(1), and no variable was found to be integrated of order two, I(2). This heterogeneous mix of I(0) and I(1) variables confirms that the ARDL bounds testing approach is the most appropriate and valid methodology for this analysis (Pesaran et al., 2001).

Results of the ARDL Bounds Test

The ARDL bounds test, shown in Table 5, rejects the null hypothesis of no cointegration at the 1% significance level. The F-test statistic of 7.6461 exceeds the crucial I(1) upper bound (3.90, $p < 0.01$). Therefore, the model parameters display a specific cointegrating relationship, and that variation in all of these variables influences CO_2 emissions in Bangladesh.

Table 5. Results of the ARDL Bounds Test

Test Statistic	Value	k
F-statistic	7.6461	7
Significance Level	Critical Bounds	
	I(0)	I(1)
10%	1.92	2.89
5%	2.17	3.21
2.5%	2.43	3.51
1%	2.73	3.90

ARDL Short-run and Long-run Estimation

Table 6. ARDL Short-run and Long-run Estimation

Variables	Long-run Coefficient	Std. Error	t-Statistic	Short-run Coefficient	Std. Error	t-Statistic
CH_4_CHG	2.702392*	1.346146	2.007503	D(CH_4_CHG)	*Not included in ECM*	
ELEC_ACCESS	-0.018612	0.498242	-0.037355	D(ELEC_ACCESS)	0.687510***	0.063089
FDI_NET	-22.12260*	12.49538	-1.770462	D(FDI_NET)	-2.479029**	0.839928
GDP_GR	7.287908**	3.330141	2.188468	D(GDP_GR)	*Not included in ECM*	
IND_VA	1.157943	2.285713	0.506600	D(IND_VA)	1.952474***	0.273289
				D(IND_VA(-1))	-2.706800***	0.343829
N_2O_CHG	0.117439	0.389064	0.301849	D(N_2O_CHG)	0.805704***	0.060723
TRADE_GDP	0.660752	0.691414	0.955654	D(TRADE_GDP)	-0.108639	0.065345
				D(TRADE_GDP(-1))	-0.413326***	0.061552
ECT (CoinEq(-1))				-0.272619*	0.026216	-10.39896
Constant	-56.17657	55.45685	-1.012978	D(CO_2_TOT(-1))	0.241410***	0.062735
R-squared				0.911346		
Adj. R-squared				0.879109		
F-statistic				12.00 (Prob. 0.0000)		
Durbin-Watson				2.118158		

****p < 0.01, **p < 0.05, p < 0.10*

Table 6 presents the results for the selected ARDL (2, 0, 1, 0, 2, 0, 1, 2) model, which was chosen based on the Akaike Information Criterion (AIC). The above table utilises the ARDL framework to illustrate how GDP_GR,

FDI_NET, IND_VA, ELEC_ACCESS, CH_4_CHG, N_2O_CHG, and TRADE_GDP on CO_2_TOT in Bangladesh in the short-term and long-term.

In the long run, a 1-percentage-point rise in GDP_GR (GDP Growth) leads to a 7.288-unit (Mt CO_2e) increase in CO_2_TOT emissions. This result suggests that Bangladesh's economic growth is still energy-intensive, largely because of fossil fuel use and industrial production. As GDP grows, so does the need for electricity, transportation, and infrastructure, which are all strongly linked to carbon emissions. These results support the view that unregulated or carbon-heavy growth strategies can significantly contribute to environmental degradation. This trend aligns with previous findings by Rahman and Kashem (2017) regarding Bangladesh and Sarkodie and Strezov (2019) for developing economies. When examining foreign investment, the coefficients for FDI_NET reveal a distinct negative correlation with CO_2_TOT. Specifically, a 1-percentage-point increase in FDI leads to an immediate emissions reduction of 2.479 units (significant at the 5% level) and a long-term decrease of 22.122 units (significant at the 10% level).

These results lend credence to the 'Pollution Halo' hypothesis. The mechanism suggests that foreign entities transfer cleaner, more efficient technologies and rigorous environmental standards, which then spill over into the domestic economy. While this contradicts the 'Pollution Haven' narrative where capital seeks lax regulations (Cole et al., 2011), it strongly corroborates Zhu et al. (2016), who similarly identified FDI as a driver for environmental improvement.

Furthermore, IND_VA (Industrial Value Added) has a significant positive relationship with CO_2 emissions in the short term. A 1-percentage-point increase in industrial value-added results in an immediate increase in CO_2_TOT of 1.952 units (M_tCO_2e). The heavy reliance on energy-intensive processes in industrialisation, particularly in the ready-made garment (RMG) sector, results in a significant release of greenhouse gases. This finding is reinforced by the highly significant short-run coefficient for ELEC_ACCESS (+0.687), which shows that the expansion of the current energy grid is directly linked to higher emissions. A similar outcome was reported by Rahaman, Chen & Jiang (2023), who linked industrial activity and energy consumption directly to emissions in Bangladesh.

The influence of non-CO_2 greenhouse gases is a particularly new finding of this study. The CH_4_CHG (Methane) coefficient demonstrates that over time, a 1% rise in methane emissions ($MtCO_2e$) causes a 2.702 unit rise in CO_2_TOT emissions (at the 10% significance level). In the same way, a 1% rise in N_2O_CHG (Nitrous Oxide) emissions leads to a 0.806 unit ($MtCO_2e$) rise in CO_2_TOT emissions in the short term. This shows a very critical effect of pollution. These gases, mainly from agriculture (rice cultivation and fertilizer use) and waste, are not just separate problems; they are also linked to the same economic and agricultural activities that produce CO_2. These findings are corroborated by Alam et al. (2016) and FAO (2023), which highlight the environmental impact of unsustainable agricultural intensification occurring alongside industrial expansion.

Finally, the error correction term (CoinEq(-1)) shows that this entire model is stable. The coefficient of -0.272619 is highly significant with p=0.0000, which means that the system is stable and adjusts back to its long-run equilibrium at a speed of 27.3% per year following any short-term shock.

Diagnostic and Stability Tests

Table 7. Diagnostic and Stability Tests

Test	Null Hypothesis (H_0)	Test Statistic	Value	Probability	Conclusion
Serial Correlation	No serial correlation	Breusch-Godfrey LM (F)	1.763186	0.2131	Fail to Reject H_0
Heteroskedasticity	Homoskedasticity	Breusch-Pagan-Godfrey (F)	0.688871	0.7645	Fail to Reject H_0
Normality	Residuals are normally distributed	Jarque-Bera	1.096605	0.577930	Fail to Reject H_0

Table 7 shows the findings of the diagnostic test. The results from these tests indicate a well-specified model. For every diagnostic check, the null hypothesis was upheld, reinforcing the conclusion that the model is robust.

- **Normality Test:** The Jarque-Bera (JB) assessment (Jarque & Bera, 1980), with a p-value of 0.5779, means the distribution is normal.
- **Serial Correlation Test:** The Breusch-Godfrey (LM) examination (Breusch, 1978; Godfrey, 1978) reveals no serial correlation in the residuals, with an F-statistic p-value of 0.2131.
- **Heteroskedasticity Test:** The Breusch-Pagan-Godfrey test (Breusch & Pagan, 1979) implies no evidence of heteroscedasticity in the residuals, reporting an F-statistic p-value of 0.7645.

Stability Checking by CUSUM & CUSUM Square Test of the Model

The Cumulative Sum (CUSUM) and Cumulative Sum of Squares (CUSUM-SQ) tests proposed by Brown et al. (1975) were used to determine if the model's parameters remained constant during the sample period. As seen in the statistics, the test results for both metrics remain well inside the 5% threshold limit. This indicates that the model can be used to examine long-term policy because the estimated parameters are fundamentally stable and consistent.

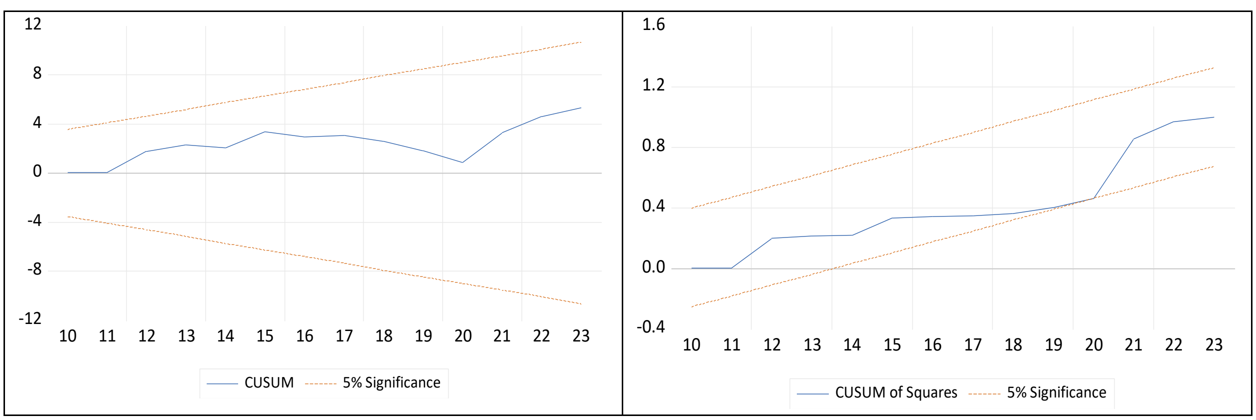

Figure 2. CUSUM & CUSUM Square Test

Discussion and Policy Implications

This study employed the ARDL framework to investigate the intricate nexus linking energy consumption, economic expansion, and environmental degradation in Bangladesh. The empirical results reveal a nuanced dynamic. In the long run, both economic growth (GDP_GR) and methane output (CH_4_CHG) act as significant drivers of CO_2 emissions, underscoring the environmental cost of current agricultural and developmental practices. Conversely, Foreign Direct Investment (FDI_NET) exerts a negative impact on emissions; this finding supports the 'Pollution Halo' hypothesis, suggesting that foreign capital facilitates the transfer of greener technologies. In the short run, however, the expansion of electricity access (ELEC_ACCESS), industrialization (IND_VA), and nitrous oxide emissions (N_2O_CHG) all contribute to immediate spikes in carbon output. The ARDL bounds test confirms a stable long-run cointegration among these variables. Furthermore, the Error Correction Term (ECT) is negative and highly significant (-0.272619, $p < 0.01$), indicating that the system self-corrects at a speed of approximately 27.3% annually following a shock. The findings of this study underscore the critical requirement for policies that strike a balance between the preservation of the environment and the promotion of energy efficiency and growth, with the ultimate goal of steering Bangladesh in the direction of reaching its Sustainable Development Goals (SDG) objectives 7, 8, and 13.

Specific Actions and Implementation

To tackle the identified challenges, Bangladesh can adopt clear and effective policies based on the successful experiences of other countries. The following strategies are directly informed by the sign and significance of the model's coefficients.

It is important to note that while this econometric model identifies the *direction* and *magnitude* of the problem, it cannot generate specific political targets. Therefore, the numeric goals (e.g., MW of solar, number of farmers) mentioned in the implementation plans are presented as illustrative examples of the scale of action required, not as direct outputs of the model.

Table 8: Policy Recommendations Based on ARDL Findings

Policy Recommendation	Result Alignment (Based on ARDL Model)	Recommended Action (Global Example)	Illustrative Implementation Strategy
1. Green FDI Framework	Justified by the negative and significant long-run coefficient (-22.122, $p < 0.10$) of FDI_NET. This suggests that for every 1-percentage-point rise in FDI, CO_2 emissions *decrease* by 22.12 units, supporting the Pollution Halo hypothesis.	Attract foreign investment in renewable energy and eco-tourism, inspired by Costa Rica's model, which generates over 98% of its electricity from renewables (UNIDO, 2023).	Offer tax breaks and streamline regulatory processes specifically for green FDI projects that involve verified technology transfer.
2. Carbon Pricing & Energy Efficiency	Justified by the positive and significant coefficients of GDP_GR (long-run: +7.288, $p < 0.05$) and IND_VA (short-run: +1.952, $p < 0.01$). These results confirm that both long-run growth and short-run industrial activity significantly increase emissions.	Develop mandatory energy efficiency standards and implement a carbon pricing mechanism, inspired by Japan's Top Runner Program (IEA, 2022) and Sweden's carbon tax (World Bank, 2023).	*Illustrative Target:* Set an initial carbon tax rate of \$10/ton of CO_2 for high-emitting sectors (e.g., textiles, cement). Use revenue to subsidise energy-efficient appliances.
3. Sustainable Agriculture Practices	Justified by the positive and significant coefficients of CH_4_CHG (long-run: +2.702, $p < 0.10$) and N_2O_CHG	Promote organic farming and modern agricultural techniques to reduce Methane and Nitrous	*Illustrative Target:* Train 50,000 farmers in organic farming and alternate wet-drying

	(short-run: +0.806, $p < 0.01$). This novel finding confirms a cross-gas pollution linkage.	Oxide emissions, following India's Zero Budget Natural Farming (ZBNF) initiative (FAO, 2021).	(AWD) techniques for rice. Support the setup of biogas plants to capture methane from waste.
4. Decarbonising the Grid	Justified by the positive and significant short-run coefficient (+0.687, $p < 0.01$) of ELEC_ACCESS. This result shows that expanding the grid with its current carbon-intensive fuel mix directly increases CO_2 emissions.	Aggressively expand off-grid and grid-tied renewable energy, drawing inspiration from Germany's *Energiewende* policy (IEA, 2022) and Kenya's success with solar home systems (World Bank, 2023).	*Illustrative Target:* Partner with the private sector to install 5,000 MW of solar capacity by 2030. Install 2 million new solar home systems by 2025.
5. Green Industrial Zones & Circular Economy	This policy directly targets the positive short-run coefficient of IND_VA (+1.952, $p < 0.01$). Since industrial activity is a major immediate driver of emissions, dedicated green zones are a logical intervention.	Promote a circular economy in the RMG sector and develop eco-industrial parks, following the example of China's Suzhou Industrial Park (UNIDO, 2023) and the Netherlands' approach (EU, 2023).	*Illustrative Target:* Create three green industrial zones by 2027, offering tax incentives. Establish 10 textile recycling hubs in major industrial zones by 2026.

Limitations of the Study

The author acknowledges several limitations in this study that provide avenues for future research. The first limitation is the relatively small sample size. The analysis is based on 33 annual observations (1991-2023). While the selected ARDL (2, 0, 1, 0, 2, 0, 1, 2) model was chosen based on the robust Akaike Information Criterion (AIC) and passed all diagnostic and stability tests (as shown in Table 7 and Figure 2), a small sample size can increase the risk of overfitting. The findings should therefore be interpreted with this constraint in mind.

A second limitation is the potential for endogeneity, particularly reverse causality, between CO_2 emissions and key drivers like GDP growth. For instance, while GDP growth impacts CO_2 emissions, climate policies designed to *reduce* CO_2 could in turn affect GDP growth. This study attempts to mitigate this issue by using a dynamic ARD-ECM framework, which is more robust to endogeneity than a static OLS model. However, this remains a key consideration.

Future Research Direction

I. Because the sample size was so small, future studies could use data from every three or four months, if that's possible, to get more information.

II. To deal with endogeneity more clearly, future studies should use different estimators, such as Fully Modified OLS (FMOLS) and Dynamic OLS (DOLS), that are made for cointegrated models and are used to do robustness checks. These ways might help make sure that the long-term coefficients are correct.

III. To build on the model's results, one useful way to do more research would be to use the non-linear ARDL (NARDL) method to look at the different effects, both good and bad, that these economic factors have on CO_2 emissions.

Declaration

The author affirms that this content is wholly original and has not been submitted or published elsewhere. The author was solely responsible for the research, composition, and final approval of the paper.

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Author's contribution: Saikat Pande: Conceptualisation, Methodology, Software, Validation, Formal analysis, Investigation, Data Curation, Writing – Original Draft, Writing – Review & Editing, Visualisation.

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RESEARCH ARTICLE

The Role of Digital Economy in Shaping Economic Growth in Belt and Road Initiative Countries

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Abstract
Global trade dynamics have been re-shaped by the rapid development of digital technologies, but the role played by these changes in economic growth in countries is poorly understood. The study considers 149 developing countries that are engaged in the Belt and Road Initiative to explore the relationship between the digital economy, international trade and economic growth. Using data between the years 2000 and 2024 and dynamic panel models, results demonstrate that international trade helps the growth of economic growth significantly while the overall digital economy has a negative impact, which may indicate existing digital infrastructure is a barrier. The interplay between trade and the digital economy drives the need for policies that unite both trade and the digital initiative approach. The study suggests that digital capabilities must be improved in the sample countries for the maximum trade benefits to be generated and for growth to be stimulated. Policymakers should look into improving digital infrastructure and digital literacy in order to make international trade more efficient and facilitate higher economic growth.

Keywords: Digital economy; international trade; economic growth

Introduction

Raising economic growth has been placed at the center of many countries in the world (Bei, 2018; Zhang et al., 2022; Luo et al., 2024). This concept also emphasizes on the integration of technological innovations in addition to openness and coordinated development (Dai et al., 2025; Pan et al., 2021; Zhou et al., 2020). The speed up of the global economy highlights the importance of identifying radical drivers that can be effective for increasing growth. In this era of fast technology development, digitalization has become one of the major forces, changing the conventional economic system and promoting the adjustment of the structure for sustainable long-term growth. The digital economy has taken over a fast-growing set of industries, such as digital infrastructure, internet-based services, digital platforms, digital finance, and ICTs (Zhang & Zhao, 2024). By introducing broadband internet and mobile networks as well as digitized business processes, digitalization has been able to significantly improve efficiency and productivity. These technologies have revolutionized many industries such as finance, manufacturing, and logistics, as they have allowed businesses to optimize their operations, reduce costs and access global markets (Li et al., 2017; 2020). The evidence shows that digital tools change the traditional economy resulting in higher growth. Theories of what a healthy digital economy implies is that it spurs new innovations, aligns the asymmetries of information, disseminates knowledge, and new business models (Huang et al., 2023; Razzaq et al., 2023). Digitalization is also a key driver for the spread of technology so that small and medium sized enterprises can be included in global value chains and economies can be diversified. These processes are essential for growth (Dai, 2025) and they are only possible through the transformation of the traditional paradigms. Advanced economies have invested in the digitized infrastructure extensively to realize higher growth rates whereas, in comparison, developing countries, due to affordability issues, face complications in adopting digital technologies in trade and economic activities and, as such, are left behind creating a digital divide for greater growth opportunities. The international trade has been a core pillar of economic growth, allowing exchange between countries of whatever goods and services globally (Rodriguez & Rodrik, 2000). In today's digital era, however, digital technologies and infrastructure are key to competing in the trade arena and without these assets, trade will never be effective. Thus, the inclusion of digital platforms and online services in trade presents new problems for developing countries (particularly those without affordability). There is a weak understanding of how Belt and Road Initiative (BRI) countries can use digital technologies to hasten growth through international trade. Studying the extent of business digitalization in these economies is important in terms of promoting such trade and boosting growth. Many studies have analyzed the trade-growth relationship, but very few have considered the influence of digital infrastructure, which has become the main part of trade transactions. While some research has examined the impact of the digital economy on growth, often it has used one single proxy. Digitalization has different components and those are digital access, usage, and skills which are essential to enabling trade and economic activity. This work is addressing this gap by examining how digital access, use and skills and the digital economy in general affect growth considering the implications for international trade in BRI developing economies. The findings offer policy recommendations for BRI economies to grow to reap the benefit of digital tools to boost global trade and economic growth. This paper is structured as follows: part 2 is methodology, part 3 is results and discussions and part 5 is discussion and policy suggestions.

Methodology

Data and empirical models

Taking economic growth as the dependent variable, we focus on the impact of digital economy indicators (digital access, digital usage and digital skills) on growth, when international trade is incorporated. We are also looking at the trade-X interaction with these digital factors and examine the contribution of each factor to growth. The interaction effects are analysed for 149 countries that are part of the Belt and Road initiative between 2000 and 2024. Data is derived from known databases such as the World Development Indicators and World governance indicators. We make four regression equations to explore deep relationship between digital factors, trade and economic growth. Many previous studies have used various indicators to proxy the digital economy, but none has divided the digital economy into digital access, digital usage and digital skills as we do. Chen and Xing (2025) also incorporated measures of digital economy, but they have different indicators and have not split the categories, digital access, use and skills. Equation 1 shows the impact of these three categories of digital as well as trade on GDP growth, which can be used to component-wise measure the contribution of the digital economy.

$$GDP_{it} = \beta_0 + \beta_1 GDP_{it-1} + \beta_2 TRD_{it} + \beta_3 Digacc_{it} + \beta_4 Digusg_{it} + \beta_5 Digsk_{it} + \beta_6 CTR_{it} + \varepsilon_{it} \ldots\ldots\ldots\ldots\ldots. (1$$

In equation 1, GDP is the economic growth, TRD is the trade, Digacc is the digital access, Digusg is the digital usage and Digsk is the digital skills. CTR represents control variables which consist of financial development, consumer price index, foreign direct investment, exchange rate, population, government expenditure, labor force and fixed capital formation. eit is the error term. Equation 2 expands equation 1 by adding interaction terms between trade and one of each of the digital indicators. These interactions - Digacc x TRD, Digusg x TRD and Digsk x TRD, are represented by INT1, INT2 and INT3, respectively.

$$GDP_{it} = \beta_0 + \beta_1 GDP_{it-1} + \beta_2 TRD_{it} + \beta_3 Digall_{it} + \beta_4 CTR_{it} + \beta_5 (INT1) + \beta_6 (INT2) + \beta_7 (INT3) + \varepsilon_{it} \dots\dots\dots\dots\dots\dots.(2$$

Equation3 aggregates the digital economy into one index (Digall) whilst retaining the structure of equation1. Equation 4 includes the aggregate digital index and its interaction with trade (INT4).

$$GDP_{it} = \beta_0 + \beta_1 GDP_{it-1} + \beta_2 TRD_{it} + \beta_3 Digall_{it} + \beta_4 CTR_{it} + \varepsilon_{it} \dots\dots\dots\dots\dots\dots.(3$$

$$GDP_{it} = \beta_0 + \beta_1 GDP_{it-1} + \beta_2 TRD_{it} + \beta_3 Digall_{it} + \beta_4 CTR_{it} + \beta_5 (INT4) + \varepsilon_{it} \dots\dots\dots\dots\dots\dots.(4$$

Variables explanation

GDP per capita is used as a measure of growth and trade as a percentage of GDP. The digital economy is summed up by three indicators: Digital access proxied as fixed telephone subscriptions/100 inhabitants, mobile cellular subscriptions/100 inhabitants, Secure Internet servers/million people. Digital usage is the percentage of people using the internet and fixed broadband subscriptions per 100 inhabitants while digital skills is taken as the duration compulsory education. Control variables include financial development measured as domestic credit to private sector as income percent of GDP, Consumer price index, Foreign direct investment net inflow % of GDP, Exchange rate which is measured as official rate as it is set by national authorities. Population growth taken as annual percentage increase in population, Government expenditure taken as expenditure on education as a percent of GDP, Labor force measured as the overall workforce and Fixed capital formation % of GDP. Table 1 summarizes descriptions of the variables. Table of correlations is shown in Table 2 and Figure 1 effects of each variable on economic growth.

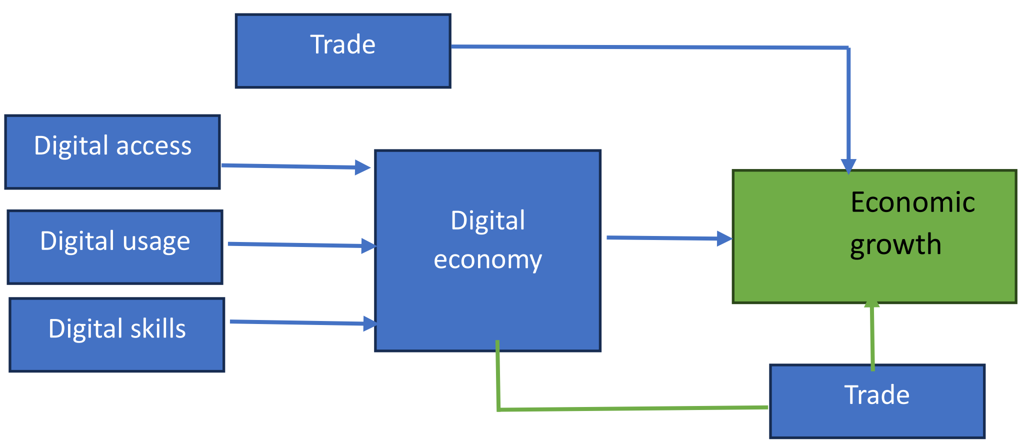

Figure 1: The effect of digital economy on economic growth via trade

Econometric Models

To examine how nexus factors between economic growth, trade, and digital economy in this research uses static and dynamic panel models. The static models include Ordinary Least Squares (OLS) and Fixed Effect Estimators and the dynamic model employed is the Two Step Generalized Method of Moments (GMM). The OLS estimator is a preliminary estimator to give a foundation knowledge of the variable relationships and is known for its efficiency in providing estimates of linear relationships (Wooldridge, 2010). Controlling for unobserved heterogeneity across countries, the study further uses a fixed effect regression model to control for time and invariant characteristics. This model separates the influence of independent variables on economic growth. In the case of panel data analysis, a fixed effect model is regarded as useful in addressing individual-specific traits that can possibly cause biased OLS estimates (Baltagi, 2005). Consequently, the difference GMM and the two-step system GMM are respectively deployed in order to overcome the problem of endogeneity, in this study. The difference GMM controls unobserved effects by data transformation while the two step system GMM deals with the equation in level and difference level resulting in efficient estimation (Arellano & Bover, 1995). The importance of this method is in the presence of dynamic panel data and lagged dependent variables (Blundell & Bond, 1998). By using the above methods, the research proves its results and states the validity of the results as well as reducing the biases caused by omitted variables and errors in the analysis. These methods have been also supported by the prior studies of e.g. Roodman (2009) which emphasizes the effectiveness of the GMM estimator when analyzing the panel data.

Table 1. Descriptive statistics

Variable	Mean	Std. Dev.	Min	Max
GDP	1.067	1.017	-5.932	4.013
TRD	4.357	.509	0.792	5.080
FTS	1.693	1.657	-6.570	5.144
MCS	3.608	1.785	-4.035	4.399
SIS	3.743	3.1348	-3.907	10.484
ITU	2.504	1.708	-8.148	5.605
FBBS	-.0005	2.743	-10.79	4.819
CED	2.179	0.270	1.386	2.833
FD	3.275	1.33	-6.429	5.539
CPI	4.663	0.568	1.067	10.56
FDI	1.013	1.319	-6.684	6.107
EXR	3.266	2.823	-3.112	22.62
POP	0.317	0.978	-5.490	2.963
GOVEXP	1.367	0.438	-2.062	2.808
LBF	14.99	1.640	10.49	20.47
FCF	3.059	0.378	-.1615	4.356

Table 2. Correlation

	GDP	TRD	FTS	MCS	SIS	ITU	FBBS	CED	FDPVT	CPI	FDI	EXR	POP	GOVEXP	LBF	FCF
GDP	1.000															
TRD	0.010	1.000														
FTS	-0.042	0.308	1.000													
MCS	-0.033	0.404	0.625	1.000												
SIS	-0.078	0.537	0.658	0.661	1.000											
ITU	-0.048	0.479	0.774	0.750	0.846	1.000										
FBBS	-0.014	0.474	0.864	0.668	0.803	0.869	1.000									
CED	0.027	-0.119	0.324	0.252	0.214	0.319	0.312	1.000								
FDPVT	0.033	0.352	0.693	0.555	0.632	0.646	0.746	0.135	1.000							
CPI	-0.110	-0.191	-0.21	-0.007	0.111	0.054	-0.029	0.022	-0.225	1.000						
FDI	0.024	0.571	0.226	0.201	0.239	0.173	0.183	0.009	0.129	-0.15	1.000					
EXR	0.061	-0.402	-0.41	-0.339	-0.412	-0.41	-0.373	-0.204	-0.322	0.255	-0.214	1.000				
POP	0.040	-0.196	-0.54	-0.415	-0.509	-0.52	-0.590	-0.147	-0.411	0.059	0.017	0.344	1.000			
GOVEXP	-0.043	0.255	0.276	0.250	0.217	0.306	0.216	0.315	0.189	-0.08	0.128	-0.276	-0.126	1.000		
LBF	0.168	-0.509	-0.05	0.033	-0.119	-0.04	0.049	-0.092	0.144	0.201	-0.396	0.313	-0.028	-0.232	1.000	
FCF	0.22	0.048	-0.06	0.033	-0.055	-0.00	0.009	-0.194	0.114	0.107	0.046	0.130	0.103	-0.012	0.174	1.000

Results and discussions

Table 3 shows the results of the impact of international trade and the digital economy on economic growth. Column 1 contains variables, column 2 are the results of the two-step system GMM model using the digital economy indicators and column 3 the results of the same model but using the digital economy index as a variable. In both of the models social and economic development, we have a positive and significant coefficient of international trade, which mean that international trade has positive effect in economic growth. Prior studies also find that trade leads to growth, by stimulating market access, technology transfer and competition. These results support that trade is a strong contributor to economic growth. The digital economy index produces negative and significant coefficients, suggesting there may be costs and inefficiencies in traditional sectors associated with digital economy growth in the sample countries, and that they can impede economic growth. Digital economic expansion could entail structural transformations or inequalities and workforce adjustment of countries might be problematical resulting in negative effects on growth at least in the short run. The results suggest that countries should focus on developing digital tools and infrastructure for facilitating trade and growth. The individual indicator, digital access, also has a negative impact on economic growth, showing that the more efficient access to digital technologies can be, the more economic activities and opportunities can be increased. However, inequalities of access potentially minimize the total benefits of technology to growth. Chen & Xing (2025), Van Deursen & Van Dijk (2019) point out that while digital tools reshape the economic landscape and provide bridges for development disparities between countries and regions and encourage inclusiveness, unequal access to these technologies may still limit growth. Digital usage coefficients are also negative but significant and show that high expectations of digital platforms can result in lower productivity in physical, erode the traditional economic activities of people and increase risks such as digital addiction such that short-term performance is hampered. Conversely, digital skills do have a positive impact on growth, as a skilled workforce stimulates innovation, productivity and competitiveness. Proficient workers use modern technology to enhance efficiency, to build high-value jobs and to drive deeper engagement in global markets, as direct contributors to GDP growth (Brynjolfsson & McAfee, 2023).

Table 3: Digital access, digital usage and digital skill nexus with trade and GDP

Variables	(Sys. GMM)	(Sys. GMM)
TRD	0.008***	0.008***
	(0.000)	(0.000)
DigDx		-0.480***
		(0.003)
DIGACC	-0.065***	
	(0.014)	
DIGUSG	-0.458***	
	(0.008)	
DIGSK	0.031***	
	(0.004)	
FD	-0.012***	-0.0131***
	(0.000)	(0.000)
CPI	-0.014***	-0.014***
	(0.0002)	(0.000)
FDI	0.011***	0.011***
	(0.001)	(0.000)
EXR	0.0001***	0.0001***
	(0.0001)	(0.0001)
POP	-0.683***	-0.672***
	(0.030)	(0.007)
GOVEXP	-0.191***	-0.184***
	(0.019)	(0.003)
LBF	0.0001***	0.0001***
	(0.0001)	(0.0001)
FCF	0.0871***	0.085***
	(0.002)	(0.000)
L.GDP	0.249***	0.250***
	(0.0007)	(0.000)
Constant	2.301***	2.504***
	(0.0721)	(0.0353)
Observations	911	911
R-squared		
Number of id	105	105
AR1	3.55(0.010)	-3.21(0.001)
AR2	0.49(0.621)	-0.68(0.499)
Sargan test	1295.03(0.000)	1140.18(0.000)

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

Among them, financial development demonstrates a negative significant effect on growth with Belt and Road Initiative countries. Excessive development in the financial area can lead to instability, inefficiencies and pressures of inflation. Another act the knocked up the effects, the consumer price index, also having a negative impact on growth, with high inflation leading to uncertainty, which reduce investment, and consumer, as well as erosive, the purchasing powers of household, reducing overall growth.

Table 4. Interaction effect of digital economy indices and international trade

Variables	Sys. GMM	Sys. GMM
TRD	0.028***	0.015***
	(0.001)	(0.000)
Digdx		-0.000***
		(0.000)
DIGACC	-0.296***	
	(0.039)	
DIGUSG	-0.393***	
	(0.012)	
DIGSK	0.157***	
	(0.009)	
FD	-0.009***	-0.019***
	(0.000)	(0.0002)
CPI	-0.013***	-0.014***
	(0.0003)	(0.000)
FDI	0.011***	0.011***
	(0.000)	(0.000)
EXR	0.0001***	0.000***
	(0.0001)	(0.0001)
POP	-0.487***	-0.924***
	(0.0277)	(0.005)
GOVEXP	-0.194***	-0.161***
	(0.0143)	(0.002)
LBF	0.0001***	0.0001***
	(0.0001)	(0.0001)
FCF	0.094***	0.090***
	(0.00)	(0.001)
DigDx*TRD		-0.008***
		(0.0001)
DIGACC*TRD	0.000	
	(0.0005)	
DIGUS*TRD	-0.0005**	
	(0.0002)	
DIGSK*TRD	-0.001***	
	(0.0001)	
L.GDP	0.247***	0.252***
	(0.000)	(0.000)
Constant	0.0001***	2.364***
	(0.0001)	(0.034)
Observations	911	911
R-squared		
Number of ID	105	105
AR1	-3.21(0.001)	-3.23(0.001)
AR2	-0.69(0.491)	-0.68(0.498)
Sargan test	1138.1(0.000)	1132.0(0.000)

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

The positive and statistically significant impact of FDI on growth is in line with existing literature in that it is these elements of foreign investment - capital, technology, managerial expertise - boost domestic productivity and generate jobs to boost the economy in the long term. Other control variables have a positive impact on FDI Exchange rate Labor Force Fixed formation Population Government expenditure Financial Development has a negative impact on growth.

The finding in Table 4 is very similar to the one in Table 3, except that the interaction terms between digital economy index and international trade are negative and significant. These results show that this positive effect of trade on growth is reduced when the index of the digital economy is higher. A rise in digital economy may have decreased the impact of the trade to the growth through possible reason of digital challenge or inefficiency of the trade cannot overcome. Likewise, the interaction between digital access and trade does not give any considerable results, thus indicating that trade and growth are not also greatly impacted by digital accessibility levels. However, digital use and trade have large negative coefficients. As the use of digital rises, the positive correlation between trade and growth declines, perhaps because the markets are saturated or the resources are inefficiently allocated. Digital skills and trade interactions also demonstrate negative significance so that as digital skills increase, the positive relationship between trade and growth decreases because the digital economy sucks up economic activity, lessening the dependence on traditional trade mechanisms.

Conclusion

Considering 149 developing countries that are a part of the Belt and Road Initiative, this study does look at the associations between digital economy, international trade, and economic growth. Using data coming from 2000-2024 and dynamic panel models, the results show that international trade is a positive and significant contributor to economic growth. In contrast, there is a negative effect for the overall digital economy, which implies that the current digital infrastructure is perhaps a barrier. The nexus between trade and the digital economy puts into perspective the need for policies that bring both trade and digital initiatives together. International trade is also significantly and positively correlated to growth in GDP in all models, strengthening the argument that trade contributes to economic development. However, the digital economy index (DIGDX) shows a surprising negative correlation to GDP growth. This means there is a lack of expected economic benefits from growing digital resources and infrastructure. These results suggest that existing digital frameworks are underused or inadequately integrated into the economy of these countries and are limiting the full potential of trade. Additionally, there are nuanced dynamics between the digital index and trade. For example, digital skills have a positive impact on economic growth in combination with international trade. This highlights the importance of human capital in using digital tools to stimulate development. Without adequate digital skills, the gains from trade may not be fully achieved, representing a high demand for initiatives that enhance digital literacy and capabilities. Based on these findings, we recommend a number of actionable policy steps to look more integrated digital-trade approach: * Governments should invest heavily on digital infrastructure, particularly in rural and underserved regions to provide equal access to digital resources necessary for participation in the global economy. * Expand digital literacy programs across all ages in partnership with institutions of educational technology. * Form public-private partnerships to ensure that training is aligned with labor-market needs to ensure that workers acquire the skills needed to succeed in the digital economy. * Develop and implement regulatory frameworks, which encourage e-Commerce and digital trade while easing cross-border regulations and ensuring data security to establish trust between businesses and consumers. * Incorporate trade policies with digital economies impetus, helping small and medium-sized enterprises to leverage the use of digital trade platforms to enter international markets and enhance competitiveness. * Incentivize research and development in digital technologies that help boost trade efficiency and promote innovation to help countries adapt to the changing global business environment. While this study provides some nice insights, it does have some limitations that should be noted as well. Relying on aggregate data may conceal differences among individual countries, particularly in regard to local digitalization efforts and how well they work. Even in the long run it is impossible to fully capture the effects of fast technological change, or the effect of policy changes. Future research should use more nuanced analyses, potentially with either specific countries or regions in the Belt and Road Initiative in order to uncover local dynamics that influence the impact of the digital economy on trade and growth. Longitudinal studies should try to investigate the causality between digital economy factors and economic growth, which could also involve qualitative methods to build up quantitative findings. Investigating new technologies such as artificial intelligence and blockchain - and the interaction of the two with trade policy - can help deliver more insights into how to optimize the digital economy's contribution to development. Expanding the sample to include non-Belt and Road countries would allow the comparative values to be analyzed and pinpoint the role of different contexts in shaping the relation among digitalization, trade, and growth. In summary, this study underscores that it is important to align digital strategies and policies with trade policies if the goal is to foster economic growth. By addressing the identified challenges, policymakers can better capitalize on the potential of the digital economy and pave the way towards sustainable development. The insights gained from this research, however, can provide a wealth of information not only for academic discussions, but also offer a practical roadmap guide for policymakers as they navigate the complex digital landscape of an increasingly interconnected world.

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RESEARCH ARTICLE

Navigating Growth and Sustainability: Technological Advances, Renewable Energy, and Environmental Quality

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Abstract
The rise in economic growth driven by increased production and industrialization has led to greater energy demand, which in turn has caused higher carbon emissions and a deterioration in environmental quality. Technological innovations aimed at improving energy efficiency, enhancing production efficiency, and utilizing renewable energy in industrial processes offer potential solutions to address environmental degradation. This study investigates the impact of technological innovations, renewable energy consumption, and economic growth on environmental degradation in OECD countries from 1989 to 2024. Using fixed effects and a two-step generalized method of moments, the findings indicate that economic growth and high technology exports negatively impact environmental quality, while patent applications and R&D efforts significantly reduce emissions. The Innovation Claudia curve is confirmed through the squared term of the innovation indicator, although the innovation index itself is found to have a positive impact on carbon emissions. Notably, the study concludes that increasing the adoption of renewable energy sources leads to substantial improvements in environmental quality. These findings have important implications for the governments of the countries studied.

Keywords: Technological innovations; renewable energy consumption; economic growth; Environmental sustainability

Introduction

Economic growth is widely recognized as a key driver of carbon dioxide emissions, particularly in less developed and emerging economies. As economic activities increase, so does energy demand, leading to higher carbon dioxide emissions (Su et al., 2021; Tariq et al., 2017; Mehmood, 2021). Countries pursue economic growth to improve living standards (Esso & Keho, 2016; Deviren & Deviren, 2016), but reliance on nonrenewable energy sources during periods of economic expansion results in increased carbon emissions (Sharma, Shahbaz, Kautish, and Vo, 2021). In contrast, renewable energy is environmentally friendly and plays a crucial role in slowing environmental degradation. However, most nations have yet to achieve the desired level of renewable energy use in economic activities, a critical goal for sustainable development. Both developing and developed countries have acknowledged the need to balance economic growth with environmental quality to ensure sustainable development (Wang et al., 2018). Achieving sustainable development goals can improve living standards, enhance environmental quality, and conserve energy (L. Li et al., 2011). Many countries have designed climate action strategies under the Paris Agreement to promote environmental sustainability but have also recognized the necessity of integrating renewable energy sources and green technological innovations (Florence Twum Appiah, 2021). While renewable energy and energy efficiency can reduce pollution, modern technologies and innovations are essential for improving energy efficiency. Technological advancements can play a pivotal role in reducing environmental degradation (Mensah, Long et al., 2018; Albino, Ardito et al., 2014; Raiser, Naims et al., 2017; Zhang, Peng et al., 2017; Sharma, Shahbaz, 2021). However, a critical gap in the literature exists regarding the dual role of technological advancements. While many studies suggest that technological innovation can improve energy efficiency and reduce emissions, others argue that innovations may, in fact, worsen environmental quality by increasing carbon emissions through industrial activities (Ahmad Khattak et al., 2020; Chien et al., 2021). This contradiction leaves a significant research gap: the complex relationship between technological innovation, renewable energy consumption, and environmental quality remains underexplored. Additionally, there has been limited empirical investigation into the non-linear relationship between technological innovation and carbon emissions, often referred to as the "Innovation Claudia Curve." This theory posits that technological advancements may initially increase emissions but eventually reduce them once a critical level of innovation is reached, yet empirical evidence for this curve, particularly in OECD countries, is scarce.

To address these gaps, the present study investigates the impact of technological innovations, renewable energy consumption, and economic growth on carbon dioxide emissions in OECD countries from 1989 to 2024. The research seeks to answer several key questions: Do technological advancements contribute to higher CO2 emissions? Is there a non-linear relationship between technological innovation and CO2 emissions? What factors lead to improvements in environmental quality? This study also aims to identify weak indicators of technological innovation in relation to environmental improvement and provides insights into how technological advancements can be leveraged to improve energy efficiency, increase the adoption of renewable energy, and enhance environmental quality.By examining the individual effects of technological innovation, renewable energy adoption, and economic growth, this study offers a nuanced understanding of the environmental impacts of technological progress. It extends the current literature by empirically validating the Innovation Claudia Curve and providing policy implications to help both developing and developed countries achieve their sustainable development goals. The remainder of this study is organized as follows: Section 2 reviews the relevant literature, Section 3 presents the research methodology, Section 4 discusses the results, and Section 5 concludes with policy implications.

Literature review

Although the majority of researchers, such as Raiser et al. (2017) and Y.-J. Zhang et al. (2017), argue that technological innovation positively influences environmental quality, past research has produced mixed findings regarding its impact. Despite the general consensus on the benefits of technological innovation, a clear understanding has yet to emerge due to variations in proxies for innovation, methods, data samples, and other factors, leading to contradictory results. For instance, Shan, Genc, Kamran, and Dinca (2021) examined the role of innovation and renewable energy in Turkey's carbon neutrality efforts using the STIRPAT model on data from 1990 to 2018. Their results indicated that while economic growth, population expansion, and energy consumption negatively affected environmental quality, increased innovation and renewable energy usage helped reduce carbon dioxide emissions. In a similar study, Suki, Sharif, Afshan, and Jermsittiparsert (2022) analyzed the relationship between renewable energy technology and carbon emissions in Malaysia, employing the BARDL model. They found that technological development contributed to a significant reduction in carbon emissions, thus improving environmental quality.

Similarly, Bilal, Li, and colleagues (2022) explored the relationship between green technology innovation, globalization, and carbon emissions in Belt and Road Initiative countries, using data from 1991 to 2019. They discovered a negative correlation between carbon emissions and technological innovation across South Asia, Southeast Asia, West Asia, Central and European countries, and North Africa, showing a consistent reduction in emissions due to technological advancements. Cheng, Sinha, and others (2021) analyzed data from 48 countries between 1971 and 2015 to investigate the link between technological innovation and economic growth. They found that the relationship between economic growth, financial innovation, and overall innovation varies across income levels and periods studied. This highlights the dynamic and context-dependent nature of technological advancements. Further evidence was provided by Abid, Mehmood, Tariq, and Haq (2021), who explored the connections between carbon emissions, energy use, and technological innovation in G8 countries between 1990 and 2019. Using FMOLS models, they demonstrated a negative relationship between technological innovation and carbon emissions, showing that innovation reduces emissions over time. Their research also highlighted how urbanization negatively affects environmental quality. Mikiewicz (2021) investigated the impact of innovation and technological advancements on emissions in Visegrad Group countries from 2000 to 2019, employing DOLS and FMOLS models. Their findings indicated that patents and R&D activities contributed to slowing the release of carbon dioxide. Similarly, Chen et al. (2020) examined the transportation sector in China and found that technological advancements initially increased emissions but ultimately contributed to sustainable growth.

In contrast, Dauda, Long, Mensah, and Salman (2019) examined the relationship between carbon emissions, technological innovation, and economic growth in developed and developing nations from 1990 to 2016. They found that while technological advancements reduced emissions in G6 countries, they increased emissions in MENA and BRICS nations. Their study also suggested that higher energy consumption universally leads to higher carbon emissions and a decline in environmental quality. The role of foreign direct investment (FDI) in environmental degradation has also yielded mixed results. Zafar, Shahbaz, and others (2020) analyzed the impact of FDI, education, and renewable energy use on environmental quality in OECD countries between 1990 and 2015. They found that while FDI and natural resource extraction were linked to higher emissions, increasing education and renewable energy use improved environmental outcomes. In China, Li and Wei (2021) investigated the relationship between innovation, economic growth, and carbon emissions from 1987 to 2017. Using panel models, they identified a nonlinear relationship between these variables, with significant differences across regions. Their findings were echoed by Fan and Hossain (2018), who explored the long-term effects of technology and economic growth on carbon emissions in China and India from 1974 to 2016. They discovered that while carbon emissions and technological advancements positively correlated with economic growth over the long term, the short-term effects were less consistent. Finally, Niu (2021) examined the relationship between technological innovation and carbon emissions in 30 Chinese provinces from 2009 to 2018, using fixed-effect models. The study found that increased technological innovation led to sustainable growth in China, highlighting the potential of innovation to reduce carbon emissions in developing economies. These studies demonstrate the complex and sometimes conflicting relationship between technological innovation and environmental quality, underscoring the need for further research. The variations in findings across regions and methodologies indicate that while innovation has the potential to reduce emissions, its effectiveness is context-specific and may be influenced by other factors such as economic growth, energy consumption, and policy environments.

The existing literature on the relationship between technological innovation, renewable energy consumption, and environmental quality presents both extensive findings and significant inconsistencies. While many studies, such as those by Raiser et al. (2017) and Y.-J. Zhang et al. (2017), argue that technological innovation positively influences environmental quality, other research shows contradictory results, particularly in different regions and at various stages of economic and technological development. Despite the growing body of work, the exact mechanisms through which technological innovation affects carbon emissions remain unclear, especially when considering the role of renewable energy and foreign direct investment (FDI) in both developed and developing nations. A key gap in the literature is the lack of consensus on the nonlinear effects of technological innovation on carbon emissions. Some studies suggest that early-stage innovations may increase emissions before achieving long-term reductions, while others find more immediate positive impacts. This highlights the need for further empirical validation of concepts like the Innovation Claudia Curve, particularly in different regional contexts, such as OECD, Belt and Road Initiative countries, and rapidly industrializing economies like China and India. Moreover, existing research often uses a variety of proxies for innovation and different econometric models, making cross-comparisons difficult. The heterogeneity of findings across countries such as the differing impacts of technological advancements in G6 versus BRICS nations further underscores the necessity for a standardized approach to analyzing these relationships. Another underexplored area is the interplay between technological innovation, renewable energy use, and FDI in driving environmental quality improvements. While some studies suggest FDI and innovation together can reduce emissions, others indicate that without stringent environmental regulations, FDI may exacerbate pollution, particularly in developing countries. Finally, recent studies (e.g., Gomez and Santos, 2023; Kumar et al., 2024) have shown that the impacts of technological innovations differ depending on a country's stage of development and policy environment, yet few studies have fully investigated how these contextual factors influence the effectiveness of green technologies. The role of innovation in emerging economies, particularly in regions like Southeast Asia and Sub-Saharan Africa, remains underexplored, leaving a gap in understanding how these economies can leverage innovation for sustainable development.

This study aims to address these gaps by empirically examining the nonlinear relationship between technological innovation, renewable energy consumption, economic growth, and environmental degradation. It will also investigate the influence of FDI on carbon emissions and the role of policy frameworks in moderating the effects of technological innovations on environmental sustainability in various regions, including OECD countries and emerging economies. By standardizing the analysis and utilizing recent data (1989-2024), this study will provide a more comprehensive understanding of how technological innovation interacts with economic and environmental variables across different contexts.

Methodology

The primary aim of this study is to examine the influence of technological innovations, renewable energy consumption, and economic growth on carbon dioxide emissions in OECD countries over the period 1989 to 2024. The data for all variables were sourced from the World Bank's World Development Indicators database. Prior to conducting the formal analysis, the stationarity of the data was verified. This preliminary check ensures that the data is suitable for further analysis. To test for stationarity, second-generation panel unit root tests were employed. Specifically, the CIPS and CADF tests were used, which assume that each series across cross-sections is independently distributed. These tests rely on cross-sectional delay mean values and a first-difference series to enhance the ADF regression. By addressing cross-sectional correlations, these tests help eliminate common factors across the panels and establish the null hypothesis of homogeneity within each region, allowing for the consideration of both regional and national variations in the analysis.

Once the data were confirmed to be stationary, the researchers applied both fixed effect and two-step system GMM models. The fixed effect model serves as a baseline for comparison, while the two-step system GMM model is the primary focus due to its superior ability to provide accurate results. The GMM model is widely regarded as an effective approach for handling panel data, as noted by Weili, Khan, and Han (2022). Static models, such as the fixed effect model, are prone to several econometric issues, particularly when the error term correlates with both the explanatory and dependent variables. This can result in inefficient, unreliable, and biased estimates. Additionally, the instruments used in the fixed effect model's IV estimator may exacerbate these inefficiencies.

The GMM estimator addresses these challenges, offering two subcategories: the difference GMM and the system GMM models. The difference GMM model eliminates country-specific effects by taking the first difference between dependent and independent variables, while instrumenting the lagged dependent variable with prior levels. This approach corrects for autocorrelation; however, the use of lag levels as instruments in the first difference can reduce the model's efficiency. To overcome this, Arellano and Bover (1995) and Blundell and Bond (1998) developed the system GMM estimator, which improves the overall performance of the model.

The key distinction between the difference GMM and system GMM models lies in their structure. The system GMM incorporates two equations: a level equation and a difference equation. As demonstrated by Kurul (2021), the second equation uses the first-order difference of the variables, while the lagged levels are used in the first equation. This two-equation approach enhances the efficiency of the system GMM model, making it more effective than the difference GMM model in many cases. Arellano and Bover (1995) and Blundell and Bond (1998) found that the system GMM is particularly advantageous when applied to panel data with a short time dimension (T) and a large number of countries (N). This makes the system GMM well-suited for this study's dataset, which spans multiple countries over several decades.

Although both fixed effect and two-step system GMM models are employed in this study, the primary emphasis is on the system GMM model, as it is expected to yield the most accurate and reliable results.

This study investigates the effect of economic growth, technological innovations and renewable energy consumption on carbon dioxide (CO2) that is released into the atmosphere. The study's baseline model is presented as follows;

$$CO2_{it} = \beta_0 + \beta_1 CO2_{it-1} + \beta_2 TIV_{it} + \beta_3 GDP_{it} + \beta_4 RE_{it} + \beta_5 TR_{it} + \beta_6 UP_{it} + \varepsilon_{it} \quad (1)$$

In this equation, CO2 represents environmental degradation, measured in metric tons per capita, and serves as the dependent variable. The first lag of CO2 emissions, denoted as CO2_(it-1), explains how the emissions from the previous year affect the current year's emissions. Carbon dioxide (CO2), a greenhouse gas, is a primary driver of this effect. Technological innovation is represented by the symbol TIV, which uses four key indicators as proxies: high technology exports, patents held by non-residents, patents held by residents, and research and development expenditure. Recent studies by Wusiman & Ndzembanteh (2020), Knott & Vieregger (2018), Maradana et al. (2017), and Coluccia et al. (2019) have utilized these indicators. Dangelico and Pujari (2010) suggest that technological innovation may positively affect environmental quality, and that stringent environmental policies promoting innovation could further enhance this. Similarly, Wang, Yang, Zhang, and Yin (2012) proposed that technological advancements can explain variations in CO2 levels. They also argued that effective pollution management boosts a nation's innovation capacity and competitiveness in the global market. Wajahat Ali (2020) supports this view, stating that technological advancements benefit both the economy and the environment by creating cleaner environments and fostering economic growth.

Previous studies have consistently found that economic growth leads to increased CO2 emissions and a decline in environmental quality, suggesting a direct correlation between growth and environmental degradation.

According to Apergis & Li (2016), Krueger & Grossman (1995), and Bai et al. (2020), a nation's per capita income is a key determinant of its emissions levels. These studies were conducted in 2016, and they highlight the importance of GDP per capita as a factor influencing CO2 emissions. The Environmental Kuznets Curve (EKC) hypothesis, which is often illustrated by including the squared term of GDP per capita as the dependent variable, explains this relationship. According to the EKC, in the early stages of economic development, growth is associated with increased emissions. However, as a country reaches a certain development threshold, economic growth begins to reduce emissions. This theory, named after the environmental economist Kuznets, was developed to explain the nonlinear relationship between economic growth and environmental impact. Building on this foundation, the current study employs the quadratic function of economic growth to analyze the nonlinear impact of per capita GDP on CO2 emissions.

Researchers argue that the use of fossil fuels for electricity generation negatively impacts environmental quality due to the increased CO2 emissions, whereas the use of renewable energy sources is expected to lower these emissions. "RE" refers to renewable energy consumption. Khan and his team (2021) suggest that renewable energy generation can benefit from advancements in technological innovation.

This model also accounts for the impact of international trade on carbon emissions. Antweiler, Copeland, and Taylor (2001) found that trade's effects on environmental quality can be positive or negative, depending on factors such as the composition, scale, technology, and techniques used in trade. The "scale effect" refers to environmental degradation that results from the expansion of a nation's economy and increased openness to trade. This is commonly referred to as an externalization effect. The "technical effect," on the other hand, refers to the comparative advantage that global specialization provides businesses, even in environmentally damaging industries. Trade can also have a positive influence on environmental quality by encouraging better environmental practices and technological upgrades, thereby improving a country's overall environmental standards.

Similarly, UP represents urban population, and it is generally accepted that as the urban population grows, CO2 emissions increase. Population growth leads to greater demand for resources such as food and energy, which in turn drives up emissions. Li, Fang, and He (2019) highlight the role of urbanization in facilitating the transition from rural to urban areas, as well as from agricultural economies to industrial economies. Urbanization accelerates emissions growth due to increased population density, higher living standards, and industrialization. Solarin and Lean (2016) argue that the population agglomeration resulting from urbanization helps achieve economies of scale and improves energy efficiency. However, earlier studies (Nguyen et al., 2018; Canh, 2019; Ghisellini & Ulgiati, 2020; H. Khan, Weili, & Khan 2022) have demonstrated that urbanization significantly contributes to increased emissions.

The next step in this research involves analyzing the nonlinear relationship between technological progression and CO2 emissions. The study assumes a nonlinear association between technological development and environmental conditions. To capture this relationship, the term "innovation squared" is employed, allowing the analysis to examine the earlier stages of technological innovation, which may initially lead to higher emissions due to limited accessibility, and the later stages, where innovations reduce emissions through increased patenting and technological dissemination. This approach tests the Claudia Curve of Innovation. The model suggested by Li et al. (2018) forms the basis of this analysis.

The equation is structured as follows:

$$CO2_{it} = \beta_0 + \beta_1 CO2_{it-1} + \beta_2 INV_{it} + \beta_3 (TIV)^2_{it} + \beta_4 GDP_{it} + \beta_5 RE_{it} + \beta_6 TR_{it} + \beta_7 UP_{it} + \varepsilon_{it} \quad (2)$$

The variables are described in table 1, the descriptive statistics is given in table 2 while the correlation is given in table 3.

Table 1: Description of variables

Variables Description	Symbols
Carbon dioxide emission metric tons per capita	CO2
Research and development expenditure	RD
Patent application residents	PAR
Patent application nonresidents	PANR
High technology exports	TEXP
Per capita gross domestic product	GDP
Renewable energy consumption % of total final energy consumption	RE
Trade % GDP	TR
Population % of total population	POP

Table 2: Descriptive statistics

Variable	Mean	Std. Dev.	Min	Max
CO2	8.365	4.567	0.920	30.43
RD	1.693	1.027	0.129	4.95
PAR	20689.78	64956.3	8.00	384
PANR	10914.9	35650.92	1.00	336
TEXP	16.23	8.439	1.857	60.71
GDP	2.178	3.117	-14.26	23.99
RE	17.507	15.572	.441	77.344
TR	86.320	52.605	16.01	408.36
POP	48.95	.970	45.789	50.52

Table. 3 Correlation matrix

Variables	CO2	RD	PAR	PANR	TEXT	GDPPC	RE	TR	POP
CO2	1.000								
RD	0.413	1.000							
PAR	0.130	0.281	1.000						
PANR	0.272	0.251	0.872	1.000					
TEXP	-0.041	0.153	0.057	0.090	1.000				
GDP	-0.114	-0.213	-0.009	-0.005	-0.042	1.000			
RE	-0.319	0.027	-0.226	-0.301	0.218	-0.008	1.000		
TR	0.292	-0.109	-0.254	-0.372	-0.092	0.075	-0.171	1.000	
POP	0.111	0.308	0.018	0.108	0.291	-0.169	0.163	-0.249	1.000

Results and discussions

Results

In the initial phase of the process, the stationarity of the variables was analyzed using second-generation unit root tests, specifically the CIPS and CADF tests. These tests assume that the series within the panel are independently distributed across cross-sections. To enhance the ADF regression, these tests rely on the mean value of cross-sectional lag as well as the single series representing the first difference. This approach is utilized to analyze the data more effectively. Cross-sectional correlation helps eliminate common factors and ensures that the null hypothesis of homogeneity is established for each region within every panel. By considering various alternatives, the analysis can account for both local and national differences. At both the level and the first-difference level, all variables exhibit stationarity. After confirming stationarity, the investigation proceeds with the application of econometric models and formal analysis. The findings of the panel unit root tests are presented in Table 4.

Table 4: Panel unit root tests

	CIPS		CADF	
Variables	I(0)	I(1)	I(0)	I(1)
CO2	-2.050	-5.011***	-2.064	-3.719***
RD	-1.111	-3.297***	-1.473	-2.503***
PAR	-2.233*	-4.826***	-2.181**	-3.746***
PANR	-2.778***	-4.794***	-2.595***	-3.541***
TEXP	-2.242**	-3.935***	-2.531	-3.284***
GDP	-4.028 ***	-5.679***	-3.307***	-4.600***
RE	-2.169	-4.836***	-1.982	-3.553***
TR	-1.947	-3.931***	-2.447***	-3.423***
POP	-1.020	-0.741***	-3.994***	-4.952***

Note: **, *** shows significance level at 5 percent and 1 percent respectively

The results of the fixed effect model are displayed in Table 5, which presents the tabular data. As discussed in the methodology section, the primary focus of this investigation is the two-step system GMM, as it is widely considered by experts to be the most accurate estimator available. For clarity, the variables are listed in the first column of Table 5. The innovation indicators—RD (research and development), PAR (patent applications by residents), TEXP (high-tech exports), and PANR (patent applications by non-residents)—are used in the model and presented in columns 2 through 4. PANR is also incorporated into the model. Similarly, each innovation indicator is integrated into the same model, with the results summarized in column 6.

The findings show that the estimated coefficient for per capita economic growth is statistically significant and positive in absolute terms, indicating that higher per capita economic growth is associated with greater environmental degradation and higher carbon dioxide emissions. This suggests that economic growth contributes to the increase in CO2 emissions. Additionally, the data indicate that greater use of renewable energy sources leads to an improvement in overall environmental quality, as renewable energy consumption has a negative effect on CO2 emissions.

Furthermore, the coefficient for urban population is also significant and negative, implying that an increase in the urban population leads to a reduction in CO2 emissions in the sample countries. This conclusion is supported by the substantial weight of the urban population coefficient. Lastly, each individual indicator of technological innovation significantly contributes to the overall increase in carbon dioxide emissions, as reflected by the positive and significant coefficients of the innovation indicators.

Table 6 summarizes the findings obtained using the two-step system GMM across models 1 through 6. The models incorporate variables such as R&D spending, patent applications by residents, high-tech exports, patent applications by non-residents, and an innovation index. In Model 1, shown in column 2, the focus is on the impact of research and development (R&D) on carbon dioxide emissions, along with other key variables. The estimated economic growth coefficient is positive and significantly different from zero, indicating that increased economic activity is associated with higher carbon emissions. Specifically, the results suggest that a 1% increase in economic growth leads to a 0.005 percentage point rise in carbon dioxide emissions. Population growth also produces positive and significant coefficients, while renewable energy usage yields negative coefficients. In contrast, commercial activity has little discernible impact on CO2 emissions. The first innovation indicator, R&D, exhibits a significant negative coefficient, demonstrating that increased investment in research and development leads to a substantial reduction in carbon emissions. A 1% increase in R&D spending results in a 0.04 percentage point decrease in CO2 emissions in the studied countries. These findings align with recent research by Martinez et al. (2024) and Zhao et al. (2023), further reinforcing the idea that investments in R&D improve environmental quality by reducing emissions.

The results of Model 2 are presented in column 3 of the table. Here, the estimated coefficient for economic growth remains positive and significantly different from zero, further supporting the link between economic expansion and higher carbon emissions. In this model, the effects of population growth and renewable energy are not particularly emphasized. However, the impact of global trade, both positive and negative, is considered. The PAR indicator, representing patents by residents, generates a negative but statistically insignificant coefficient, suggesting that resident patent activity has a negligible effect on total carbon emissions, a finding consistent with Ahmed and Fischer (2023).

Table 5: The effect of technology innovations and economic growth and renewable energy consumption on carbon dioxide emission

	Model-1	Model-2	Model-3	Model-4	Model-5
GDP	0.010**	0.009**	0.015***	0.009**	0.013**
	(0.004)	(0.004)	(0.005)	(0.004)	(0.005)
RE	-0.211***	-0.194***	-0.222***	-0.194***	-0.202***
	(0.016)	(0.016)	(0.026)	(0.016)	(0.029)
TR	-0.068	-0.086**	0.0292	-0.060	0.044
	(0.043)	(0.038)	(0.081)	(0.041)	(0.089)
POP	-2.628*	-2.836*	-6.724***	-4.131***	-3.363*
	(1.437)	(1.491)	(2.461)	(1.438)	(2.995)
RD	0.014*				-0.056
	(0.028)				(0.047)
PAR		0.046***			0.041
		(0.015)			(0.030)
TEXP			0.051**		0.065**
			(0.024)		(0.026)
PANR				0.004**	0.027**
				(0.005)	(0.013)
Constant	12.96**	13.59**	27.83***	18.78***	14.40**
	(5.584)	(5.804)	(9.578)	(5.585)	(11.67)
Observations	329	358	189	358	171
R-squared	0.542	0.521	0.490	0.509	0.468
Number of id	33	32	32	32	31

Note: Standard errors are shown in parentheses where the significance level is *** p<0.01, ** p<0.05, * p<0.1

Model 3 replaces the innovation variable with TEXP, representing high-tech exports. The results show that while renewable energy use continues to have a negative effect on CO2 emissions, the impact of other factors remains relatively insignificant. Economic growth again positively influences CO2 emissions, and the high-tech export indicator shows a significant and positive relationship with carbon emissions. This suggests that high-tech exports, as an innovation indicator, contribute notably to increased carbon dioxide levels. Similar conclusions were drawn in recent studies by Kumar et al. (2024), who found that technological advancements through exports often lead to increased industrial emissions.

In Model 4, the variable PANR (patents by non-residents) is used to assess its influence on carbon emissions. The results show that patent applications by non-residents significantly reduce greenhouse gas emissions, indicating that innovations from abroad have a notable impact on lowering CO2 levels. Meanwhile, economic growth continues to correlate positively with CO2 emissions, while renewable energy usage is associated with lower emissions, improving environmental quality. These findings are consistent with Gomez and Santos (2023), who demonstrated that foreign innovation can drive reductions in emissions in emerging markets.

Table 6: Two step system GMM results

Variables	Model-1	Model-2	Model-3	Model-4	Model-5	Model-6
GDP	0.005***	0.006***	0.006***	0.006***	0.001***	-0.001**
	(0.000)	(0.000)	(0.001)	(0.000)	(0.000)	(0.000)
RE	-0.028**	-0.033**	-0.065*	-0.028*	-0.304***	-0.227***
	(0.021)	(0.034)	(0.043)	(0.033)	(0.0226)	(0.028)
TR	4.060	-0.000*	7.400	-0.000	0.001***	0.331***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.007)
POP	0.084**	-0.384	1.071	-1.053	0.772***	0.001**
	(0.037)	(4.387)	(2.719)	(4.716)	(0.025)	(0.001)
RD	-0.040*				-0.084***	
	(0.021)				(0.025)	
PAR		-9.090			1.140	
		(1.540)			(8.570)	
TEXP			0.001*		0.003**	
			(0.001)		(0.001)	
PANR				-1.150*	-1.770**	
				(4.370)	(7.510)	
TIV						0.001***
						0.010
TIV^2						-1.195***
						(0.209)
L.CO2	0.887***	0.847***	0.773***	0.855***	0.001***	0.001***
	(0.0540)	(0.0795)	(0.102)	(0.0779)	(0.002)	(0.001)
Constant	0.0001***	1.960	-3.561	4.474	0.0001***	0.0001***
	(0.0001)	(17.07)	(10.65)	(18.35)	(0.0001)	(0.0001)
Observations	404	442	251	442	225	225
Number of id	33	32	32	32	31	31
AR2	-1.11	-1.30	-0.96	-1.33	-2.48	-1.03
	(0.266)	(0.195)	(0.335)	(0.184)	(0.013)	(0.019)
Sargan test	333.55	386.41	200.69	387.85	172.40	122.06
	(0.987)	(0.944)	(0.969)	(0.937)	(0.953)	((0.583)

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

Model 5 combines all four innovation indicators into a single model. The results show that economic growth continues to contribute to increased carbon emissions, aligning with previous models. The coefficient for renewable energy remains negative, underscoring that greater use of renewable energy sources leads to lower CO2 emissions. Both population growth and trade openness exhibit positive effects on carbon emissions. In this model, innovation indicators—both non-resident patents (PANR) and private sector R&D—show significant negative values, highlighting their role in reducing carbon emissions. In contrast, high-tech exports continue to have a positive and significant effect, contributing to increased carbon emissions. The coefficient for resident patent applications remains insignificant, having no discernible impact on emissions.

Finally, Model 6, presented in the last column, utilizes an innovation index constructed using principal components analysis, incorporating all four innovation indicators. The model indicates that renewable energy consumption has a significantly negative coefficient, suggesting that higher renewable energy use leads to lower CO2 emissions. Interestingly, this model also shows that increased economic growth can have a negative impact on emissions, contrary to earlier findings, implying that higher economic development may eventually lead to improved environmental quality through better resource utilization. However, the innovation index itself shows a positive coefficient, indicating that technological innovation, in its early stages, may contribute to environmental degradation by increasing carbon emissions. This aligns with the findings of Su et al. (2024), who identified similar trends in industrialized countries. Additionally, the square term of technological innovation yields a negative coefficient, suggesting the existence of an Innovation Claudia Curve, where initial increases in innovation contribute to higher emissions, but beyond a certain threshold, innovation starts to reduce emissions.

Overall, these findings reveal the complex and nuanced effects of technological innovation, economic growth, and renewable energy on carbon dioxide emissions, providing valuable insights for policymakers aiming to balance growth and sustainability.

Discussions

The findings from this study suggest that economic growth in the analyzed countries is closely linked to an increase in carbon dioxide (CO2) emissions. This can primarily be attributed to the reliance on fossil fuels for production, industrialization, and various other economic activities, which lead to greater energy demand and consumption. As a result, higher levels of carbon emissions are inevitable. This growing discharge of carbon significantly deteriorates environmental quality, highlighting the dilemma that many nations face: striving for economic growth while simultaneously contributing to environmental degradation. The core of many countries' strategies for improving living standards focuses on economic growth, but this focus often comes at the cost of worsening environmental conditions. This outcome is exacerbated by the fact that most countries have not yet achieved the desired level of renewable energy use in their production and industrial processes to mitigate pollution. The analysis also reveals that renewable energy plays a critical role in improving environmental quality and reducing CO2 emissions. Countries that actively promote and invest in renewable energy stand to significantly enhance their environmental standards. Renewable energy sources can be integrated into economic activities such as production and industrialization while maintaining growth, ultimately contributing to a reduction in pollution and fostering sustainable, long-term economic development. This finding is consistent with studies by Khoshnevis Yazdi and Shakouri (2017) and Zoundi (2017), both of which have shown that economic growth, in the absence of sufficient renewable energy adoption, exacerbates environmental degradation. The results of our sixth model provide further insight into this dynamic: while the innovation index shows a negative coefficient, suggesting a mitigating effect on emissions, economic growth continues to exhibit a positive coefficient. This could be explained by the comprehensive nature of the innovation index, which aggregates several indicators, compared to other models focusing on a single factor, thereby suggesting that economic growth alone still drives CO2 emissions upward.

The presence of improved technological innovations alongside economic growth appears to play a dual role. Although innovation is vital for improving environmental quality through enhanced energy efficiency and facilitating access to renewable energy sources, the negative effect implies that economic growth can still negatively affect carbon emissions even when technological advancements are in place. This underscores the complexity of balancing economic expansion with environmental sustainability, particularly when innovations have not yet reached their full potential. The impact of renewable energy is more pronounced in the later models, where it significantly reduces CO2 emissions. This reaffirms that renewable energy use is instrumental in lowering emissions across the countries studied. The results from both the innovation index model and the combined indicator models indicate that renewable energy substantially contributes to reducing carbon emissions, reinforcing the notion that technological advancements in renewable energy are essential for environmental sustainability.

The relationship between renewable energy and innovation is further evidenced by the fact that recent technological advancements have expanded the variety and efficiency of renewable energy sources. Substituting non-renewable energy with renewable alternatives in economic sectors such as production and industrialization will enhance environmental quality, although continued innovation will be necessary to increase the share of energy generated from renewable sources. These findings align with those of Zhang et al. (2017) and Khan et al. (2021), who demonstrated that the use of renewable energy directly correlates with a reduction in CO2 emissions and an improvement in environmental quality. Their research emphasizes that expanding renewable energy use not only mitigates emissions but also enhances overall environmental conditions. A notable exception in our findings is R&D expenditure, which has a significant negative impact on CO2 emissions, suggesting that investments in research and development are pivotal in reducing emissions. However, other innovation indicators, along with the innovation index, have a positive impact on emissions, indicating that innovation, particularly in its early stages, may contribute to increased carbon emissions. This could reflect the relatively low rates of technological innovation across the sample countries. To mitigate this, nations can enhance their innovative capacities by integrating advanced technologies and fostering international collaboration to acquire cutting-edge innovations. By doing so, technological advancements can improve energy efficiency, thereby reducing overall energy consumption and its associated emissions.

Although renewable energy use is growing, which is beneficial for the environment, the early stages of innovation seem to increase CO2 emissions. This phenomenon is reflected in the squared innovation coefficient, which produces a negative value, signaling that once innovations reach a certain level of maturity, they begin to lower emissions. This finding supports the establishment of the Claudia Curve for innovation, which posits that technological advancements in their initial phases may raise emissions due to increased production and industrialization, but as technology matures and knowledge spillover occurs, emissions begin to decline.

The results suggest that countries need to prioritize improving technological innovation to enhance energy efficiency and incorporate more renewable energy sources into their economic activities. As innovations progress into later stages, they will contribute to reduced CO2 emissions, foster economic growth, and promote cleaner, more sustainable economic practices. This will lead to a significant improvement in environmental quality, especially as innovations transition from merely increasing production to actively reducing pollution. The research underscores the importance of advancing technological innovation and renewable energy to achieve the dual goals of economic growth and environmental sustainability.

Conclusion

This paper explores the factors influencing environmental quality in OECD countries, focusing on the roles of technological innovation, economic growth, and renewable energy consumption. The analysis covers data from 1989 to 2024, sourced from the World Bank's development indicators. The study begins by investigating the stationarity of the data using second-generation unit root tests. Once the stationarity of the variables was confirmed, the formal analysis was conducted using fixed effects and two-step system GMM models. The findings indicate that economic growth is closely associated with higher carbon dioxide (CO2) emissions, while technological innovation plays a complex role in emissions reduction. Specifically, renewable energy consumption is shown to mitigate CO2 emissions, thereby offsetting some of the negative effects of urbanization and international trade on the environment. However, except for research and development (R&D), the individual innovation indicators and the overall innovation index have a positive impact on emissions, which initially increases CO2 levels. Notably, the negative square term of innovations validates the Innovation Claudia Curve for the sample countries. According to the Claudia Curve, early-stage technological innovations tend to increase emissions due to limited accessibility and initial inefficiencies. As these technologies become more widespread through patenting and knowledge spillover, emissions gradually decrease, leading to long-term environmental improvements. Despite the potential benefits of technological innovation, the findings suggest that innovation in the sample countries has not yet reached a stage where it can significantly reduce emissions. The positive effects of economic growth on CO2 emissions further emphasize that economic expansion, driven by traditional industrialization and fossil fuel consumption, continues to degrade environmental quality. This is compounded by the relatively low levels of renewable energy use in industrial production and other economic activities. Countries in the sample have yet to fully harness the potential of renewable energy to counterbalance the adverse effects of economic growth on the environment.

To address the environmental challenges posed by economic growth, policymakers should prioritize enhancing technological innovation, particularly in energy efficiency and renewable energy technologies. Governments need to create incentives for increasing investments in R&D, especially in sectors related to clean energy and sustainable industrial practices. As shown in the results, higher R&D spending contributes to lower emissions, suggesting that increased public and private sector investment in research could significantly improve environmental quality. Additionally, governments must formulate policies that promote the wider adoption of renewable energy across all economic sectors. This can be achieved through subsidies for renewable energy projects, tax incentives for companies that adopt clean energy technologies, and stricter environmental regulations that encourage a transition away from fossil fuels. By advancing renewable energy use and innovation, countries can achieve long-term sustainable growth without sacrificing environmental quality. Furthermore, international cooperation on technological innovation and knowledge sharing should be encouraged. Since innovation spillovers can play a critical role in reducing emissions, collaborative efforts between countries to share best practices in renewable energy and eco-friendly technologies are essential. Joint R&D projects and technology transfer initiatives could expedite the global shift toward cleaner energy sources and industrial practices.

This study, however, is not without limitations. One primary constraint is the sample size, which is restricted to OECD countries. While this focus provides insights into the role of economic growth, innovation, and renewable energy in developed nations, it limits the generalizability of the findings to other regions, particularly developing and emerging economies where different factors may influence environmental quality. Additionally, the study uses a limited set of variables, focusing on economic growth, technological innovation, and renewable energy, without considering other potentially influential factors such as institutional quality, government policy frameworks, and social factors like education and public awareness. Another limitation is the methodology employed, as the study primarily relies on fixed effects and system GMM models. While these models are robust in addressing certain econometric issues, they may not fully capture the dynamic and non-linear relationships between innovation and environmental quality. The analysis could be expanded to include more advanced econometric techniques to better understand these complex interactions.

Future research should broaden the scope by incorporating additional variables and employing a wider range of econometric methodologies. For example, future studies could examine the role of institutional quality, government regulations, and international trade agreements on the effectiveness of technological innovations in reducing carbon emissions. Additionally, investigating how social factors such as education and public engagement with environmental issues influence the adoption of clean technologies could provide valuable insights for policymakers. Researchers could also expand the geographical scope to include developing countries, where the relationship between economic growth, innovation, and environmental degradation may differ from that of OECD nations. Developing economies face unique challenges, such as limited access to advanced technologies and differing levels of industrialization, which could offer a more nuanced understanding of the global efforts to combat climate change. Finally, future studies could explore the potential for a global innovation spillover effect, examining how technological advancements in one region impact environmental quality in others. This could provide crucial insights into how international collaboration and technology transfer can accelerate the transition to a greener global economy.

In conclusion, this study highlights the complex relationship between economic growth, technological innovation, and environmental quality in OECD countries. While economic growth continues to drive higher CO2 emissions, technological innovations—particularly in renewable energy—have the potential to reverse this trend over time. However, the current level of innovation in the sample countries is not yet sufficient to counteract the environmental degradation caused by traditional economic activities. As countries continue to invest in technological advancements and renewable energy sources, they can mitigate the negative environmental impacts of economic growth, leading to more sustainable development in the future. Policymakers must take immediate action to promote renewable energy and innovation, supported by international cooperation and stronger regulations, to ensure that economic growth no longer comes at the cost of the environment. The transition to a greener economy requires not just technological progress but also a comprehensive policy framework that aligns economic objectives with environmental sustainability.

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