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Dottorando

Khursheed Muhammad Aqib

Tutor

Prof.ssa Verna Ida

Coordinatore

Prof. IANNI LUCA

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DEDICATION

This thesis is dedicated to my respected supervisor, loving parents, siblings, family members, and friends

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Abstract

Public administration is undergoing rapid transformation driven by growing demands for transparency, efficiency, and sustainable development. Governments must now demonstrate not only operational effectiveness but also the ability to innovate and deliver public services. The objective of this thesis is to examine how governance performance can be improved through management control systems, digital transformation, and sustainability-oriented public policies. It focuses on two main areas: (i) the use of Total Quality Management tools, QFD, and the PDCA framework to enhance teaching, learning, and institutional decision-making in higher education, and (ii) the role of digitalization, e-government, and government expenditure in promoting environmental quality and sustainable development across EU countries. Therefore, this thesis is structured into four chapters within the field of Public Administration. The first two chapters focus on governance performance and management in higher education. In comparison, the other two chapters explore digital transformation in public administration, addressing key challenges and developments related to governance and digitalization. The thesis comprises four peer-reviewed publications, with the first chapter providing a comprehensive overview of the study and its underlying themes. The second chapter is a systematic literature review of the application of Total Quality Management (TQM) and Quality Function Deployment (QFD) in higher education. This review highlights current research trends, leading themes, and the theoretical underpinnings of contemporary research. The Results provide a well-informed, theoretical understanding of how QFD enhances the teaching-learning process, while also outlining key gaps and future research directions. The third chapter is a bibliometric analysis of the integration of the Plan-Do-Check-Act (PDCA) framework into the teaching learning process to enhance TQM in higher education. This section assesses publishing trends, key authors, core research clusters, and the field's intellectual structures to show how PDCA has been interpreted and used in academia. The findings provide a comprehensive overview of the growth of this study topic, revealing emerging trends that support continued advances in educational quality management. The fourth chapter investigates the influence of digitalization and government expenditure on sustainable development across the EU27 countries. Using panel data from 27 European Union states, the study employs the Method of Moments Quantile Regression (MMQR) and the Two-Stage Least Squares (2SLS) estimation technique to capture both distributional heterogeneity and potential endogeneity. The findings reveal that advancements in digital technologies, when accompanied by appropriate public spending, significantly improve environmental quality and sustainable development. These results provide valuable policy insights, emphasizing the critical role of digitalization and fiscal interventions in fostering green growth and supporting long-term sustainable development in the digital era. The final chapter evaluates the contribution of e-government development, government fiscal expenditure, natural resource rents, and energy transition to sustainable development in selected EU countries. Employing the MMQR and Panel-Corrected Standard Errors (PCSEs), the study examines how digital governance, public spending, resource management, and clean energy adoption shape environmental and institutional outcomes. The results demonstrate that e-government advancement and well-targeted fiscal policies significantly enhance long-term sustainability and strengthen institutional performance across the European Union, while natural resource dependence continues to exert pressure on ecological systems. These findings underscore the pivotal role of digital governance and strategic public expenditure in supporting sustainable growth and effective environmental management.

Keywords: Governance Performance, QFD, PDCA, Higher education, Digitalization, Government expenditure, EU, E-Government

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1. Introduction

This thesis, entitled *"Governance Performance and Management Control Systems, Change Management, and Digital Transformation in Public Administration,"* is a result of an in-depth research activity carried out during the three years of my PhD course in Accounting, Management and Business Economics (AMBE) at the Department of Management and Business Administration, University of G. d'Annunzio of Chieti-Pescara, Italy. The research activities were carried out under the supervision of Prof. Ida Verna. The research topic was also explored during my research visiting periods at the Centre for Business and Economics Research (CeBER), University of Coimbra, Faculty of Economics, Portugal, under the supervision of Prof. José Alberto Fuinhas.

Public administration is undergoing an unprecedented transformation driven by global pressures for transparency, efficiency, accountability, and sustainable development. Governments are now required to demonstrate not only operational effectiveness but also the ability to innovate, coordinate, and deliver public value in more complex settings (Bryson et al., 2014). The intersection of digital transformation, sustainable development imperatives, public sector reforms, and changing citizen expectations is transforming public institutions' operations, performance evaluation, and change management (Hartley et al., 2017). At the core of these transitions are the requirements for effective governance, robust management control mechanisms, and strategic change management frameworks that enable public enterprises to navigate uncertainty while maintaining confidence and legitimacy (Pérez-Morote et al., 2020). As public sector activities extend beyond traditional administrative borders to encompass digital services, environmental stewardship, and quality assurance, governance demands become increasingly complex and interdependent (Silal & Sharma, 2024). This PhD thesis is situated within this evolving landscape and investigates how governance mechanisms, management control practices, digitalization, and policy interventions collectively influence organizational performance and sustainable public value creation.

The primary aim of this thesis is to evaluate how governance performance can be enhanced through the integration of management control systems, digital transformation, and sustainability-oriented public policies in both higher education and public administration. Specifically, the thesis seeks to: (i) analyze the role of Total Quality Management tools, namely QFD and the PDCA framework, in improving teaching, learning, and institutional decision-making; (ii) investigate how digitalization, e-government, and government expenditure contribute to environmental quality and sustainable development across European Union countries. Through this multi-dimensional approach, the thesis aims to provide an evidence-based understanding of how structured management frameworks and digital sustainable governance strategies can collectively strengthen institutional and environmental performance. To achieve the objectives, this thesis is anchored on four interconnected scholarly contributions that examine Total Quality Management (TQM), environmental governance, digital transformation, and sustainable policy outcomes within European and higher education contexts.

Within the framework of this thesis, a diverse set of methodological approaches is employed to comprehensively examine the multi-dimensional nature of governance performance, quality management, and digital transformation. For the higher education–focused studies, Systematic Literature Review (SLR) and bibliometric analysis are adopted to map existing knowledge, identify research trends, and establish conceptual foundations for the application of TQM tools such as QFD and the PDCA cycle. For empirical investigations in public administration and sustainability, the thesis utilizes advanced econometric techniques, including the Method of Moments Quantile Regression (MMQR) to capture heterogeneous effects across the distribution of indicators, and Two-Stage Least Squares (2SLS). Furthermore, CUP-FMOLS and BA-OLS are used to ensure robustness and address potential endogeneity issues. In addition, the Prais–Winsten regression with Panel-Corrected Standard Errors (PCSEs) is applied to account for autocorrelation and cross-sectional dependence in panel data. Together, these methodologies provide a rigorous analytical foundation for exploring how quality management practices, fiscal policies, and digital innovations contribute to enhanced institutional performance and sustainable development outcomes.

Therefore, the first pillar of this research is grounded in the study "**Total Quality Management through QFD in Teaching and Learning Process of Higher Education: A Systematic Literature Review Analysis.**"[1] This work provides a foundation for examining how management and governance principles translate into quality enhancement within educational institutions. The article emphasizes that understanding and integrating customer requirements within higher education, primarily the needs and expectations of students, is essential for designing effective academic services. Within the TQM framework, QFD serves as a strategic

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[1] This paper, entitled "**Total Quality Management through QFD in Teaching and Learning Process of Higher Education: A Systematic Literature Review Analysis,"** has been submitted to the ***INTERNATIONAL JOURNAL OF MANAGEMENT EDUCATION*** (Q1, ANVUR A-ranked). **Authors**: Khursheed, M. A., & Verna, I. **Status:** Submitted

tool to systematically translate these requirements into actionable design and management specifications. Through a comprehensive systematic literature review of 141 peer-reviewed studies sourced from Scopus, Web of Science, and complementary snowball sampling, the article demonstrates the growing relevance of QFD in higher education. The findings highlight its application in multiple domains, including curriculum development, course design, teaching quality assessment, learner performance evaluation, and overall academic management. By offering a structured, data-driven method for aligning institutional practices with student needs, QFD reinforces continuous improvement processes and strengthens decision-making in teaching, learning, and governance. This study, therefore, contributes to the broader thesis objective by demonstrating how management control systems and quality-oriented methodologies can support effective governance and enhance performance within public and educational institutions.

The second article underpinning this thesis is titled **“Implementing Plan-Do-Check-Act Framework for Teaching and Learning Process to Achieve TQM: A Bibliometric Analysis,”**[2]. This study advances the discussion on quality enhancement in higher education by examining the application of the Plan-Do-Check-Act (PDCA) cycle as a continuous improvement mechanism aligned with TQM principles. Through a structured literature review of 107 peer-reviewed studies retrieved from the Scopus database, the article provides a comprehensive mapping of publication trends, thematic clusters, and conceptual developments related to the use of PDCA in teaching and learning. The findings demonstrate that the PDCA cycle contributes to systematic course design during the Plan phase, enables effective implementation during the Do phase, strengthens performance assessment and feedback mechanisms during the Check phase, and reinforces continuous refinement during the Act phase. The study highlights the increasing relevance of PDCA for curriculum development, student engagement, and learning outcomes, while also revealing that research in this area remains fragmented and in its formative stages. By synthesizing existing evidence and identifying gaps for future inquiry, this article highlights the potential of integrating PDCA with robust measurement techniques to support evidence-based instructional design and more effective governance of teaching and learning processes. In doing so, it complements the first

[2] This paper, entitled **“Implementing Plan-Do-Check-Act Framework for Teaching and Learning Process to Achieve TQM: A Bibliometric Analysis”,** has been submitted to the ***HIGHER EDUCATION*** (Q1, ANVUR A-ranked). **Authors**: Khursheed, M. A., & Verna, I. **Status:** Submitted

article by further illustrating how structured quality frameworks can enhance management control systems and promote continuous improvement within higher education institutions. However, Higher education has an important role in national capacity development, innovative systems, and public sector competence. Ensuring quality in this industry becomes a critical governance challenge. Public universities can improve organizational performance by incorporating customer-driven (student-centered) quality tools like QFD and continuous improvement frameworks like PDCA. These studies show that implementing structured quality management frameworks improves decision-making, deepens strategic alignment, and facilitates performance monitoring, which are all basic features of management control systems. This ties educational quality procedures into the larger public governance agenda of transparency, accountability, and public value generation.

The third pillar of this research deepens the analysis of governance performance by situating it within the broader contexts of sustainability, environmental governance, and digital transformation. The article titled **"The Impact of Digitalization, Renewable Energy, and Natural Resources on Environmental Quality: The Role of Government Expenditure in EU27 Countries,"**[3] examines how public governance interacts with technological and environmental dynamics to influence long-term ecological outcomes. Grounded in Ecological Modernization Theory (EMT) and Resource Curse Theory (RCT), this study empirically assesses the effects of digitalization, renewable energy consumption, government expenditure, natural resource rents, and economic growth on environmental quality across 27 EU countries from 2000 to 2022. Using the Method of Moments Quantile Regression (MMQR), the analysis captures heterogeneous effects across different pollution levels, revealing that digitalization, government expenditure, and renewable energy significantly reduce CO_2 emissions, thereby enhancing environmental performance. In contrast, economic growth and dependence on natural resources are found to exacerbate environmental degradation, confirming persistent

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[3] A part of this chapter has been presented to the academic debate in the following conference and journal:

i) Presented at the Centre for Business and Economics Research (CeBER) Research Seminars - Autumn 2024, University of Coimbra, Portugal

ii) **Published in the *"Quality and Quantity"*** journal in October 2025. The journal is Springer Nature, Q1, ANVUR=A, ABDC=B

Khursheed, M. A., Fuinhas, J. A., & Verna, I. (2025). The impact of digitalization, renewable energy, and natural resources on environmental quality: the role of government expenditure in EU27 countries. *Quality & Quantity*, 1-31.

structural constraints identified in RCT. Notably, the interaction between digitalization and government expenditure demonstrates a strong complementary effect, highlighting the importance of aligning fiscal policies with digital innovation to support ecological goals. Robustness tests using CUP-FMOLS, BA-OLS, and 2SLS further validate these results. This article advances the thesis argument by showing how governance systems, when strategically oriented toward digital transformation and sustainable investments, can significantly improve environmental outcomes. In doing so, it complements the earlier pillars by linking management control systems and quality frameworks with broader policy mechanisms that shape sustainability and climate-related governance performance in public institutions.

The final paper of this thesis extends the analysis of governance and sustainability by exploring how digital public administration, fiscal policy, resource management, and energy transitions collectively shape ecological performance in selected European Union countries. The article **"The Role of E-Government, Government Fiscal Expenditure, Natural Resources Rents, and Energy Transition in Achieving Sustainable Development in Selected European Union Countries."**[4] examines how policy instruments and technological capabilities shape environmental and socioeconomic outcomes across 26 EU nations between 2000 and 2022. Employing the MMQR, the study captures heterogeneity across the conditional distribution of Ecological Footprints (EFP), enabling a deeper understanding of how digital governance and economic structures affect ecological outcomes at varying levels of environmental pressure. The analysis reveals that e-government development, government fiscal expenditure, and energy transition significantly contribute to ecological sustainability by consistently reducing EFP across all quantiles. Conversely, natural resource rents and GDP are shown to increase EFP, reinforcing the argument that resource dependency and unchecked economic expansion can undermine environmental integrity. Robustness checks using Prais–Winsten regression with Panel-Corrected Standard Errors (PCSEs) further validate these findings, ensuring the reliability of empirical evidence. This article strengthens the thesis perspective by demonstrating that governance mechanisms, particularly digitalization of public services,

[4] This chapter, entitled **"The Role of E-Government, Government Fiscal Expenditure, Natural Resources Rents, and Energy Transition in Achieving Sustainable Development in Selected European Union Countries,"** has been presented to the following conference and journal:

i) Presented at the XXII Conference of the Italian Chapter of AIS: Emerging technologies for transforming organizations and society, LIUC – Cattaneo University, on October 17th–18th, 2025, Castellanza (VA)

ii) Under Review in ***"Economic Change and Restructuring***". The journal is Q1, ANVUR=A, ABDC=B. **Current Status:** Under Review strategic fiscal allocation, and clean energy adoption, play a crucial role in minimizing ecological degradation. Its insights underscore the importance of aligning resource governance, digital transformation, and sustainability-driven fiscal strategies to support long-term ecological and socio-economic resilience in the EU context.

2. Total Quality Management through QFD in Teaching and Learning Process of Higher Education: A Systematic Literature Review Analysis

2.1. Introduction

In recent years, the demand for quality enhancement in higher education has increased, driven by the need to improve student learning outcomes, institutional accountability, and curriculum relevance. As higher education systems expand and diversify, there is an increased interest in implementing organized quality assurance frameworks to improve teaching, learning, and academic services. One such solution is QFD, a TQM tool that gathers and transforms student preferences into actionable course and curriculum design. This focus is aligned with global educational priorities, particularly Sustainable Development Goal 4 (Quality Education), which promotes inclusive, equitable, and high-quality education for all. By incorporating student-centred design ideas into QFD, educational institutions can ensure that their offerings remain flexible, dynamic, and aligned with long-term, sustainable development goals.

Total Quality Management (TQM) has emerged as a foundational element in modern management models, which aim to navigate global and local transformations. As educational reform becomes increasingly central to international development agendas, achieving total quality in education is recognized as a critical challenge for the coming decades (Al-Zoubi et al., 2023). One of the key tools for operationalizing Total Quality Management (TQM) is the Quality Function Deployment (QFD) method. This structured methodology enables the development and delivery of high-quality services tailored to the specific requirements of customers or stakeholders. QFD operates on the principle of capturing the "voice of the customer" and translating these requirements into specific, actionable service attributes using planning matrices known as Houses of Quality (HOQ) (Cohen, 1995). This approach not only ensures higher levels of customer satisfaction but also contributes to building a sustainable competitive advantage (Chan & Wu, 2002; Kamvysi et al., 2014). By streamlining communication, reducing costs and time-to-market for new services, increasing efficiency, and promoting customer-centered decision-making, QFD plays a crucial role in enhancing organizational performance. In the context of higher education, QFD applications have been categorized into four key areas: course and curriculum design (Abuzid, 2017; Verna, 2014), evaluation of student learning performance (Kanango et al., 2023), assessment of teaching effectiveness (Al-Kahlan & Khasawneh, 2024; Isa & Hadijaya, 2024), and evaluation of management performance (Agarwal, 2021). These applications demonstrate QFD's adaptability and growing relevance in enhancing the quality and effectiveness of teaching, learning, and institutional governance in higher education.

Many scholars have focused on curriculum design and development to modernize education, utilizing Quality Function Deployment (QFD) in curriculum development (Verna et al., 2019; Druzhinina et al., 2018; Abuzid, 2017). According to some researchers who have worked on curriculum development, the voice of the customer (VOC) has been noticed as magnificent. In this context, understanding stakeholders, including learners, is a crucial first Step in developing an educational curriculum (Abuzid, 2017). However, Verna and Pizzolitto (2019) suggest a customer-centric approach to curriculum development; their article reflects on how QFD was used in a university accounting course to identify the most effective teaching methods based on the needs of stakeholders and students. Learning outcomes (LO) describe the degree of homogeneity or heterogeneity in a class learning at the start, during, and after an accounting course, based on the initial target/needs. The experimental results showed that specific targets or needs are associated with the same teaching strategies over time. Furthermore, we could not find sufficient literature on using QFD to evaluate performance; however, evaluating educational training and learning is at the center of training in general, and teaching plays a crucial role in both (Isa & Hadijaya, 2024). Progress is not entirely dependent on the well-functioning of the education system; it also depends on the nature of teaching (Huang et al., 2021). Moreover, evaluating teaching performance and learning performance is essential for improving the quality of education.

In addition, only a limited number of research studies have explored the use of Quality Function Deployment (QFD) to evaluate management performance in higher education, despite its critical role in shaping the overall quality of academic institutions. Ineffective management has been linked to the decline and even closure of numerous universities worldwide (Yusuf, 2023). Research suggests that bankruptcies in higher education institutions often stem from poor governance and a lack of strategic direction (Bruckner, 2017; Hunt & Boliver, 2021; Iuliano, 2019). A key issue is the increasing allocation of management budgets without clear achievement targets or the implementation of a comprehensive strategic plan (Bruckner, 2017). At the core of this problem lies the misapplication or absence of a structured management approach, such as Total Quality Management (TQM), which emphasizes continuous improvement and stakeholder satisfaction. TQM, supported by QFD, offers a structured framework for enhancing management practices in higher education institutions (Al-Kahlan & Khasawneh, 2024). QFD provides a systematic methodology for identifying, prioritizing, and translating stakeholder (customer) requirements, such as those of students, faculty, and administrative bodies, into actionable strategies. However, effective implementation of QFD relies heavily on accurately capturing the "voice of the customer." Misjudging or misinterpreting these requirements can lead to misguided priorities and suboptimal outcomes in educational services (Kamvysi et al., 2014). Therefore, further integration of QFD in evaluating higher education management performance could help institutions achieve more transparent, accountable, and responsive governance.

However, this paper aims to provide new insights into QFD that may increase the value of information generated for prioritizing customer requirements. We present a QFD framework in curriculum and evaluation design to capture students' priorities and evaluate their effectiveness in prioritizing desired learning outcomes. Our work introduces a QFD framework for capturing the 'Voice of the Customer' and accurately prioritizing student requirements for academic courses and evaluation. In this regard, we propose and evaluate a QFD framework that combines novel methodological tools, specifically integrating the House of Quality (HOQ) into QFD for evaluating the teaching and learning process. Curriculum design, student learning performance evaluation, teaching effectiveness, and quality management practices are just a few of the important thematic areas where QFD makes a significant contribution. This study maps the current state of QFD applications in higher education by conducting a systematic literature review across major academic databases. The research highlights how QFD, when integrated thoughtfully into academic processes, can translate the "voice of the student" into actionable design and improvement strategies, aligning educational outputs with learners' needs and institutional goals. Moreover, this study positions QFD as a vital tool for supporting evidence-based decision-making in educational planning, fostering continuous improvement, and enhancing stakeholder satisfaction. In doing so, it offers practical insights for academic leaders, educators, and policymakers seeking to enhance service delivery and accountability in higher education. Notably, this work contributes to the advancement of Sustainable Development Goal 4 (SDG 4), which aims to promote inclusive, equitable, and quality education for all. By demonstrating how QFD can support strategic quality enhancement initiatives, the study offers a forward-looking perspective on embedding TQM principles into institutional practices to drive long-term educational excellence and sustainability.

2.2. Background

Like other service sectors, education is becoming increasingly competitive every day. To deal with this competition, every aspect of the education sector must be evaluated for quality assurance. The evaluation of the education sector is comparatively less discussed in scholarly publications than that of other service sectors (such as banks, hospitals, travel, and others). As a result, the idea of total quality management of the education sector is consistently somewhat disregarded in academic writing (Mou et al., 2018). We studied relevant literature, including articles from national and international journals, conference presentations, and other written works, to investigate the application of Total Quality Management (TQM) in conjunction with Quality Function Deployment (QFD) during the design process, with a focus on service quality (Kanango et al., 2023). For example, Verna and Pizzolitto (2019) utilize QFD to categorize effective teaching methods in a university accounting course, based on the needs of both stakeholders and students. Learning outcomes (LO) describe the degree of homogeneity or heterogeneity in a class's learning at the start, during, and after an accounting course, based on the initial target/needs. Experiments show that teaching strategies for specific targets or needs remain consistent.

For curriculum development, Francis's (2016) paper applies QFD to a mechanical engineering course, using course LO as the voice of the customer (VOC) and ABET student outcomes as technical requirements (HOWs). This paper outlines how faculty and engineering institutions can meet the requirements of the Accreditation Board for Engineering and Technology (ABET). In another research, Verna (2014) applies the QFD methodology to an accounting course at a university. The goal is to enhance the competitiveness of university programs through a quality methodology that identifies genuine customer needs. This study employs Quality Function Deployment (QFD) to evaluate students' learning needs in an accounting course and develop educational strategies that address these needs. Regarding the teaching and learning process, Abuzid (2017) utilized the QFD tool to objectively identify, assess, and measure students' learning needs. Instructional strategies were then designed to meet these needs. The researcher evaluated instructional strategy from the perspectives of professors, staff, and students to ensure they align with program goals. The research suggests a disconnect between students' learning needs and instructional strategies, which may not align with the university's desired outcomes.

In addition, the concept of management performance is thought to be extremely nebulous and wide. The literature on management performance also reveals that scholars disagree about how to quantify performance in higher education, as management performance is problematic even within this context (Iqbal et al., 2019). On the one hand, certain scholars believed that the financial characteristics of educational institutions influenced the effectiveness of higher education (Jumady et al., 2021). Others emphasize non-financial performance factors, such as operations, service, internationalization, innovative research, and governance (Isa & Hadijaya, 2024; Agarwal, 2021). Subsequent researchers are particularly concerned about the inadequate performance of university teaching, research, and various services, and have acknowledged three key academic responsibilities that universities must fulfill: teaching, research, and service (Iqbal et al., 2019). The literature review highlights the use of QFD as a design tool, a quality planning tool, and a means of improving product and service quality. QFD has been used to design course content by identifying the needs of key stakeholders and is also utilized in performance evaluation. The present study has noted the use of QFD-based approaches in teaching. It aims to explore the unique concept of employing QFD to optimize course content and incorporate additional factors into the planning matrix, thereby better representing the needs of participants (Kanango et al., 2023).

Despite the growing interest in quality assurance practices within higher education, the application of Quality Function Deployment (QFD) remains underexplored in this context. Most existing studies focus on QFD's industrial applications, with limited research addressing its role in aligning educational services with student expectations. Moreover, literature lacks a comprehensive and structured review that synthesizes how QFD contributes to various dimensions of academic quality, such as course and curriculum design, learning performance, teaching effectiveness, and institutional management. There is also a noticeable gap in understanding how QFD frameworks can support the achievement of SDG 4 by systematically improving teaching and learning processes. This study addresses these gaps by offering a structured literature review that highlights the relevance, application, and potential of QFD in enhancing quality in higher education.

2.3. Methodology

In this section, the current study describes the methodology used in this paper. Specifically, the following subsections outline the rationale behind employing a systematic literature review as the primary methodology for this study. In addition, we provide PRISMA with a comprehensive account of the protocol used to conduct the systematic literature review. Finally, we also explain the criteria for including and excluding the articles from our final set.

2.3.1 Systematic Literature Review

The protocol developed by Wolfswinkel et al. (2013) for systematic literature reviews (SLR) was used to conduct the research. SLR is a formulated question that employs systematic and explicit methods to identify, select, and critically appraise relevant research, as well as collect and analyze data from the studies included in the review (Khursheed et al., 2025; Moher et al., 2009). Moreover, systematic literature reviews aim to identify all research that addresses a specific question, providing a balanced and unbiased overview of the literature. The methods used to identify studies for inclusion in systematic reviews were explicitly designed to identify negative studies that may be published in low-impact journals or conference proceedings, which are not indexed in bibliographic databases but may balance the results of more easily identified positive studies (Nightingale, 2009).

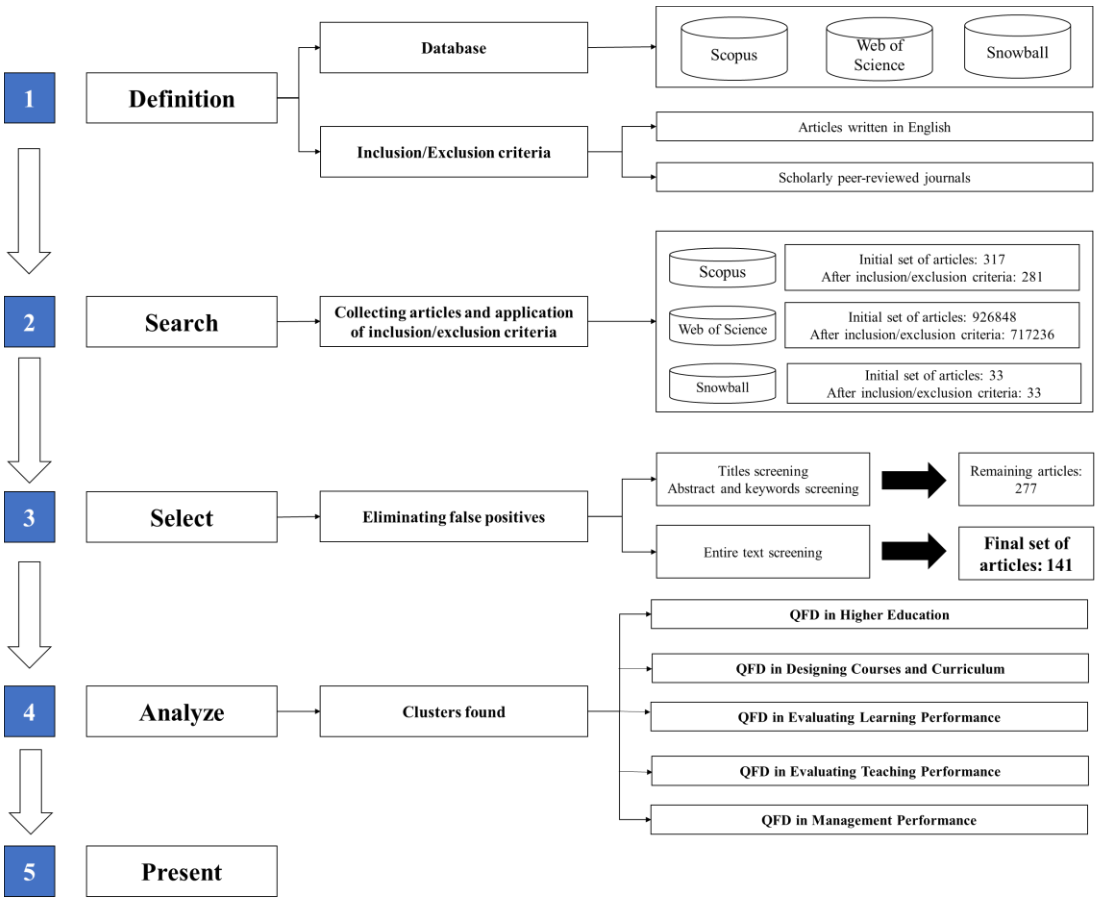

Figure 2.1: Employed Protocol

Furthermore, we selected and interpreted the articles using the PRISMA method described by Moher et al. (2009). There are several advantages to using the PRISMA guidelines. First, it enables us to develop a theoretical framework without prior knowledge (Corbin & Strauss, 1990). Second, item selection is identical to other SLR systems (Post et al., 2020). Due to these advantages, PRISMA is the ideal tool for developing content analysis in systematic literature reviews (SLR).

2.3.2 The Employed Protocol

The authors developed a predefined review protocol to address research questions and minimize researcher bias. This protocol comprises five phases: definition, search, selection, analysis, and presentation as shown in Figure 1. The database and the study's inclusion and exclusion criteria were established during the first phase (Pizzolitto, 2023). The sample only included English-language publications that had undergone peer review and were published in scholarly journals. Only articles from the SCOPUS Web of Science and Google Scholar databases were considered, ensuring that only the best publications were included. The reviewed papers are identified using keywords in referenced electronic databases, such as Google Scholar, Web of Science, and SCOPUS. Finally, keywords were assigned to the article titles, abstracts, and keywords for searching the three databases (Salam et al., 2019). The keywords were quality AND function AND deployment AND "higher education" OR university.

The second stage consisted of searching for articles. Numerous exploratory analyses were conducted at the outset to ensure that all relevant literature was included. The Web of Science was used to initiate the investigation, yielding 926,848 results. When the search was limited to peer-reviewed English-language literature, the list was reduced to 717317 results. The 717317 findings were refined in the third phase, and 717236 false positives were eliminated after titles, abstracts, keywords, and contents were reviewed. The Web of Science dataset consisted of 81 articles. We also repeated the above-mentioned protocol using the exact keywords in the SCOPUS database, which yielded 351 items. After that, we limited the search to peer-reviewed and English-language literature, and the list subsequently decreased to 281 articles. The 281 findings were refined again, and 254 false positives repeated from the Web of Science were eliminated after the title, abstract, keyword, and contents were reviewed. However, 27 items were selected from the SCOPUS database.

Additionally, we identified 33 articles on the scholarly database through exploratory analysis and subsequently added these articles by following the snowball technique. However, our final database consists of 141 articles. The procedure's last two steps were "analyze" and "present." The articles' descriptive and content analyses, or the results of these stages, are presented in the following section. When analyzing the articles, we examined the types of papers, the distribution of publications over time, the authors' productivity and connections, and the methodologies employed in the empirical studies.

2.3.3 Assessment and Extraction

The dataset comprises articles that mention QFD, higher education, or universities in their titles and/or abstracts. By following Vlachopoulos and Makri (2017), this study tested and evaluated their selection criteria using prior research. The study selection process was divided into two stages: a) the researchers screened the titles and abstracts for inclusion criteria independently, first, and then together; and b) in the event of disagreement or insufficient information, they conducted a thorough consideration of the body of the articles (i.e., methodology and results), again independently, and then together, resulting in a consensus. The decision to include or exclude the text was then discussed using predetermined criteria.

The authors analyzed the studies from various perspectives. First, they examined the characteristics of the data set, including the subject discipline, methodological research design, and the period during which most studies were conducted. The emphasis is on the articles' analysis, measurements, and design. To summarize, the review studies were selected using a systematic literature review process with predetermined criteria, ensuring that there was no deliberate bias in the chosen studies.

2.4. Results

The competitiveness in the education sector is growing at an accelerated rate due to technological advancements, globalization of education, and dynamic learning environments. As a result, higher education must take Reality into account. Time has brought about a simultaneous increase in the variety and quantity of educational resources (Mou et al., 2018). Higher education institutions must ensure quality with the limited resources available to stakeholders to thrive in the competitive market. It appears that the conventional method of instruction is no longer effective.

In this regard, the House of Quality of QFD may be helpful, and this approach is already widely used in curricula at higher education institutions (İçtenbaş & Eryilmaz, 2011). A House of Quality (HOQ) matrix, which identifies the customer requirements as "Whats" and HEI characteristics as "Hows" and establishes the relationship between "Whats-Hows" as the process's outputs, is the primary planning tool for the QFD process. However, the systematic process of identifying the needs or requirements of clients and turning them into detailed plans to satisfy those needs is known as quality function deployment. It is also known as the voice of the customer (VOC) because it focuses on the needs and expectations of the consumers (Verna, 2012). It is a team-based management tool that utilizes customer needs to guide the development of new products (Mukaddes et al., 2012; Chan & Wu, 2002). Initially, it was used in the industrial sector to improve the quality of products by listening to the voice of customers, but now it is also used in higher education to develop higher education quality by listening to the voice of students (Verna, 2023; Verna & Pizzolitto, 2019; Verna, 2014; İçtenbaş & Eryilmaz, 2011).

Researchers have contributed to strengthening concepts and integrating features to ensure the effectiveness of these practices. The thematic analysis of our study explains the uses of QFD in different domains of higher education institutions, as it is one of the most potent TQM tools and has also been applied widely in academia to assess and enhance the calibre of teaching and counselling in higher education institutions (Druzhinina et al., 2018; Raharjo et al., 2007). However, we explain the phenomenon of QFD in the following subsections using qualitative thematic and content analysis, a process designed to condense raw data into categories or themes based on valid inference and interpretation.

2.4.1 QFD in Higher Education

Due to intense competition in education, providing better services depends critically on educational quality (Mou et al., 2018). For this purpose, higher education institutions must constantly ensure and improve the quality of education (Reina et al., 2021). There are many ways to define "quality" in education, but to deliver higher-quality instruction, educational institutions must work to give their clients (students) a specific competitive edge by understanding, meeting, and surpassing their needs (Khare & Rawani, 2019). Total Quality Education (TQE), as put out by Dahlgaard et al. (1995), is "an education culture characterized by increased customer satisfaction through continuous improvement, in which all employees and students actively participate."

While many universities instruct their students in Total Quality Management (TQM), unfortunately, not all follow their teachings. A customer-driven approach was necessary to implement Total Quality Management (TQM) in education (Sahney et al., 2006). Consequently, it is crucial to pay attention to the Voice of the Customer (Verna, 2012) to provide customers with value effectively and efficiently. An alternative method for better identifying or hearing the Voice of the Customer (VOC) in the manufacturing and service sectors is the Quality Function Deployment (QFD) approach (Khare & Rawani, 2019). One of the most effective tools in Total Quality Management (TQM) is the Quality Function

Deployment (QFD). However, the concept of a customer-driven process has primarily been used in industry; it may also be somewhat applicable in education (Yusuf, 2023).

In QFD, identifying the customers and their needs is the first critical Step in making the efforts effective (Verna & Pizzolitto, 2019). Customers and stakeholders at the university can include academic staff members, students, employers of graduates, alumni, parents, the government, the local community, and others (Khare & Rawani, 2019). To keep things simple, we will only focus on the three primary internal parties: students, teachers, and administrators. Students are considered clients in terms of the services they receive from the university. Given that lecturers are seen as both the designers and the primary actors in education (Khan et al., 2016), educational institutions ought to furnish them with the resources they need to carry out their duties. Lastly, administrators are primary managers who oversee and facilitate interactions between clients (students) and teachers (Kamau et al., 2024). Ultimately, we conclude that the QFD is a methodology designed to achieve customer satisfaction by identifying and prioritizing customer requirements, and then converting them into strategies for product development and process specifications (Khan et al., 2016).

2.4.2 QFD in Designing Courses and Curriculum

The term "curriculum" is derived from the Latin word "curriculum" or "racecourse," which also refers to a course of study or syllabus. However, the scope of the curriculum has greatly expanded today. A curriculum is a planned outline of school subjects during a given academic year (Druzhinina et al., 2018). It entails organizing the subject matter, presenting the scheduled material, and accounting for the target students' backgrounds (Mou et al., 2018). A good curriculum leads to a good quality of education (Druzhinina et al., 2018). Numerous techniques are used to improve the quality of curriculum, but at the top of this list is quality function deployment. The potential of QFD to enhance curriculum design and development has been explored by educators and curriculum developers in recent years (Mou et al., 2018). The procedure entails determining the requirements and expectations of diverse education stakeholders, such as employers, parents, students, and society, and converting these needs into targeted learning objectives, curriculum, and instructional strategies (Abuzid, 2017).

However, many researchers have contributed to the development of curriculum using QFD (Abuzid, 2017; Verna, 2014; Aytaç & Deniz, 2005). In an earlier study, Kleindorfer (1994) employed Total Quality Management (TQM) to ensure quality deployment in the University of Pennsylvania's MBA program. Later, Hansen et al. (1999) focused on knowledge and skills at various phases to apply Quality Function Deployment (QFD) for course development.

Raharjo et al. (2008) identify the characteristics of quality and the desired qualities of instructors, employers, and students. They closely consider the voice of the customer (VOC) when applying the Analytic Hierarchy Process (AHP) to priorities.

Abuzid (2017) recently applied QFD to develop the curriculum process, utilizing multiple crucial sections to address the WHATS and HOWS factors. The main sections for the customer expectations (WHATS) international skills are management and general education. The curriculum, course design, and teaching strategies have been identified as crucial for the critical elements (HOWS). Numerous other subsections (e.g., quality, financial component) have been examined under these sections.

Implementing Quality Function Deployment in curriculum development provides an organized and systematic way to match educational initiatives with the requirements and expectations of students (Mou et al., 2018). Implementing student-centric learning and continuous improvement are among the many advantages it offers. However, it is crucial to listen to students to identify their needs (WHATS) and apply the appropriate strategies (HOWS) for effective curriculum development (Verna et al., 2019).

Considering QFD's potential to improve teaching methods and student learning outcomes, more investigation and real-world application are required to investigate efficient approaches for incorporating it into curriculum development (Gonzalez et al., 2011). Through a literature review, we found that applying QFD in higher education curricula can be improved by improving the basic QFD model (Mou et al., 2018). A summary of the literature reveals that QFD is a valuable tool for developing higher education curricula, taking into account the specific realities of higher education institutions. The primary goal of QFD was to develop high-quality products based on the voices of customers (students). However, before creating a final process that satisfies the standards most students require, curriculum designers and developers can identify specific information about the needs and requirements of students using listening in Quality Function Deployment (QFD) as a quality and planning tool (Sahari et al., 2017). In addition to curriculum development, QFD use has been suggested and implemented in several higher education domains (e.g., Course registration).

2.4.3 QFD in Evaluating Learning Performance (Students)

In recent years, to better serve the needs of various stakeholders, there has been an increase in interest in enhancing assessment procedures in education (Kanango et al., 2023). A structured methodology from the field of quality management, known as Quality Function Deployment

(QFD), offers a promising framework for evaluating and enhancing student learning outcomes (Abuzid, 2017). Literature on QFD in education emphasizes the importance of aligning assessment practices with student needs (WHATS), interpreting those needs into significant evaluation criteria (HOWS), and executing continuous improvement strategies are crucial for evaluating the learning performance of students (Kanango et al., 2023; Khare & Rawani, 2019; Felder & Brent, 2003).

Among these, evaluation typically has a significant impact on the quality of learning, as it establishes the degree to which the objectives are met, indicating what needs to be done to improve student performance (Nguyen et al., 2006). However, the Quality Function Deployment-based model (QFD) is used in the evaluation process and was initially adopted in a master's degree program for quality assurance purposes (Matorera & Fraser, 2016). It recommends incorporating the voice of customers (students) into transformative instruction policies, regulations, and practices to enhance students' knowledge, attitudes, skills, and behaviours, preparing them for the desired societal outcomes. Utilizing the QFD process to gauge learning performance, this study develops an assessment tool for overall quality management in higher education (Matorera, 2015). Although it may not be common or simple to apply QFD in the evaluation of student learning performance directly, educators can still adapt and apply its underlying principles, such as adaptation based on listening to the students, to improve the teaching-learning process and better meet the needs of their students, which is called summative assessment of QFD (Assiddiqi & Vanany, 2021).

On the other hand, formative assessment of QFD focuses on evaluating student learning outcomes at the end of a learning period; however, it is also intended to provide students with ongoing responses and support during the learning process. The latter provides students with quick feedback by using the data gathered about their performance as a tool (Pérez-Segura et al., 2020). However, the most effective evaluation of learning performance is the voice of customers, as it serves as a form of "Quality Function Deployment" (QFD) by representing the voice of the students (Chase & Houmanfar, 2009).

2.4.4 QFD in Evaluating Teaching Performance (Teachers)

Since higher education has entered the public development stage, the Ministry of Education and Universities has been working to improve and ensure the quality of higher education (Al-Kahlan & Khasawneh, 2024; Isa & Hadijaya, 2024; Ye & Jiao, 2011). The future universities will be determined through constant improvement in their teaching performance. Higher education now frequently uses student evaluations of courses, with the widespread distribution of evaluation results on teaching performance (Al-Kahlan & Khasawneh, 2024; Bagchi, 2010). While there are good reasons to let students judge the quality of the teaching they receive, many believe that, overall, teaching has significantly improved (Reina et al., 2021).

Furthermore, in this study, we measure the quality of teaching QFD based on the student satisfaction it produces. In addition, to meet the demands of teaching and learning the course between teachers and students, this study offers a novel method for evaluating the quality of teaching in education (Ye & Jiao, 2011). This method is based on quality function deployment (QFD), providing a qualitative foundation for teaching management decision-making to enhance teaching quality. The most crucial evaluation is the practical teaching evaluation of instructors, as assessed by students through the QFD method.

However, the first Step in QFD for evaluating teaching performance is gathering input from stakeholders, including students, faculty, administrators, parents, and employers; their perspectives offer important insights into what constitutes effective teaching (Ye & Jiao, 2011). Once requirements have been identified, they must be prioritized according to their importance to stakeholders. Each requirement must be expressed as measurable metrics or indicators. This Step involves quantifying qualitative aspects to make them more actionable and objectively evaluable (Abuzid, 2017). With metrics in hand, the next Step is to correlate them with specific teaching practices or behaviours (Chan & Wu, 2002). This alignment ensures that the evaluation criteria accurately reflect teaching performance (Isa & Hadijaya, 2024). Ultimately, the QFD is not a one-time process, but rather an ongoing improvement cycle. Evaluation should help to shape teaching strategies, curriculum design, and professional development initiatives (Yusuf, 2023).

2.4.5 QFD in Evaluating Management Performance

Improvements are sparked by measurement, and it is frequently true that "you cannot improve something if you do not measure it (Jumady et al., 2021)." The HEI's operations are typically assessed using a variety of performance metrics, and management makes decisions based on the findings (Agarwal, 2021; Mohsin et al., 2018; Jagdev et al., 1997). However, higher education institutions today face a variety of challenges in performance evaluation. Performance generally refers to flexibility, creativity, ongoing improvement, and efficiency.

Researchers are seeking more effective ways to evaluate system performance due to the limitations of conventional performance evaluation systems (Al-Kahlan & Khasawneh, 2024;

Taticchi et al., 2010). As a result, numerous TQM procedures have been developed for application in various organizations (Jumady et al., 2021).

For performance management evaluations, student feedback is necessary. In this way, we gather feedback from the students (Ekune & Anthony, 2024). In contrast to conventional QFD, which usually involves the voice of customers (students) for evaluation of performance, due to this technique we ask a range of persons who have contact with the person being evaluated for their opinions: Peers, subordinates, students, parents, and other stakeholders may be included in this to give their opinions (NWOKEOCHA, 2024).

Several writers have been drawn to the idea of feedback, including Meenakshi (2012), who methodically gathered information on a person's performance from several stakeholders and used it to enhance performance in Multi-Source Feedback. However, based on the findings from the systematic literature review (SLR), feedback evaluation of performance positively impacts employee effectiveness.

2.5. Future Research Directions

While the present study has highlighted the strong potential of QFD in improving quality assurance and curriculum design in higher education, some interesting areas for future research remain unexplored, which are as follows:

2.5.1 Cross-Disciplinary Application of QFD

Future research should explore how the Quality Function Deployment (QFD) framework can be adapted and effectively implemented across diverse academic disciplines. While current applications of QFD are predominantly concentrated in engineering and business education, its potential to enhance curriculum design and teaching quality extends well beyond these fields. Investigating how QFD principles can be tailored to the distinct pedagogical goals, assessment methods, and learner expectations within disciplines such as humanities, social sciences, and health education would provide valuable insights. For instance, in engineering or medical programs, QFD could prioritize technical competencies and practical outcomes, whereas in humanities, it might emphasize critical thinking, creativity, and reflective learning. Comparative studies across these fields could identify both universal and discipline-specific dimensions of quality in higher education. Developing such context-sensitive QFD models would not only promote greater curricular alignment with student and stakeholder needs but also foster deeper engagement, improved learning outcomes, and more evidence-based decision-making in academic program design.

2.5.2 Empirical Validation Through Case Studies

While the theoretical relevance of Quality Function Deployment (QFD) in higher education has been widely acknowledged, there remains a notable scarcity of empirical research demonstrating how it operates within real institutional contexts. Future research should therefore focus on conducting in-depth case studies within universities and colleges to capture the practical dimensions of QFD implementation. Such studies could examine how QFD influences curriculum design, teaching effectiveness, student satisfaction, and administrative efficiency when applied in actual academic settings. In addition, longitudinal case studies would help reveal the long-term benefits and challenges of sustaining QFD-based improvement initiatives across multiple academic cycles. By documenting both successes and limitations, these investigations could provide a more balanced and realistic understanding of QFD's impact on educational quality. Furthermore, cross-institutional comparisons examining universities of varying sizes, governance structures, and cultural contexts could shed light on the adaptability and scalability of QFD frameworks. Empirical validation through such evidence-based approaches would not only strengthen the theoretical foundations of QFD in higher education but also build confidence among policymakers and educators to integrate it more systematically into institutional quality assurance and continuous improvement processes.

2.5.3 Longitudinal Impact Assessment

Despite growing interest in QFD applications in education, little is known about its long-term influence on institutional and student outcomes. Future research should conduct longitudinal studies to track how QFD-based curriculum design affects key performance indicators, such as student retention, academic success, and employability, over time. Examining these outcomes across multiple academic cycles would reveal whether the benefits of QFD are sustained or diminish once initial implementation phases end. Moreover, studying how continuous use of QFD contributes to a culture of ongoing improvement and accountability could help institutions better understand its role in shaping lasting educational quality and strategic development.

2.5.4 Comparative International and Institutional Studies

Future research should prioritize comparative international and institutional studies to fully understand the diverse implementation of Quality Function Deployment (QFD) in education, moving beyond solutions that fail in varied contexts (Qingyan et al., 2023). A crucial direction is a cross-national comparison to determine how differing governance, cultural norms, and regulatory standards, such as centralised vs decentralised curriculum control, influence the vital "Voice of the Customer" component of QFD. Simultaneously, research must compare institutional types to identify best practices, contrasting the application of QFD in public versus private schools, or between K-12 and Higher Education, where the definition of "quality" and its measurable outputs differ significantly. Such detailed, context-sensitive analysis is essential to developing flexible, practical QFD models that effectively translate broad quality goals into sustainable improvements in teacher performance and student outcomes worldwide.

2.5.5 Integration with Digital Technologies and AI

As higher education adopts more digital platforms and artificial intelligence tools, there is more opportunity to investigate how QFD may be linked with new technologies. For instance, AI-based learning analytics and decision support systems could enhance the QFD data collection and analysis stages, enabling more dynamic and real-time adjustments to course design. Research in this area could investigate frameworks that combine QFD with digital feedback tools or adaptive learning systems to promote personalized education. This will lead to AI-enabled educational institutions, teachers, and students utilizing various AI tools, which necessitate a reevaluation of teaching, learning, and evaluation strategies.

While integrating AI with QFD offers opportunities to improve educational decision-making, future research should also examine its potential risks in higher education. AI-driven analytical tools may introduce algorithmic bias when decision models rely on incomplete or unbalanced data, which could lead to unfair prioritization of stakeholder requirements. In addition, the increasing use of learning analytics raises data privacy and cybersecurity concerns related to the collection and processing of student information. Moreover, excessive reliance on automated systems may reduce the role of human judgment in academic decision-making, while the growing computational demands of AI technologies may also raise environmental sustainability concerns.

2.5.6 Stakeholder-Inclusive QFD Models

Most current research focuses on incorporating student feedback into Quality Function Deployment (QFD). Future studies should expand this breadth by incorporating input from a diverse range of stakeholders, including faculty members, academic administrators, employers, and graduates. A multi-stakeholder QFD paradigm can offer a more balanced and complete approach to quality improvement, bridging the gap between academic learning and real-world demands.

2.2.6 Conclusion and Policy Recommendations

This study presents an integrated framework using QFD to interpret, capture, and prioritize students' preferences in higher education. Recognizing the challenges faced by decision-makers, such as limited cognitive processing, incomplete information, and time constraints, the proposed QFD-based model offers a structured, data-informed approach to enhancing teaching, curriculum design, and overall educational quality. However, this structured literature review examines the current state of Total Quality Management in higher education, with a specific focus on the application of QFD in enhancing decision-making and strategic action. This review draws on peer-reviewed literature sourced from two major academic databases, Scopus and Web of Science, as well as additional relevant studies identified through Google Scholar using the snowball sampling technique. After applying rigorous inclusion and exclusion criteria, a final sample of 141 peer-reviewed articles was selected for thematic analysis. By systematically translating the "voice of the customer" into measurable educational attributes, the framework improves the ability to design student-centred learning environments that balance theoretical knowledge with practical, employability-oriented skills. The findings of this structured literature review highlight the versatile application of QFD across various educational functions: course and curriculum design, evaluation of student learning outcomes, assessment of teaching performance, and institutional management. The integration of subjective judgments into QFD enhances its utility in aligning learning objectives with teaching strategies and students' needs, thereby providing an inclusive and equitable quality education. To effectively implement QFD in higher education, policymakers and institutional leaders should incorporate it into quality assurance and curriculum development frameworks. Faculty should receive training on QFD principles, while feedback mechanisms and data analytics should be strengthened to inform continuous improvement. This approach not only enhances teaching and learning outcomes but also reinforces strategic decision-making and institutional responsiveness in an increasingly competitive and dynamic educational landscape.

3. Implementing Plan-Do-Check-Act Framework for Teaching and Learning Process to Achieve Total Quality Management: A Bibliometric Analysis

3. 1. Introduction

The pursuit of quality education has become a central focus of global educational reform, reflecting increasing demands for accountability, relevance, and excellence in higher education. Institutions today are under constant pressure to enhance the effectiveness of their teaching and learning processes while remaining responsive to societal and economic transformations.

Quality education not only fosters human capital development but also catalyzes innovation, social equity, and sustainable economic growth. Consequently, embedding robust quality assurance frameworks within teaching and learning systems is essential to ensure that higher education institutions remain adaptive, competitive, and aligned with contemporary educational needs (Altbach & de Wit, 2018).

Among various strategies for improving educational quality, one of the most widely recognised frameworks is the Plan-Do-Check-Act (PDCA) cycle, a continuous improvement model rooted in Total Quality Management (TQM) principles and initially applied in industrial settings. The PDCA model has increasingly gained relevance in higher education as a systematic approach to planning, implementing, evaluating, and improving teaching and learning processes (Venkatraman, 2007). Despite its theoretical appeal, there remains a need for a structured analysis of how the PDCA framework has been applied in practice across diverse educational contexts and how it contributes to continuous quality improvement in teaching and learning. Addressing this gap, the present study conducts a structured literature review to provide insights into the strategic implementation of the PDCA approach and its implications for educational quality and institutional effectiveness.

Furthermore, while numerous experiential learning strategies have been developed, many fail to empower students as active contributors to knowledge creation. Existing studies have primarily examined students' roles as service providers in social or community-based projects (such as conservation or charity initiatives) rather than as participants in co-creative learning environments (Zhong, 2025). However, the integration of academic service projects with the PDCA cycle provides a powerful mechanism for enhancing learning outcomes for all stakeholders, students, educators, and partner organizations alike. By combining reflective practice with structured process improvement, this approach promotes shared learning, accountability, and continuous enhancement in higher education (Verna, 2020).

The PDCA cycle, developed by American statistician W. Edwards Deming, is a widely recognized framework for continuous improvement and organizational learning (Yan et al., 2025; Xuegao, 2013). Initially introduced in the field of quality management, the PDCA cycle has since been effectively adapted across various managerial and educational domains to enhance process efficiency and outcomes. It provides a structured, iterative approach for problem-solving and decision-making, promoting a culture of reflection and innovation (Hariyani et al., 2025). The cycle comprises four key stages: Plan, where objectives and strategies are defined; Do, which involves implementation; Check, focusing on evaluation and monitoring; and Act, emphasizing reflection and adjustment for future improvement (Verna et al., 2019). In the context of education, these phases are translated into actionable steps. Plan refers to course or lesson design, Do involves instructional delivery and student engagement, Check pertains to the assessment of learning outcomes, and Act involves using feedback for instructional improvement (Sangpikul, 2017). Given its alignment with the principles of action research and reflective practice, the PDCA cycle offers a robust foundation for continuous enhancement in teaching and learning (Zhong, 2025; Verna, 2020). This makes it a valuable tool for both educators and institutions seeking to align pedagogical strategies with quality assurance and learner success.

As a result, this study used it to continuously enhance instruction, which is advantageous to both teachers and students. PDCA and TQM principles can be effectively applied in education to enhance teaching and learning processes, improve outcomes, and foster continuous improvement. TQM principles can further enhance the application of PDCA in education by emphasizing the Customer focus, prioritizing the needs and expectations of students as the primary "customers" of the educational experience. It fosters a culture of continuous improvement among faculty, staff, and administrators, encouraging them to seek out opportunities for innovation and enhancement in teaching and learning practices. It also involves all members of the educational community, including faculty, staff, students, and parents, in the quality improvement process, recognizing their valuable insights and contributions. Furthermore, teaching and learning are interconnected processes that can be analyzed, optimized, and standardized to achieve consistent, high-quality outcomes. Ultimately, data and evidence should inform decision-making processes related to curriculum development, instructional design, and student support services. By integrating PDCA and TQM principles into their educational practices, institutions can create a more dynamic and responsive learning environment that promotes student success and fosters continuous organizational improvement. However, the objective of this study is:

a. To explore and synthesize prior studies on the application of PDCA in teaching-learning at higher education
b. To evaluate the impact of PDCA on course design, teaching, and student learning outcomes in the higher education context.
c. To explore the future research directions on PDCA in the teaching and learning process in higher education

While numerous studies have explored quality management approaches in education, the systematic application of the PDCA cycle within the teaching and learning process remains underexplored (Verna, 2020). The existing literature has predominantly focused on PDCA's role in institutional quality assurance, administrative operations, and accreditation processes, with limited attention given to its potential to enhance pedagogical practices, student engagement, and learning outcomes. For instance, Zhong (2025) applied the PDCA model in course design at an industrial training center, and Fu and Liu (2022) investigated its role in enhancing the professional competencies of vocational college instructors. Similarly, Yan et al. (2025) employed PDCA exclusively within the context of chemical and engineering technology curriculum. These examples illustrate a narrow and context-specific application of PDCA, lacking a broader pedagogical perspective that spans multiple disciplines and teaching strategies. As a result, a notable gap exists in understanding how iterative, data-informed PDCA cycles can be effectively integrated into classroom instruction to drive continuous improvement in teaching effectiveness and student achievement. Addressing this gap is essential, as the PDCA framework offers a structured and evidence-based approach that aligns well with the principles of reflective teaching and outcome-based education, positioning it as a valuable tool for fostering sustainable instructional innovation and improvement.

However, this study contributes to the PDCA literature in numerous ways; first, it identifies prevailing patterns and unexplored areas by categorizing the literature based on implementation strategies, theoretical foundations, research methodologies, and outcomes related to improving instructional and learning quality. The second contribution is presented by demonstrating the plan-do-check-act approach, where the planning phase enables educators to design course structures based on learning objectives, accrediting criteria, and student needs, ensuring compliance with institutional goals. This course planning is delivered to the students during the Do phase, utilizing unique teaching methodologies, instructional strategies, and technological resources to encourage student involvement. The Check Step entails assessing the course's effectiveness through feedback mechanisms, performance evaluations, and learning analytics to identify areas for improvement. Finally, the Act phase refines and optimizes the course using the insights gained, ensuring ongoing improvement and adaptation to shifting educational trends. Furthermore, implementing PDCA in course design enables higher education institutions to maintain high-quality instruction, proactively address learning gaps, and ensure continuous curriculum development.

Additionally, our contributions have been further organized into three key steps. First, the study uses a thorough bibliometric analysis to map the intellectual structure of PDCA research, identifying significant authors, influential publications, publishing patterns, and geographical distribution. This provides researchers and practitioners with an understanding of how PDCA research has evolved and where future efforts should be focused. Second, the thematic analysis offers a comprehensive evaluation of recurring issues in the literature, including the evolution of PDCA in educational settings, its application in teaching and learning, and its role in institutional quality assurance. These themes help explain the PDCA model as a strategic and educational tool. Third, the study provides future research opportunities by highlighting existing gaps in the literature, specifically the lack of studies on classroom-level PDCA implementation and its impact on student learning outcomes. This SLR not only consolidates current information but also serves as a road map for academics and educators seeking to adopt PDCA-driven continuous improvement in teaching, learning, and academic administration.

3.2. Background

A key element of contemporary quality management philosophy is the Plan–Do–Check–Act (PDCA) cycle, developed by American researcher W. Edwards Deming. Since its inception as a process improvement model in manufacturing and industrial settings, PDCA has developed into a universal framework for continuous improvement across a variety of fields, including public administration, healthcare, and education (Qingyan et al., 2023). The four interconnected phases of the model, planning, execution (doing), inspection (checking), and action, form an ongoing, iterative feedback loop to improve performance results, efficiency, and quality. Instead of being handled as discrete interventions, this cyclical nature guarantees that advancements are maintained and improved over time. According to Deming (1986), PDCA is a philosophy of learning and adaptation rather than just a procedural checklist. It helps businesses see issues, put solutions in place, assess how well they work, and take appropriate action to stop them from happening again. PDCA is a future-focused, adaptable, and logical technique for strategic decision-making because of its iterative logic. While the model's later stages institutionalize a culture of reflection and responsiveness, its structured planning phase promotes thorough problem identification, goal formulation, and data-driven analysis. Through methodical experimentation and feedback integration, PDCA promotes organizational learning and innovation, laying the groundwork for other continuous improvement models that surfaced in the later part of the 20th century, including Total Quality Management (TQM).

The PDCA cycle places a strong emphasis on the principle of continuous learning, wherein each completed iteration naturally gives rise to the next, thereby facilitating an ever-expanding accumulation of knowledge and experience. This cyclical process fosters an environment of reflection, adaptation, and systematic improvement, aligning well with the goals of modern pedagogy. In this context, the present study seeks to establish a conceptual and practical foundation for applying PDCA as a pedagogical framework within higher education. By employing the scientific logic of the PDCA methodology, Plan, Do, Check, and Act, this study articulates a structured approach to enhancing both teaching quality and learning outcomes through iterative refinement. Previous research provides valuable insights into the application of PDCA across diverse educational and managerial domains. For instance, Fu and Liu (2022) examined the integration of PDCA theory into the management of professional teacher development in higher vocational institutions. Their findings suggest that using PDCA to guide the continuous enhancement of teaching competencies effectively addresses challenges encountered in teacher training and professional practice. The study further concludes that this structured framework not only strengthens educators' theoretical understanding but also enhances their practical instructional skills, promoting a balance between academic rigor and pedagogical effectiveness. Consequently, the PDCA cycle has evolved from a quality management tool in industry to a dynamic educational methodology capable of driving sustained improvement in teaching, learning, and institutional performance.

Furthermore, Matsuo and Nakahara (2013) investigated the impact of the PDCA cycle on workplace learning, finding that its systematic structure enhances employees' capacity for reflection and knowledge sharing, ultimately leading to improved learning outcomes and enhanced organizational adaptability. Their findings underscore that the iterative nature of PDCA fosters a learning-oriented environment where individuals continuously refine their practices based on feedback. Similarly, Chien (2007) emphasized that in educational contexts, teachers must prioritize enhancing students' learning satisfaction through systematic feedback and continuous improvement, both of which are central principles of the PDCA framework. In higher education, Carroll et al. (2006) demonstrated how PDCA can serve as an effective self-assessment mechanism to improve educational processes, curriculum design, and overall institutional performance by promoting evidence-based decision-making. Extending this approach, Verna (2020) examined a holistic teaching model that integrates L'Ascolto, a reflective listening technique, within the PDCA cycle to foster continuous pedagogical improvement. The study revealed that embedding PDCA in instructional practice not only enhances teaching flexibility but also contributes to higher levels of student engagement and performance. This holistic use of PDCA emphasizes its dual role as both a quality assurance mechanism and a pedagogical innovation tool that enhances experiential learning for educators and students alike.

Few studies have examined the integration of PDCA in the teaching-learning process or its impact on reflective thinking in curriculum design in the learning process. According to the preceding debate, course design can be utilized to foster reflective thinking, whereas the PDCA cycle can ensure the quality of course design through reflection and continuous improvement. As a result, we believed that implementing the PDCA cycle technique in course design would improve students' skills and reflective thinking.

Research Gap

While prior literature provides valuable insights and a foundational understanding of PDCA in higher education, there are still considerable gaps that require more investigation. Firstly, existing research primarily focuses on the role of PDCA in institutional quality assurance, administrative processes, and accreditation systems, with few investigations examining how the model enhances pedagogical practice, student engagement, or learning outcomes (Schendzielorz et al., 2024; Matsuo & Nakahara, 2013; Venkatraman, 2007). Secondly, there is a lack of thorough synthesis that examines how the PDCA cycle is implemented in different educational settings, disciplines, and levels. Furthermore, little research has examined the individual influence of each phase, Plan, Do, Check, and Act, on educational outcomes or performance. The present body of literature also lacks consistency in measuring efficacy, with limited empirical data supporting the model's impact on measurable teaching and learning outcomes. The theoretical framing of PDCA is also inconsistently applied, with few researchers basing their work on continuous improvement theory or connecting PDCA to larger models of educational transformation. Furthermore, the rapid transition to digital and hybrid learning after 2020 has presented new complexities in teaching delivery; nevertheless, research into how PDCA has been modified to address these challenges in varied instructional environments is limited. These gaps highlight the need for thorough study systematically synthesizing research on the implementation, effects, and limitations of PDCA in teaching and learning contexts across higher education institutions.

3.3. Methodology

3.3.1 Theoretical Underpinning

This study is based on Continuous Improvement Theory (CIT), which emphasizes the continuous, circular improvement of processes, systems, and results through systematic reflection, measurement, and responsive action (Zangwill & Kantor, 1998). CIT is based on Deming's (1986) quality management principles and Total Quality Management (TQM) development. It states that continuous organizational success is achieved through a methodical, collaborative process of incremental change, rather than through discrete initiatives (Murray & Chapman, 2003). The PDCA cycle is a fundamental operationalization of CIT in practice, offering a systematic framework for executing continuous improvement in various situations, including higher education. In the context of higher education, CIT offers a theoretical framework for understanding and improving academic quality, organizational learning, and institutional performance (Yurkofsky et al., 2020). According to the theory, institutions are dynamic systems that must regularly evaluate their performance, include stakeholders, and modify their approach based on empirical facts and reflective practice. This makes CIT particularly important in current higher education contexts, which are characterized by rapid technological development, increased accountability, and shifting stakeholder expectations.

Operationally, this research employs the PDCA cycle as a realistic model for CIT implementation. The PDCA cycle, which stems from Deming's continuous improvement technique, provides an organized, cyclical procedure for making changes, implementing them, assessing results, and institutionalizing beneficial practices. Within higher education, the PDCA approach has been widely adopted in various fields, including curriculum development, quality assurance systems, e-learning environments, and institutional accreditation. By combining CIT with PDCA, this study acknowledges the need for continual, evidence-based reforms in higher education procedures. These frameworks emphasize that achieving sustainable excellence requires an ongoing process of planning, action, assessment, and adaptation, rather than adhering to static norms. As such, they form the theoretical basis for examining the implementation of PDCA in the teaching and learning process in higher education.

3.3.2 Structured Literature Review

This section outlines the methodological approach used for the structured literature review. According to Massaro et al. (2016), literature reviews are a collection of instruments that assist researchers in examining a field's past, formulating critical thoughts, and outlining its prospects for future study (Kaur & D'Andreamatteo, 2025). Additionally, they offer several guidelines that we used in our research.

3.3.3 Employed Protocol

Following the prior literature (Mehmood et al., 2025; Khursheed et al., 2025; Sangpikul, 2017), we used Scopus, a popular indexing platform among academic social studies practitioners, to create the collection of documents. This database offers substantial coverage of peer-reviewed journals. This database is highly dependable for similar investigations (Meho & Yang, 2007). Furthermore, the data in this database is both high-quality and impactful. Scholars argue that this database encompasses all the most important journals, allowing for a more comprehensive collection of publications (Meho & Yang, 2007).

We searched Scopus using specific queries to find relevant peer-reviewed articles, conference articles, and book chapters. Defining the research query is crucial for collecting relevant papers on the topic. However, we iterated over various keyword sets. We began researching with keywords such as “pdca” OR "plan do check act" OR “pdca cycle”. This search yielded a staggering number of papers, including 3068. The terms "PDCA" or "plan-do-check-act" refer to a generic PDCA phenomenon explored in various domains, including engineering, medicine, and neurology, which is why numerous studies have been conducted. This study focuses on PDCA research in higher education; therefore, utilizing relevant keywords could assist in finding relevant publications. Finally, we searched for "pdca" or "plan do check act" OR "pdca cycle" AND "education" OR "universities" in titles, abstracts, and keywords. As a result, we specifically collected 519 publications. The second Step involves search limiting; we restricted our search to the time (2002-2026), peer-reviewed journals, book chapters, and conference papers published in the English language only, with the following final research query:

TITLE-ABS-KEY ("pdca" OR "plan do check act" OR "pdca cycle" AND "education" OR "universities") AND PUBYEAR > 2001 AND PUBYEAR < 2027 AND (LIMIT-TO (DOCTYPE , "ar") OR LIMIT-TO (DOCTYPE , "cp") OR LIMIT-TO (DOCTYPE , "ch")) AND (LIMIT-TO (LANGUAGE , "English"))

However, we obtained 381 items. These articles were then extracted from Scopus and downloaded into a Microsoft Excel file, complete with full reference details. Additionally, the final database was expanded to include eight papers that employed the snowball method (Mazzocato et al., 2010). Finally, we cleaned the dataset to make it ready for data analysis. We screened all articles for PDCA-related content and removed duplicates. A total sample of 107 articles was included in the final investigation.

In Addition, this study employed the PRISMA method, as outlined by Moher et al. (2009), to select and analyze articles, as illustrated in Figure 1. PRISMA offers several benefits. Firstly, it facilitates the development of a theoretical framework without requiring prior background knowledge. Secondly, it ensures consistency in item selection, comparable to other structured literature review (SLR) methods. Given these advantages, PRISMA is an ideal approach for conducting content analysis.

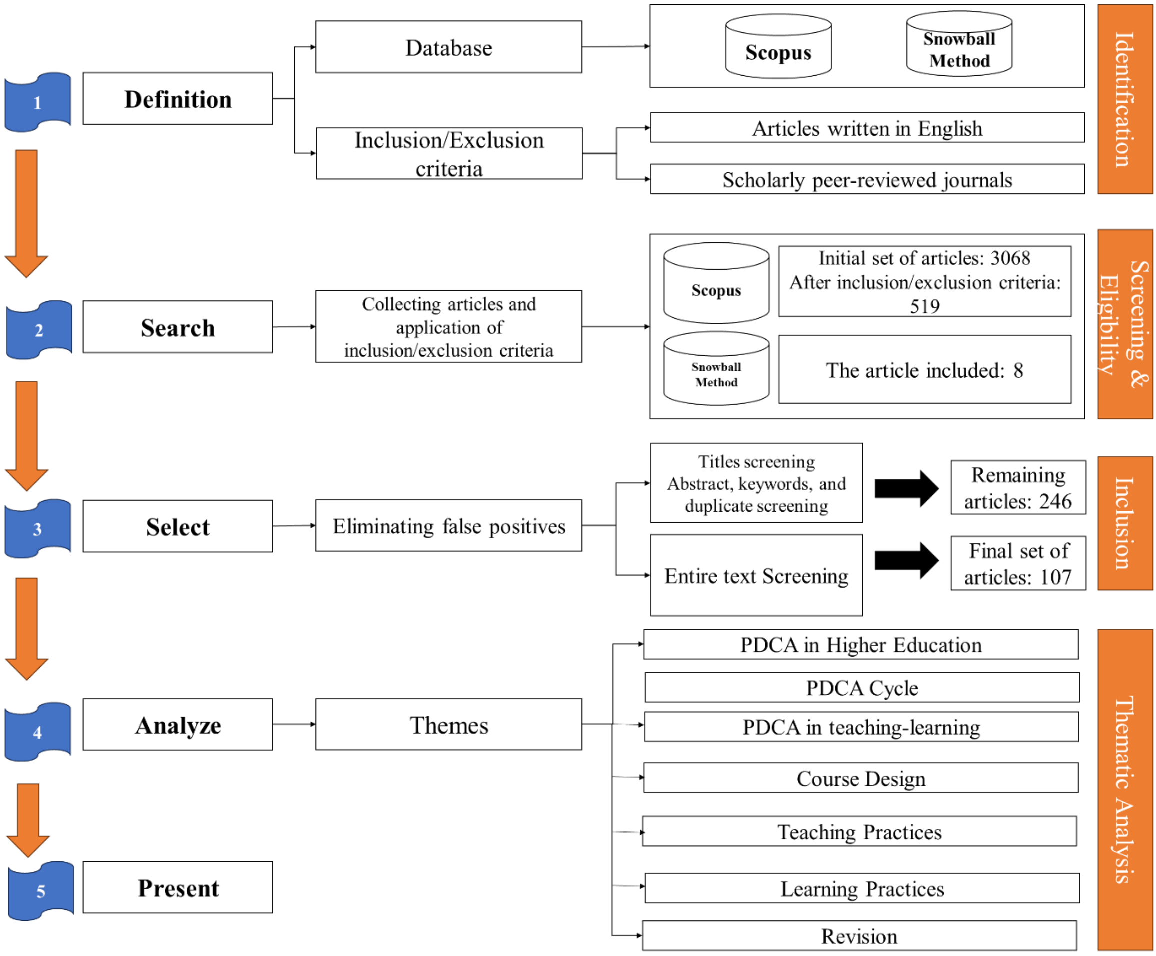

Figure 3.1: Applied protocol – PRISMA Framework

3.4. Results

3.4.1 Main Bibliometric Findings

This section presents an analysis of research on the PDCA approach in higher education. It begins by assessing publication trends over time and evaluating the most prominent journals and their influence. Finally, the analysis examines the important countries involved in scholarly discussions over PDCA.

3.4.1.1 Publication Trend Over the Years

Figure 2 illustrates the research on PDCA in higher education published during the last 30 years. Most articles were published in 2024 and 2023, followed by 2022, 2021, 2020, and 2019. The number of publications on this topic considerably increased in 2020. Since 2020, there has been a significant increase in publications each year, as the pandemic prompted institutions to transition to online learning and remote administration rapidly, necessitating ongoing process changes. Furthermore, since 2020, there has been an increase in open-access publications, particularly on educational methods during and after the COVID-19 pandemic. This made it easier for institutions to publish and discuss case studies that employed PDCA, resulting in additional publications. However, research on PDCA in higher education reveals a growing trend, demonstrating its popularity among scholars.

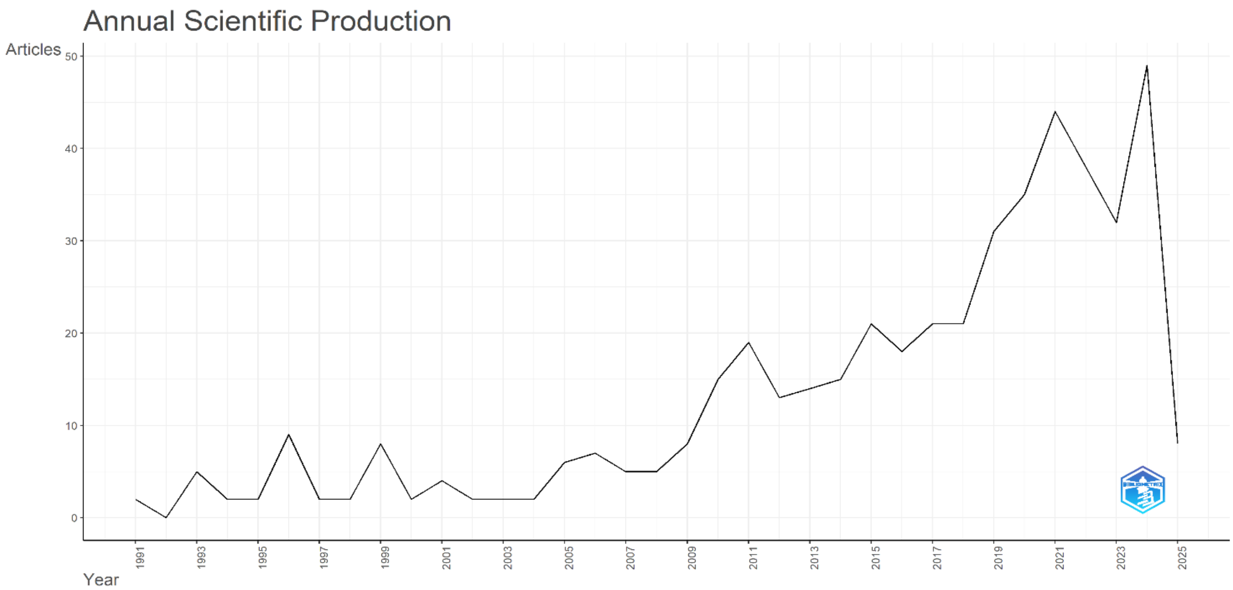

Figure 3. 2: Yearly publication frequency since 1994

3.4.1.2 Studies Published in Most Relevant Journals

Figure 3 shows the most relevant journals that have published studies on PDCA in higher education. The ACM international conference proceeding series has published the most studies on PDCA compared to others. The Applied Mathematics and Nonlinear Science Journal is ranked second, followed by BMC Medical Education and The Joint Commission Journal on Quality Improvement.

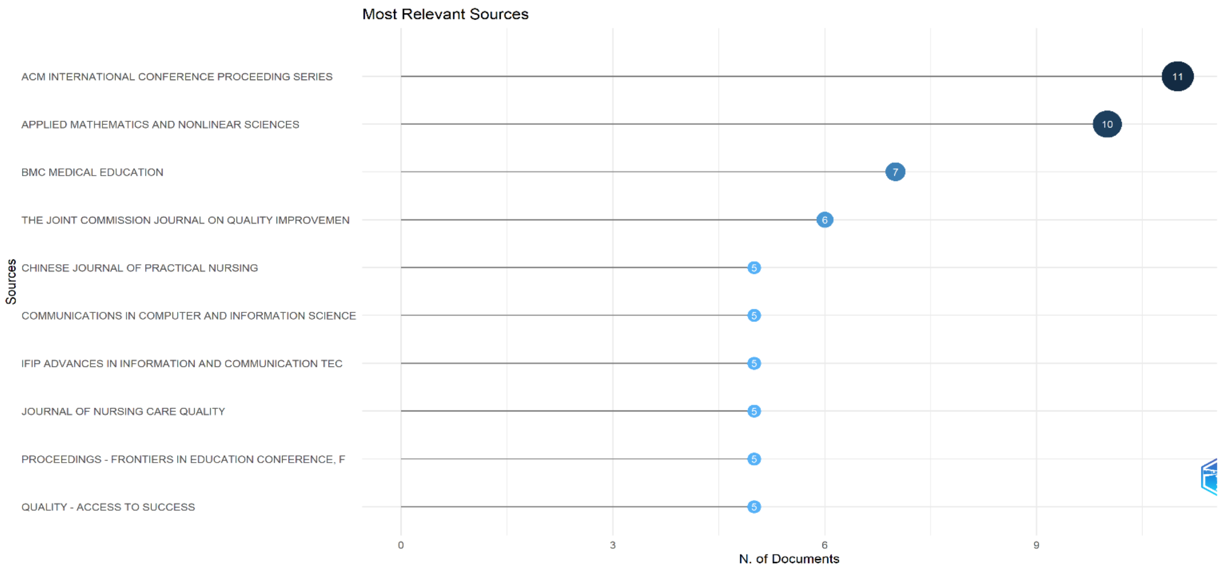

Figure 3. 3: Publication in the most relevant journals

3.4.1.3 Studies in the Most Relevant Countries

Figure 4 illustrates the country-wise distribution of research on the chosen topic. The United States leads in publications, reflecting its historical role in developing and popularizing the PDCA cycle and the strong research infrastructure supporting studies in quality management, education, and continuous improvement. China ranks second, followed by Germany, indicating growing scholarly interest in these countries. Other contributors include India, Japan, the Netherlands, Canada, and Italy. The relatively lower output from the United Kingdom and Brazil suggests varying levels of focus and institutional support for PDCA research. Overall, these trends highlight the global relevance of PDCA while emphasizing the United States' central role as a hub for both theoretical and applied research in this field.

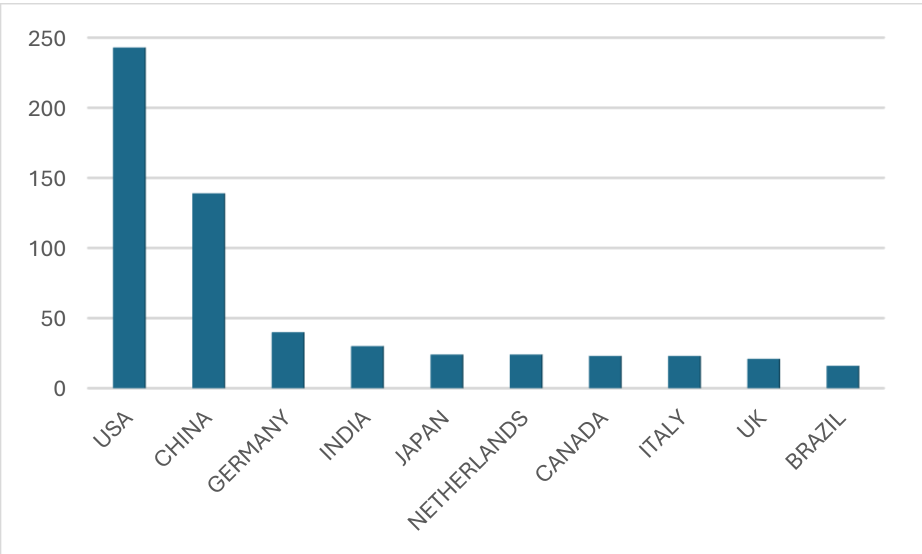

Figure 3.4: Article published across countries

3.4.1.4 Most Productive Authors

Figure 5 depicts the annual output of ten authors based on at least three papers in the dataset, using the Scopus ID of the authors to avoid ambiguities and duplications. This analysis presents a potential bridge between conversations about PDCA in higher education across diverse disciplines of study and related information. Simply put, this analysis can help determine both the relevant field and the precise material addressed by a particular author. Earlier in this section, we discussed the various sectors in which research on PDCA has been conducted. In contrast, the following section focuses on central questions and themes raised in discussions about PDCA in higher education. At this point, we focus on the most productive authors with at least three PDCA publications.

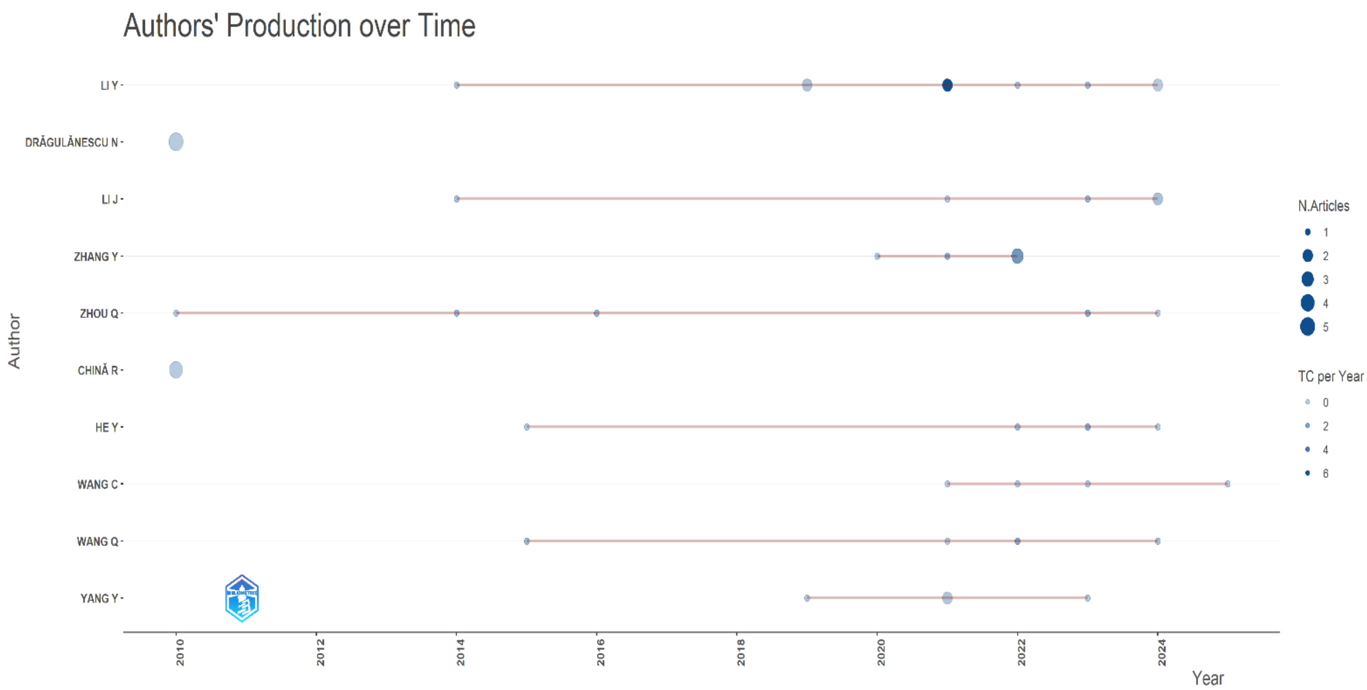

Figure 3. 5: Most Productive Authors

3.3.1.5 Most Cited Articles

Figure 6 illustrates the most cited papers, highlighting the foundational contributions that have shaped the field of study. These highly cited studies offer insight into the creation, application, and success of the PDCA cycle across various disciplines. By examining these prominent publications, we discovered key themes, methodological approaches, and practical applications that have influenced both academic research and real-world practice. Furthermore, the citation patterns of these papers demonstrate their influence on the growth of PDCA-related research, allowing us to better understand how the concept has evolved and expanded over time.

Incorporating these foundational publications into our analysis enables us to map the intellectual landscape of PDCA research and monitor its growth across many domains.

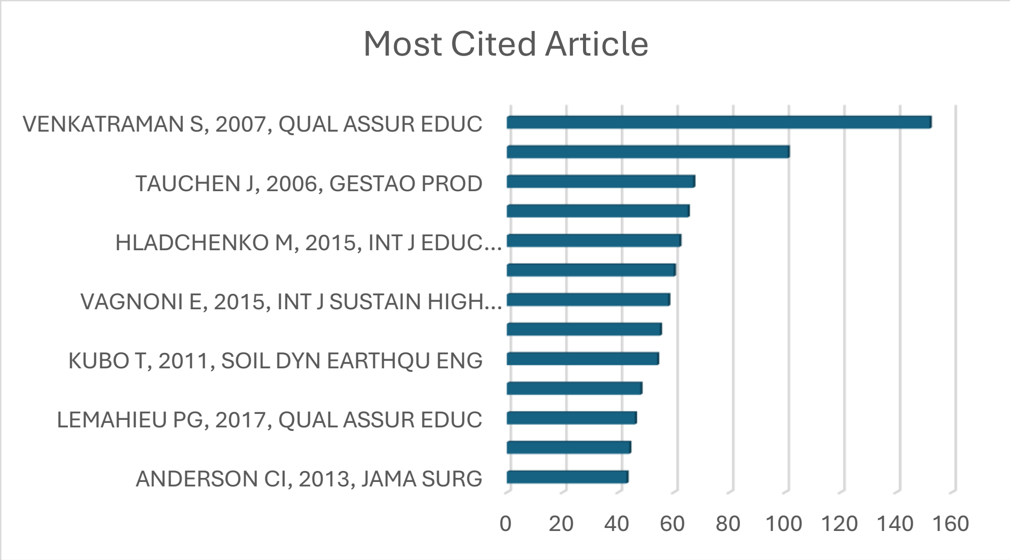

Figure 3.6: Most Cited Articles

3.4.2 Thematic Analysis

This study conducted a thematic analysis of chosen articles to gain a deeper understanding of the implementation of the PDCA cycle in higher education. Thematic analysis of the selected studies was conducted inductively, allowing key themes to emerge naturally through careful reading and interpretation of the literature. This approach ensured that the identified themes reflect the most prominent and recurrent concepts across the reviewed articles. This method enables the identification of common trends, essential concepts, and emerging themes across various institutional contexts and instructional applications. Thematic analysis is especially beneficial for synthesizing qualitative observations and identifying the underlying structures that guide the use of PDCA in teaching, learning, and academic quality improvement. After examining the findings of each chosen article, several important themes appeared. These themes provide the foundation for understanding the practical applications and theoretical implications of PDCA as a strategic tool for enhancing educational quality in higher education.

3.4.2.1 PDCA in Higher Education

Higher education has expanded significantly in recent decades, prompting universities and colleges to continually refine their teaching methods to better prepare graduates for the evolving demands of the workforce (Sangpikul, 2017). For this purpose, institutions employ various techniques in the teaching and learning process. The PDCA cycle is one of the most valuable and adaptable frameworks for achieving continuous improvement in academic contexts. Its cycle structure promotes data-driven decision-making and reflective teaching methods by developing interventions, implementing them, evaluating results, and making informed modifications (Deming, 1986).

However, this review identified the application of PDCA in higher education as a key theme, as shown in Figure 1, but the PDCA applications vary in concept and implementation. For instance, Chen (2012) employs the PDCA cycle of Total Quality Management (TQM) in higher education to assess the quality of higher education and finds that quality auditing and continuous improvement are key strategies employed by education providers to enhance their systems. Similarly, Verna (2020) used the holistic method L'Ascolta by applying the Deming PDCA cycle for the instruction process. Moreover, it is found that the PDCA positively affects students' performance and teaching.

Furthermore, Total Quality Management (TQM) has been adopted in educational institutions for some time, with the PDCA cycle serving as a fundamental tool for its implementation (Deming, 1982). While the PDCA framework has been extensively applied across various industries, the education sector still lags manufacturing due to the absence of robust quality assurance and control mechanisms. Unlike the manufacturing sector, which benefits from well-defined quality standards, the education system often aligns more closely with the service sector, where quality measurement is less standardized. Educators also face significant challenges in fostering effective quality management practices. As higher education expands from elite to mass and now universal access, there is an increasing emphasis on enhancing quality and operational performance. In today's competitive and dynamic global context, building a strong quality management system is essential for educational institutions seeking to implement TQM successfully (Chen, 2012).

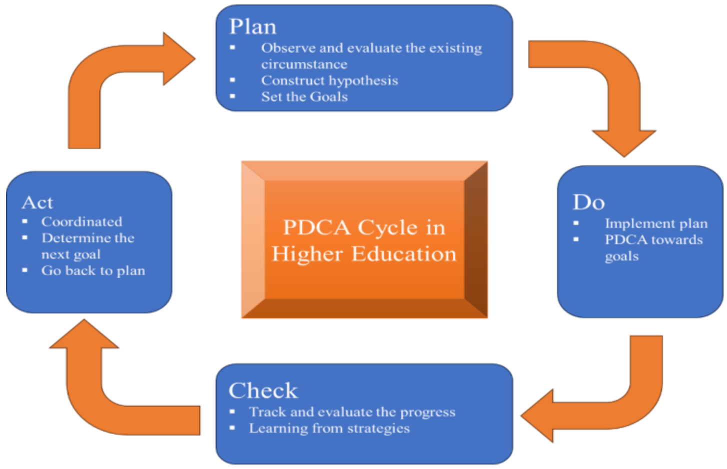

Figure 3.7: PDCA in Higher Education

3.4.2.2 PDCA Cycle

From the thematic analysis of the reviewed literature, one prominent theme that emerged is the evolution of the PDCA cycle over time and its adaptation across various disciplines. The PDCA model has experienced significant transformation since its early development, reflecting changes in quality management practices and organizational learning approaches. Initially conceptualized by Walter A. Shewhart as the Shewhart Cycle (Plan-Do-Study), it was later refined and popularized by W. Edwards Deming as the PDCA cycle (Deming, 1986; Wani et al., 2019). While it originated as a tool for industrial process control, the PDCA cycle has since been applied to various sectors, including healthcare, agriculture, public administration, and education, demonstrating its broad applicability. In educational contexts, PDCA is increasingly recognized for its ability to facilitate systematic improvements in teaching and learning by encouraging reflective practice, error prevention, and process standardization. This evolution illustrates the model's versatility and its growing relevance in supporting evidence-based, continuous improvement strategies in higher education.

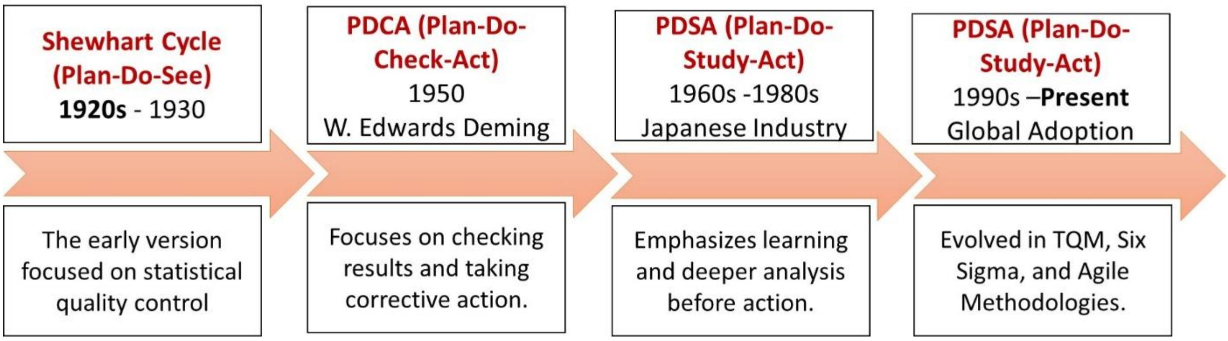

Figure 3.8: PDCA evolution

However, in the "Plan" phase, the goal statement is explicitly defined to highlight the project's principal purpose. Setting the target condition for a project outlines the desired future state in which the project will be adequately concluded. The "Do" phase focuses on implementing recommended countermeasures. Naturally, it takes longer, partly due to the initial run or test before full implementation. The "Check" phase entails monitoring and reflecting on the improvement to identify any potential refinement. The results of before and after implementation are compared using appropriate visual or graphical analyses. To sustain project improvement, the "Act" phase is the most crucial of all stages—project standardization and monitoring after implementing the countermeasure to ensure that workers are following through on the implementation. Following the completion of the project, practitioners are urged to undertake Yokoten, which is sharing project-related experiences and knowledge with other departments. The PDCA cycle continues until the goal is met. It is not unusual for PDCA to undergo multiple iterations before the goal is achieved.

3.4.2.3 PDCA in Teaching and Learning

Another important theme emerging from the thematic analysis is the use of the PDCA cycle in higher education teaching and learning activities. The PDCA cycle, as a structured continuous improvement process, promotes systematic course planning, instructional delivery, assessment, and iterative revision, all of which improve teaching effectiveness and student learning outcomes (Sangpikul, 2017). Several studies have demonstrated its practical use in curriculum design and education. For example, Kim et al. (2019) demonstrated that integrating the National Competency Standards (NCS) with the PDCA model enabled universities to develop more flexible, competency-based curricula that align with labour market expectations. Their findings suggest that PDCA promotes greater alignment between desired learning outcomes and industry expectations, resulting in enhanced graduate employability. However, the successful adoption of PDCA in academic contexts depends on several enablers, including faculty development programs, institutional commitment, and robust feedback mechanisms that facilitate ongoing adaptation and improvement. These findings support the potential of PDCA as a dynamic tool for improving educational practice.

3.4.2.4 Course Design (The Plan Phase)

The "PLAN" or planning phase of the methodology (Course Design & Learning Objectives) is the first Step in implementing Total Quality Management (TQM) in the course. The implementation of the "Plan" phase of the PDCA cycle improved teaching and learning outcomes through innovative course design (Schendzielorz et al., 2024). It defines educational goals and objectives based on curriculum standards, student needs, and institutional priorities (Aggarwal & Lynn, 2012). For instance, Zhong (2025) explored how the PDCA is used to improve curriculum design by identifying gaps in student engagement. However, by explicitly identifying learning objectives and aligning them with curricular standards and student needs, teachers were able to create a more structured and engaging learning environment. The planning Step also included an analysis of students' prior knowledge and learning preferences, which helped to guide the selection of acceptable teaching methods and assessment methodologies. This connection provided that educational activities were not only appropriate and interesting but also effective in supporting the targeted learning objectives.

For instance, in the planning phase, Verna (2020) used the quality function deployment (QFD) strategy to describe the aims of courses by listing students' needs. Furthermore, the early implementation of feedback systems and the careful use of educational technology increased accessibility, enabling rapid help and intervention. As a result, both teaching methods and student involvement showed significant gains, emphasizing the importance of the "Plan" Step in laying the groundwork for continual educational reform.

3.4.2.5 Teaching (The Do Phase)

The second phase is the "Do" or implementation phase (Course Delivery & Teaching Strategies). Implement teaching strategies and activities by the planned curriculum. Engage students actively in learning through various instructional methods, including lectures, discussions, hands-on activities, and multimedia presentations (Verna & Perozzi, 2014). Digital technologies and interactive resources were integrated into the educational process, enhancing accessibility and student engagement. Throughout this phase, instructors constantly evaluated student feedback and gathered formative assessment data to track development (Aggarwal & Lynn, 2012). Regular feedback is provided to students to help them learn and reflect on their progress. Furthermore, it addresses issues in real-time and adapts teaching approaches based on student feedback. The implementation process served as a practical testing environment for the course design, enabling instructors to evaluate how effectively the teaching approaches supported learning objectives. This phase provided valuable insights into classroom dynamics, learner engagement, and instructional efficacy, laying the groundwork for future evaluation and continual improvement in the PDCA cycle.

3.4.2.6 Learning (The Check phase)

The third stage is the "Check" or evaluation phase (Learning), which assesses student learning outcomes using various assessment and evaluation methods, including tests, quizzes, projects, and presentations. During this phase, the teacher employs both quantitative and qualitative methods to assess students' learning needs (Verna, 2020). Analyze assessment data to evaluate the effectiveness of teaching methods and identify areas for improvement. Collect student feedback through surveys, focus groups, or course evaluations to understand their perspectives on the teaching and learning experience (Lu et al., 2024). Identifying learning gaps, inconsistent information delivery, and opportunities for improvement, comparing course efficacy with previous iterations or comparable programs.

According to Kim et al. (2019), universities have measured the success of the competency-based curriculum using a variety of assessment measures, including student performance statistics, employer feedback, and faculty reviews. Institutions regularly undertake curriculum audits and surveys to discover discrepancies between learning outcomes and industry expectations. Additionally, stakeholder engagements with businesses and graduates were conducted to assess whether students were developing the requisite workforce competencies. This phase enabled the identification of curriculum shortcomings early on, allowing for data-driven decisions in future curriculum modifications.

3.4.2.7 Revision (The Act Phase)

The final stage is the "Act" or improvement phase (Course Revision & Enhancement), which adjusts teaching strategies, curriculum content, and assessment methods based on assessment results and student feedback to meet students' needs better. Implement changes and improvements systematically, ensuring that they are communicated effectively to all stakeholders. Continuously monitor and evaluate the impact of changes, iterating the PDCA cycle as necessary to drive ongoing improvement and establish a cycle of ongoing development for upcoming course offerings (Aggarwal & Lynn, 2012). Similarly, Kim et al. (2019) employed the PDCA methodology as a continuous improvement approach in universities in South Korea to ensure that curriculum updates were carried out systematically. Institutions revised course material, teaching practices, and evaluation standards in response to input from the Check phase (Schendzielorz et al., 2024). This iterative procedure enabled institutions to adapt to changing industry trends and rising skill demands. Additionally, the study emphasized the importance of institutional support and policy changes in sustaining long-term curricular development efforts. The "Act" phase thus played a crucial role in completing the quality loop and fostering a culture of continuous improvement in the educational process.

3.5. Future Research Directions

Higher education course design that incorporates the PDCA cycle provides an organized approach for ongoing development. The following crucial areas can be investigated in future studies to increase their efficacy.

3.5.1 Course Design Based on Data and Continuous Improvement

Future research could explore how advanced learning analytics and AI-powered assessment tools can enhance the implementation of the PDCA cycle in higher education course development. By leveraging real-time data on student engagement, learning progress, and performance outcomes, institutions can systematically integrate evidence into the Check and Act phases, allowing for timely and data-driven adjustments to instructional design. Such an approach would enable educators to identify learning gaps, adapt teaching strategies, and personalize learning experiences more effectively, fostering a truly responsive curriculum. Moreover, combining PDCA with predictive analytics could help anticipate challenges before they arise, optimize resource allocation, and enhance the overall quality and efficiency of course delivery. Future studies might also examine how AI-supported dashboards, automated feedback systems, and adaptive learning platforms contribute to continuous improvement, bridging the gap between pedagogical theory and practical classroom innovation. Ultimately, integrating data-driven decision-making within the PDCA framework has the potential to transform course design into a dynamic, evidence-informed process that continually evolves to meet students' needs and aligns with institutional quality standards.

3.5.2 Institutional Implementation of PDCA for Curriculum Enhancement

Although the PDCA cycle has traditionally been applied to quality improvement in business and manufacturing contexts, there is a growing need to explore its systematic adoption within higher education institutions. Future research could examine how universities can implement PDCA comprehensively across departments to ensure consistency in course design, delivery, and assessment. Such studies might focus on aligning curriculum development with institutional goals, maintaining accreditation standards, and fostering ongoing faculty development. Additionally, research could explore how PDCA can be embedded into institutional policies and administrative processes to support continuous monitoring, feedback, and iterative improvement of academic programs. By investigating these applications, scholars can provide guidance on scaling PDCA from individual courses to an institution-wide framework, thereby enhancing overall educational quality, promoting consistency across programs, and creating a culture of continuous improvement throughout the university.

3.5.3 Empirical Studies on PDCA

While the principles of the PDCA cycle align closely with established quality assurance frameworks, there remains a notable lack of empirical research on their concrete application in university course design. To address this gap, future studies could focus on in-depth, real-world case studies from Italian universities to explore how PDCA is implemented in practice. Such investigations might examine the ways institutions plan, execute, monitor, and refine their curricula, highlighting both successes and challenges in operationalizing continuous improvement processes. Additionally, research could analyze the role of faculty engagement, administrative support, and institutional policies in facilitating or hindering the adoption of PDCA principles. By documenting these practical experiences, scholars can generate evidence-based insights on the effectiveness of PDCA in enhancing course quality, aligning teaching with student needs, and fostering a culture of iterative improvement within higher education institutions.

3.5.4 Standardization and Implementation Frameworks

To fully leverage the potential of the PDCA cycle in higher education, it is essential to develop standardized models and practical implementation tools that guide educators and institutions in its application. Future research could focus on designing and rigorously evaluating these frameworks to ensure that they are consistent, scalable, and adaptable across different academic disciplines and learning environments. Such investigations might explore best practices for integrating PDCA into curriculum planning, assessment strategies, and faculty development programs, as well as methods for monitoring outcomes and sustaining continuous improvement. By establishing clear guidelines and user-friendly instruments, universities can enhance the effectiveness of PDCA, promote uniformity in quality assurance practices, and embed iterative improvement processes as a core element of strategic educational planning. Ultimately, these efforts would contribute to institutionalizing PDCA as a central mechanism for achieving long-term educational excellence and responsiveness to evolving student and societal needs.

3.5.5 Ethical and Sustainability Implications of AI in PDCA-Based Education

While the integration of AI and digital analytics can significantly enhance the implementation of the PDCA cycle in higher education, future research should also examine its potential challenges and unintended consequences. The growing reliance on AI-supported learning analytics and automated decision systems may raise important ethical concerns, including algorithmic bias, data privacy risks, and issues related to transparency in academic decision-making. In addition, excessive dependence on automated systems could reduce the role of human pedagogical judgment in curriculum planning and evaluation. Beyond ethical considerations, the expansion of digital infrastructures and AI-based educational technologies may also generate environmental pressures, particularly through increased energy consumption and the growing computational demands of large-scale data processing. Future research should therefore investigate how AI-driven digital transformation within PDCA-based course design can balance improvements in efficiency with the ethical and environmental dimensions of the Sustainable Development Goals (SDGs).

3.6 Conclusion

The use of the PDCA cycle in higher education can improve teaching and learning and make it a continuous process. This structured review analyzes 107 articles, focusing on how the PDCA approach offers a structured technique for iterative teaching and learning improvement, encouraging data-driven decision-making and student-centered learning experiences.

However, the Plan phase enables educators to create course structures based on learning objectives, accrediting criteria, and student needs, assuring alignment with institutional aims. Courses are implemented during the Do phase, utilizing novel teaching approaches, instructional strategies, and technological resources to enhance student engagement. The Check phase involves evaluating the course's effectiveness using feedback systems, performance evaluations, and learning analytics to find areas for improvement. Finally, the Act phase refines and optimizes the course based on the insights obtained, ensuring continual improvement and adaptation to changing educational trends. By implementing the PDCA cycle in course design, higher education institutions can sustain high-quality instruction, proactively address learning gaps, and ensure ongoing curriculum growth. Furthermore, PDCA promotes accreditation and quality assurance processes, making it an important framework for sustaining educational excellence. In addition, this study employs bibliometric analysis to identify publishing trends and influential authors, highlighting a growing scholarly interest in recent years. Thematic analysis further reveals key areas of concentration, such as PDCA's transition from quality management to pedagogy, its application in instructional improvement, and its incorporation into service learning. The paper identifies significant research gaps, highlighting the importance of conducting broader empirical studies across disciplines and gathering more evidence on the impact of PDCA on student and faculty outcomes. By aligning the PDCA framework with Sustainable Development Goal 4 (SDG 4), this study emphasizes its potential to enhance inclusive, equitable, and quality education through continuous curriculum improvement and evidence-based teaching practices.

This study is subject to several limitations that should be acknowledged. First, the selection criteria used for including and excluding articles in the structured literature review, as well as the coding and categorization applied during thematic analysis, may have inadvertently excluded relevant studies or emerging perspectives, which could affect the comprehensiveness of the findings. Additionally, while the review provides insights into the application of the PDCA cycle in higher education, it primarily synthesizes published literature and may not fully capture unpublished practices or contextual variations across different institutions and countries. The scope of this study is also limited in terms of disciplinary diversity, as the majority of the analyzed studies focus on general higher education programs rather than specialized or professional courses. These limitations highlight opportunities for future research, including examining the implementation of PDCA across multiple fields, diverse educational contexts, and varying institutional structures, as well as evaluating its long-term effects on student learning outcomes, faculty professional development, and curriculum innovation. Despite these constraints, the PDCA cycle remains a structured yet adaptable methodology that empowers educators and administrators to systematically plan, execute, assess, and refine courses, foster continuous improvement, and enhance the overall quality and effectiveness of the teaching and learning process.

3.7 Policy Recommendations

For higher education institutions to successfully integrate the Plan-Do-Check-Act (PDCA) cycle into course design, it is essential to cultivate an institutional culture grounded in continuous improvement and evidence-based quality assurance. This requires universities to embed the PDCA framework systematically within their curriculum development and review processes, ensuring that planning, implementation, assessment, and refinement occur in a structured and iterative manner. Faculty development should be treated as a strategic priority, providing instructors with professional training, pedagogical resources, and reflective practices necessary to operationalize the PDCA model effectively. In addition, incorporating systematic feedback mechanisms such as student evaluations, satisfaction surveys, and performance data analysis can strengthen the Check phase by ensuring that curriculum adjustments are responsive to learners' evolving needs and expectations. Sustaining such an approach also depends on adequate institutional support, including technological infrastructure, administrative commitment, and dedicated funding. When these conditions are met, universities can establish a self-renewing system of teaching and learning that remains agile, outcome-oriented, and aligned with both academic standards and labor market requirements.

4. The Impact of Digitalization, Renewable Energy, and Natural Resources on Environmental Quality: The Role of Government Expenditure in EU27 Countries

4.1 Introduction

In recent years, the persistent encouragement and transmission of environmental protection ideas across many nations have significantly increased awareness among businesses and citizens regarding environmental governance (Ding et al., 2024). This phenomenon indeed emphasizes the intention of governments to prevent ecological harm. The rapid evolution of conventional and modern factors influencing global economic growth has led to consensus on advancing low CO_2 emissions (Silva et al., 2023; Yu et al., 2023). The decline of CO_2 emissions has emerged as the primary development strategy for numerous nations, particularly in advanced countries (e.g., the EU27) that are minimizing CO_2 emissions as their principal source for production and consumption (Fuinhas et al., 2017; Shen et al., 2023). Decarbonization is driven by the demand for and availability of different fuels and the move from high dependency on biomass and high-carbon fossil energy to large-scale production through new technologies. However, national governments worldwide are now concentrating on whether this decarbonization transition is feasible given the current structure of production and consumption of goods and services (Shahbaz et al., 2022).

Numerous initiatives have been taken to tackle socioeconomic and environmental issues effectively; as part of this commitment, United Nations member states introduced the Sustainable Development Goals (SDGs) in 2015. Among them, SDG 7, which aims to ensure that everyone has access to affordable, dependable, sustainable, and modern energy, is becoming increasingly important. The integration of digital technology has the potential to improve energy efficiency, optimize renewable energy systems, and promote energy innovation. Similarly, SDG 13, which focuses on urgent climate action, emphasizes the necessity of lowering carbon emissions and strengthening resilience to climate-related risks. Effective governance and targeted public spending may accelerate the adoption of green technologies and sustainable energy practices, balancing economic growth with the protection of the environment.

Many researchers have examined the factors influencing CO_2 emissions as a proxy for environmental quality, highlighting diverse perspectives to address the challenges in this field and accelerate sustainable development. The advancement of digital technologies has significantly altered residents' consumption patterns and reduced the demand for conventional energy and physical presence in service consumption. Within this context, Ecological Modernization Theory (EMT) provides a useful framework, as it argues that technological innovation and institutional support can simultaneously advance economic development and environmental sustainability. From this perspective, digitalization acts as an eco-innovation driver that promotes environmental quality by improving the efficiency of public service delivery, streamlining documentation, and enabling online monitoring (Zou et al., 2023). It also facilitates communication between citizens and government authorities through digital platforms and applications, thereby decreasing transportation needs, minimizing physical presence, and reducing CO_2 emissions. Furthermore, by fostering two-way interactions between social actors and public officials (Shahbaz et al., 2022) and by enabling automated systems that enhance transparency, authenticity, and operational efficiency (Ding et al., 2024), digitalization aligns with the assertion of EMT that modern technologies can restructure social and industrial processes to achieve both economic and ecological gains.

Governments play a crucial role in promoting environmental quality during the digital transition process, as evidenced by their impact on economic growth and spending decisions. Empirical evidence suggests that government investment in R&D and green projects reduces environmental pollution (Abbass et al., 2022). Even though government spending can undeniably promote economic growth, it also affects environmental quality. The relationships between government expenditures, digitization, and environmental quality have been largely overlooked in the current research. However, government spending affects the environment directly and indirectly (Le et al., 2020). Government spending on public goods such as social transfers and household subsidies can generate an income effect, encouraging demand for "green products" and thereby reducing pollution (Wang et al., 2024). Similarly, expenditure on infrastructure (such as transportation, communication, and energy) and on the development of human and physical capital through education and healthcare exerts an indirect effect, influencing both production growth and environmental outcomes (Le et al., 2020). Public investment in R&D and knowledge sharing can also stimulate the adoption of cleaner technologies (López et al., 2011). In line with Ecological Modernization Theory, these forms of targeted spending enable governments to combine economic growth with ecological sustainability by promoting eco-innovation, environmental regulation, and technological upgrading. However, as highlighted by the Resource Curse Theory, misallocation of government revenues or overdependence on resource-based rents can undermine these benefits, reinforce unsustainable practices, and exacerbate environmental degradation. Thus, the environmental impact of government expenditure depends on whether spending is strategically aligned with modernization-oriented policies or trapped in resource dependency.

In the pursuit of sustainability, renewable energy (REN) and natural resource utilization stand at the forefront of debates on environmental quality. A growing body of evidence confirms that REN adoption reduces CO_2 emissions and fosters long-term ecological sustainability (Ansari et al., 2024; Javed et al., 2023, 2024; Wang et al., 2024; Mohammed et al., 2024; Banday & Aneja, 2020). Conversely, reliance on total natural resource rents (TNRR), particularly from non-renewable sources, often exacerbates carbon emissions because extraction and processing are highly energy-intensive (Raihan et al., 2024; Tahir et al., 2024). Drawing on Resource Curse Theory (RCT), resource abundance can thus intensify environmental degradation through institutional weakness and rent-seeking, yet this outcome is conditional: strong ecological governance, institutional quality, and investments in green technologies can redirect resource rents toward sustainable development (Miao et al., 2023; Afolabi, 2023; Zafar et al., 2023).

Therefore, several researchers have studied the variables affecting carbon emissions in different nations. Such as Işık et al. (2024) explore the effect of governance and technological factors on environmental quality for G7 countries, Ulussever et al. (2024) for GCC countries, and Qayyum et al. (2024) for Mercosur countries. Concerning the EU27, the European Union (EU) has achieved tremendous progress in decreasing CO_2 emissions during the last several decades. Furthermore, targeted investment under initiatives such as the European Green Deal, the Recovery and Resilience Facility, and Horizon Europe supports renewable energy, energy-efficient buildings, and green technologies, contributing to the EU's transition to carbon neutrality by 2050 (European Commission 2020). Despite the EU's substantial progress toward carbon neutrality, several member states continue to face challenges in fully decarbonizing their economies, particularly in energy-intensive sectors such as transportation and heavy industries. Eastern European countries, which remain heavily dependent on coal and other fossil fuels, are transitioning to clean energy at a slower pace compared to their Western European counterparts. Collectively, the EU-27 remains one of the world's largest emitters of CO_2, underscoring persistent regional disparities in environmental performance. This heterogeneity highlights the need for coordinated yet country-specific policy approaches to effectively mitigate emissions and achieve shared climate goals. Against this backdrop, the primary objective of the present study is to examine how DIGIT, GOV, REN, GDP, and TNRR influence environmental quality across EU-27 economies from 2000 to 2022. By integrating both the Ecological Modernization Theory (EMT) and the Resource Curse Theory (RCT), the study aims to uncover how technological advancement and resource dependence jointly shape the regional environmental outcomes.

The significance of the EU nations for economic growth and their goal to achieve the SDGs encourages researchers to assess the environmental quality. However, this study contributes to the body of literature in various ways. First, based on the dynamics of the EU27 economies, the analysis considers complete and unique characteristics regarded as CO_2 drivers such as DIGIT, GOV, REN, GDP, and TNRR. Other research considered limited parameters for analyzing the impact of different factors on CO_2 in the EU27 countries. For instance, Mehta and Prajapati (2024) examine the effect of environmental tax and environmental spending on CO_2 emissions in EU27 countries. Similarly, Mohammed et al. (2024) analyzed the impact of energy consumption, population, and GDP on CO_2 emissions in EU27 countries. Based on the existing literature, this study is the first to comprehensively examine the combined effect of DIGIT, GOV, REN, GDP, and TNRR on CO_2 emissions across the EU27 countries. Secondly, this study makes a novel contribution by introducing the interaction effect of digitization and government expenditures on environmental quality in the setting of EU27 countries. To the best of our knowledge, no previous research has particularly investigated how digital transformation and fiscal policy interaction shape environmental outcomes in the EU27. By exploring this interaction, the study adds new empirical evidence to the synergistic effects of technical innovation and government spending in driving environmental quality.

Third, this study advances the methodological framework by employing the Method of Moments Quantile Regression (MMQR), addressing key constraints identified in previous studies. Prior literature mostly used means estimation (Yasmeen et al., 2024), which captures average effects, and Panel Quantile Regression (Javed et al., 2024), which has incidental parameter and potential bias issues. On the other hand, MMQR solves these problems, providing consistent outcomes without demanding estimation of individual-specific effects (Machado and Silva, 2019). In addition, this study uses the set of 2^{nd} generation panel diagnostic tests. These tests include cross-sectional dependence, slope heterogeneity, and second-generation panel stationarity tests such as the CIPS test. Furthermore, we employ Westerlund co-integration. In addition, we utilize some tests for robustness, including FMOLS, DOLS, and FE-OLS. Moreover, these tests evaluate the long-run relationships among the variables; they do not capture causal linkages. However, we used Dumitrescu and Hurlin's (2012) Granger causality test to investigate the direction of causality between the variables.

Fourth, by covering the period from 2000 to 2022, the study integrates both pre- and post-climate policy initiatives in the EU, thereby offering updated evidence that reflects recent technological and policy developments. These contributions highlight the originality and relevance of the study in extending the existing literature on environmental sustainability in the EU context. Finally, Theoretical perspectives such as the ecological modernization theory and the resource curse framework offer important insights into these relationships. However, existing studies often analyze these factors in isolation, with limited attention to their combined effects or the moderating role of institutional and technological factors. This study contributes to the literature by simultaneously examining the influence of digitalization, renewable energy, government expenditure, natural resource rents, and GDP on environmental degradation across the EU-27

4.2 Literature Review

4.2.1 Digitalization and CO_2 Emissions

Several previous studies have examined the influence of digitalization on CO2 emissions. These studies imply that digitalization has dramatically cut CO2 emissions due to its impact on infrastructure, technological innovation, and resource allocation (Edquist and Bergmark, 2024). Notably, Wang et al. (2023) conducted a study to analyze the effect of the digital economy on CO_2 emissions in G7 countries. They found that the digital economy considerably reduces CO_2 emissions per capita. Digitalization may indirectly impact CO_2 emissions per capita by influencing technological innovation. Digitalization can also shift energy consumption patterns towards renewable energy sources and reduce emissions. Similarly, Shahbaz et al. (2022) explored the effect of digitalization on energy transition for 72 countries and found that digitalization positively transitions energy consumption to renewable energy.

The internet's ability to reduce CO_2 emissions has drawn much attention as an essential aspect of the ICT sector. For instance, Higón et al. (2017) found that internet development can improve environmental quality by reducing CO_2 emissions across 142 countries. Technological advancements, effective government policies, and human capital contribute to this improvement. ICT promotes energy efficiency, improves industrial processes, and reduces transportation demand, leading to emission reductions. ICT can promote decarbonization, dematerialization, and productivity, reducing resource use and decreasing CO_2 emissions (Sundaramoorthy et al., 2023). Grounded in Ecological Modernization Theory, digitalization is viewed as a transformative force that fosters eco-innovation, improves energy efficiency, and reduces reliance on resource-intensive processes. EMT suggests that technological advancement, when accompanied by supportive institutional frameworks, can simultaneously enhance economic performance and environmental outcomes. Within this perspective, digitalization contributes to cleaner production systems, smarter energy use, and reduced emissions.

Consequently, we propose the research hypothesis (H1):

H1: Digitalization positively and significantly affects EQ (environmental quality).

4.2.2 Government expenditure and CO_2 Emissions

In recent decades, government spending has increasingly focused on promoting environmental quality. Prior literature regarding governance, government expenditure, and ecological interrelations includes some articles that examine the government expenditure, digital economy, and environmental quality nexus. For instance, Yasmeen et al. (2024) studied the role of government expenditure and digital economy on economic and ecological sustainability in G7 countries from 1996 to 2020. The results show that government expenditure and the digital economy significantly enhance the economic and ecological sustainability of the underlying countries. Similarly, Yan et al. (2025) examined the impact of green finance on energy security across Chinese provinces using machine learning approaches. Their findings suggest that financial instruments play a crucial role in shaping the trajectory of energy systems, ultimately leading to greater sustainability. Conversely, Yuelan et al. (2019) examined the impact of fiscal policy instruments, including government expenditures and total revenue, alongside GDP and energy consumption, on China's environmental degradation from 1980 to 2016, revealing that all these variables contributed to environmental degradation. Consequently, the government's role, particularly regarding expansionary fiscal policy, may exacerbate environmental deterioration.

Similarly, Mohammed Saud et al. (2019) examined the impact of government expenditure and financial development on environmental degradation in Venezuela from 1971 to 2013 via the ARDL approach, revealing that government expenditure exacerbated pollution while financial growth enhanced ecological quality. Similarly, López et al. (2011) analyzed the effects of fiscal spending on environmental quality for 47 countries from 1980 to 2005. They found that redirecting government spending towards social and public goods minimizes pollution. Another study by Adewuyi (2016) acknowledged that, by using data from 40 top emissions countries during the period 1990-2005, a rise in government expenditure in the transportation and production sectors decreases CO_2 emissions.

However, drawing on the frameworks of Ecological Modernization and Resource Curse theories, government expenditure is posited to enhance environmental quality when strategically allocated to green infrastructure, innovation, and sustainable public goods, thereby countering the traditional resource curse paradigm. Consequently, we propose the research hypothesis (H2)

H2: Government expenditure has a positive and significant effect on EQ (environmental quality)

4.2.3 Renewable Energy and CO_2 Emission

Renewable energy (REN) has been widely recognized as a cornerstone of sustainability and a critical instrument in mitigating CO_2 emissions. Ansari et al. (2024) demonstrated that REN significantly reduces environmental degradation, with its effectiveness further enhanced through the integration of digital finance and strong institutional quality. In a similar vein, Javed et al. (2024) highlighted that the transition to REN, when supported by green technological innovation and stringent environmental policies, plays a decisive role in addressing ecological crises and advancing long-term ecological sustainability. Expanding this perspective to different regions, Wang et al. (2024) provided evidence from Africa, showing that REN consumption serves as a vital tool for CO_2 mitigation in the post-COP26 era. Their findings further emphasize that the environmental benefits of REN are amplified when combined with technological innovation, robust financial development, and strategic government expenditure. Focusing on Europe, Mohammed et al. (2024) revealed that REN adoption is a key driver of environmental sustainability in EU-27 countries, reinforcing the region's progress along the Environmental Kuznets Curve. Complementary evidence from major emerging economies is offered by Banday and Aneja (2020), who, using bootstrap panel causality analysis within BRICS nations, confirmed a causal relationship between REN consumption and reductions in CO_2 emissions. This broad body of evidence underscores the universal role of REN as a mechanism for curbing CO_2 emissions across diverse economic and institutional settings. Therefore, we propose the research hypothesis (H3)

H3: Renewable energy consumption has a positive and significant effect on environmental quality

4.2.4 TNRR and *CO_2 Emission*

The impact of natural resource wealth on environmental quality, particularly in terms of CO_2 emissions, has been the subject of extensive empirical inquiry, often producing complex and sometimes contradictory results. The extraction, processing, and utilization of fossil fuels and minerals are highly energy-intensive and remain among the primary sources of global greenhouse gas emissions. Consequently, economies heavily reliant on natural resource rents, especially from non-renewable sources, tend to exhibit a strong positive correlation between resource dependence and CO_2 emissions, reflecting the carbon-intensive nature of their industrial structures. A substantial body of evidence supports this positive nexus. For instance, Raihan et al. (2024) report that TNRR exerts a significant positive influence on CO_2 emissions in Bangladesh, highlighting the environmental costs of resource-driven growth. Similarly, Miao et al. (2023) show that in G7 nations, the environmental consequences of resource exploitation are fundamentally shaped by the quality of ecological governance. Their findings emphasize that strong regulatory institutions are crucial to channel resource rents into sustainable development, suggesting that the resource curse is not inevitable but conditional on governance quality. In the context of Sub-Saharan Africa, Afolabi (2023) provides further evidence that the relationship between TNRR and environmental quality is mediated by regulatory effectiveness, underscoring that robust institutional frameworks are indispensable for mitigating the environmental externalities of resource extraction. Complementary factors such as governance quality, economic development, and investment in green technologies also play decisive roles in shaping environmental outcomes, either exacerbating or alleviating the ecological impacts of resource dependence. Reinforcing this view, Tahir et al. (2024) find that in OECD countries, higher natural resource consumption significantly increases CO_2 emissions, reflecting the persistent environmental challenges in resource-intensive economies. Taken together, these studies suggest that while natural resource abundance frequently contributes to environmental degradation, particularly through elevated CO_2 emissions, this outcome is not deterministic. Drawing on Resource Curse Theory (RCT), resource wealth often amplifies ecological stress, but strong governance and green innovations can redirect resource rents toward sustainable outcomes, thereby countering the traditional resource curse paradigm. Based on the mixed empirical evidence surrounding the resource-environment nexus, the hypothesis (4) is proposed:

H4: TNRR adversely affects environmental quality

Table 4.1: Literature Summary

Authors	Sample	Time-Period	Methodology	Outcomes
Ulussever et al. (2024)	6 GCC Countries	2000-2019	Panel AMG	DIGIT, PRI → LCF (+)
Mehta and Prajapati (2024)	EU27 Countries	1995-2022	ARDL	Environmental tax&spendings → CO_2 emissions (-)
Javed et al. (2024).	G7 Countries	1994-2018	Panel Quantile	GTI, EP, REN→EFP (-)
Mohammed et al. (2024)	EU27 Countries	1990-2019	EKC	Energy Consumption → CO_2 emissions (-)
Ansari et al. (2024)	Pakistan	2004-2021	ARDL	DIGIT, REN → CO_2 emissions (-)
Bergmark (2024)	181 Countries	2002-2020	Fixed Effect	DIGIT → CO_2 emissions (-)

Qayyum et al., 2024	MERCOSUR countries	1990-2021	CS-ARDL	IQ, ICT, → EFP (-)
Wang et al. (2024)	5 African Economies	1990-2018	MMQR, CS-ARDL	G.EXP, REN, TI→CO_2 emissions (-)
Shen et al. (2023).	Top7 Hydrogen Countries	1995-2019	MMQR	DIGIT, EEF →CO_2 emissions (-)
Mohammed Saud et al. (2019).	Venezuela	1971-2013	ARDL	G.EXP →CO_2 emissions (-)
Higón et al. (2017)	142 Countries	1995-2010	OLS, IV FE	DIGIT, RL → CO_2 emissions (-)
Adewuyi (2016)	40 Countries	1990-2005	FE, RE	G.EXP →CO_2 emissions (-)
López et al. (2011)	47 Countries	1980-2005	OLS, FSE	G.EXP, IQ → SO2 (-)

Note: LCF= Load Capacity Factors, EFP= Ecological footprints, GTI = Green technology innovation, REN = Renewable Energy, AMG=Augmented mean group, DIGIT=Digitalization, G.EXP= Government expenditure

4.2.5 Research Gap

After a comprehensive review of the existing literature, it becomes evident that the relationship between DIGIT, GOV, REN, GDP, TNRR, and CO_2 emissions remains underexplored for EU-27 countries. While prior studies have offered valuable insights into the determinants of environmental quality, several important gaps persist. First, most earlier studies have examined the individual effects of DIGIT or GOV on CO_2 emissions, yet none have analyzed their joint (interaction) impact, particularly within the European context. This omission is critical, as government expenditure can amplify the environmental benefits of digital transformation through targeted investments in digital infrastructure, smart governance, and technological innovation. Such synergy aligns with the Ecological Modernization Theory (EMT), which posits that technological progress and institutional reforms can simultaneously drive economic growth and ecological improvement. Second, the environmental implications of natural resource dependence and economic growth have been insufficiently assessed in the EU framework, despite the Resource Curse Theory (RCT) suggesting that reliance on resource rents can exacerbate environmental degradation and weaken sustainable development pathways. Third, most prior research relies on traditional mean-based estimation techniques such as FMOLS, DOLS, or Panel Quantile Regression (PQR), which overlook heterogeneity across emission levels and may yield biased or incomplete findings. To overcome these limitations, this study employs the Method of Moments Quantile Regression (MMQR), which captures the heterogeneous effects of explanatory variables across the conditional distribution of CO_2 emissions and accounts for unobserved cross-sectional heterogeneity. Moreover, to ensure the robustness of the results and to address cross-sectional dependence (CSD) and potential endogeneity concerns, the study further applies advanced long-run estimation techniques, including CUP-FMOLS, BA-OLS, and Two-Stage Least Squares (2SLS). This integrated empirical framework allows for a more comprehensive and reliable assessment of how digitalization, fiscal policy, renewable energy, and resource dependence jointly shape environmental quality across EU-27 economies.

4.2.6 Theoretical Framework

4.2.6.1 Ecological Modernization Theory

This study is based on Ecological Modernization Theory (EMT), which is a prominent school of thought in the social sciences that argues maximum economic benefit can be achieved by aligning economies with principles of environmental sustainability (Hajer & Kwa, 1998). As a systematic eco-innovation perspective, EMT emphasizes conserving the environment through technological progress and innovation while simultaneously advancing organizational growth and societal development (Pal et al., 2023). Grounded in the principle of rational self-interest among governments, industries, and NGOs, EMT suggests that economic and ecological objectives can be effectively integrated. Environmental productivity, the efficient use of natural resources and ecological systems such as air, water, soil, and ecosystems, has become a foundation for future growth alongside labor and capital productivity. This is pursued through energy and resource efficiency, achieved by product and process innovations such as environmental management, sustainable supply chains, clean technologies, the substitution of hazardous materials, and eco-friendly product design. Such innovations reshape industrial metabolism by lowering resource turnover and reducing carbon emissions.

Consequently, EMT has received growing attention among scholars and policymakers over the past decades (Bidone, 2022). Government agencies and large industries apply EMT to design supply chains that balance environmental performance with productivity and profitability (Pal et al., 2023). EMT also highlights the transformative role of clean transportation technologies, encouraging innovation that enables decarbonized consumer choices. In this view, regulatory frameworks and policy initiatives that stimulate environmental innovations, such as incentives for automakers, serve as catalysts for ecological modernization. Importantly, EMT recognizes that technological advancement alone is insufficient to improve environmental outcomes without strong institutional frameworks and supportive public investment. This perspective theoretically justifies the inclusion of government expenditure as a moderating variable in the present study. By investing in digital infrastructure, renewable energy, and green innovation, governments provide the institutional and financial capacity necessary to amplify the environmental benefits of digitalization. In contrast, insufficient public expenditure may limit digitalization's potential or even lead to rebound effects that increase energy consumption.

By integrating these insights, the present study develops a theoretically grounded framework to examine how digitalization, renewable energy, natural resources, and government expenditure interact to shape environmental quality in the EU-27. Government expenditure is theorized to strengthen the capacity of digitalization to reduce emissions, thereby ensuring that eco-innovation translates into meaningful environmental improvements. Accordingly, this study develops an empirical framework to test how digitalization, renewable energy, and natural resources influence environmental quality, and whether government expenditure strengthens these relationships. The resulting hypotheses are directly derived from EMT, which positions institutional support as essential for translating eco-innovation into measurable ecological benefits.

4.2.6.2 Resource Curse Theory

The Resource Curse Theory (RCT) presents an alternative viewpoint by emphasizing the possible negative consequences of relying too much on natural resources on both economic and environmental outcomes. In contrast to economies with limited resources, this perspective holds that nations with abundant natural resources frequently have slower economic growth, less developed institutions, and more ecological degradation (Sachs & Warner, 1995; Gylfason, 2001). Resource rents have the potential to overexploit environmental systems, hinder innovation, and produce institutional inefficiencies, which gives birth to this conundrum. When it comes to the environment, it has been demonstrated that dependence on fossil fuels and other extractive resources increases carbon emissions and slows the switch to cleaner energy sources. The RCT literature does, however, also indicate that these risks can be reduced by effective governance, open institutions, and focused public spending. Natural resources are viewed in this study's framework as a factor that could endanger environmental quality unless institutional support and government spending are in place to mitigate it (Manzano & Gutiérrez, 2019). By doing this, the research acknowledges the dual function of resources: unrestrained reliance may jeopardize ecological sustainability in the EU-27, even as they can generate fiscal income for green investment.

4.3. Materials and Methods

4.3.1 Data

The primary objective of this study is to investigate the impact of DIGIT, GOV, REN, GDP, and TNRR on CO_2 emissions in EU27 countries. For this purpose, we use annual panel data from 2000 to 2022 for the EU27 countries, according to data availability. The dependent variable is CO_2 emissions (measured in metric tons per capita). However, independent variables: digitalization, which is computed as Individuals using the Internet (% of the population), Government expenditures (General Governmental final expenditures % of GDP), economic growth measured by GDP per capita, Renewable Energy consumption (defined as % of total final energy consumption), and Total natural resources rents (which is % of GDP). The data on these variables were extracted from the World Development Indicators. All variables are transformed into natural logarithms except for indices to deal with outliers and variability in the data series. Table 2 describes the variables, acronyms, and sources. Furthermore, Fig. 1 shows the expected graphical association among dependent and exploratory variables.

4.3.2 Model

Grounded in Ecological Modernization Theory (EMT) and Resource Curse Theory (RCT), this study develops an empirical framework to examine the effect of DIGIT, GOV, REN, GDP, and TNRR on CO_2 emissions in EU27 countries. In line with Chishti and Sinha (2022), CO_2 emissions serve as a vital proxy for environmental quality, as higher emissions are closely associated with environmental deterioration and climate risks. Given the CO_2 emissions concept addressed in recent studies by Elmassah and Hassanein (2023), the environmental quality function is as follows:

$$CO_2 = f(Digit, GOV, REN, GDP, TNRR) \tag{1}$$

The regression model expressed by equation (1) is:

$$CO2_{it} = \alpha_{it} + \beta_1 Digit_{it} + \beta_2 GOV_{it} + \beta_3 REN_{it} + \beta_4 GDP_{it} + \beta_5 TNRR_{it} + \varepsilon_{it} \tag{2}$$

To evaluate the moderating impact of DIGIT and GOV, we propose the following econometric model with multiplicative interaction terms:

$$CO2_{it} = \alpha_{it} + \beta_1 Digit_{it} + \beta_2 GOV_{it} + \beta_{3_{it}} REN_{it} + \beta_4 GDP_{it} + \beta_5 TNRR_{it} + \beta_6 Digit * GOV_{it} + \varepsilon_{it} \tag{3}$$

In equation (3), "t" represents the time, "i" for cross-section, "β" denote parameter coefficient and "ε" signifies the stochastic error terms. Furthermore, CO_2 emissions are a proxy for the environmental quality, DIGIT stands for digitalization, and GOV represents government expenditure, REN for renewable energy, TNRR for total natural resources rent, and GDP for economic growth per capita. The interaction term DIGIT×GOV allows testing whether fiscal policy amplifies the environmental benefits of digitalisation, consistent with Ecological Modernisation Theory, which posits that proactive state involvement and technological advancement can jointly drive eco-innovation and sustainable transformation.

Table 4.2: Data Description

Variables	**Symbols**	**Measurement Unit**	**Sources**
CO_2 emission	CO_2	CO_2 emissions (metric tons per capita)	WDI
Digitalization	DIGIT	Individuals using the Internet (% of the population)	WDI
Government expenditure	GOV	General Government final expenditures (% of GDP)	WDI
Renewable Energy Consumption	REN	Renewable-energy consumption % of total final energy consumption	WDI
Gross Domestic Product	GDP	Per Capita GDP	WDI
Total Natural Resources Rent	TNRR	Total natural resources rents (% of GDP)	WDI

Note: WDI (World Development Indicators), Sample: 27 European Union countries, period 2000-2022

List of Countries: Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden

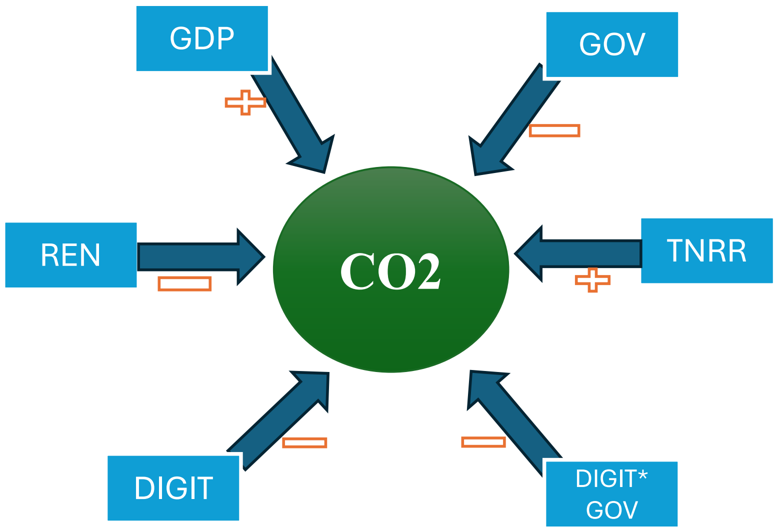

Figure 4.1: Expected association between variables

4.3.3 Empirical Strategy

Before conducting the relationship between dependent and independent variables of this study, we perform several pre-estimation panel data diagnostic tests. We started with slope heterogeneity by Pesaran and Yamagata (2008) to evaluate parameter variation across cross-sectional units. Following this, the presence of cross-sectional dependence is evaluated using the Pesaran (2007) CD test, which is critical given the interconnectedness of EU nations. Next, the stationarity properties of the variables are examined through the second-generation CIPS unit root test, which accounts for cross-sectional dependence and heterogeneity. Once the integration order is established, we apply Westerlund's (2007) cointegration test to investigate whether a long-run equilibrium relationship exists among the study variables. Subsequently, to estimate the long-term effects, we used FMOLS, DOLS, and FE-OLS methods. In addition, the MMQR technique is implemented to capture the heterogeneous impact of indpendent variables across diverse quantiles of the CO_2 emissions distribution. Finally, the Granger causality test (Dumitrescu and Hurlin, 2012) has been applied to check the causality direction among the variables under investigation. The graphical representation of the estimation strategy is shown in Fig. 2.

4.3.3.1 Slope heterogeneity

We examined the nature of slope coefficients in the first estimation step. Slope coefficient homogeneity in the panel data set is assumed by conventional estimators, which are used in panel data analysis. These conventional slope heterogeneity tests cannot handle the slope coefficient heterogeneity problem and yield skewed and misleading results. However, the current study used the Pesaran and Yamagata (2008) slope heterogeneity test to investigate the slope coefficient heterogeneity to prevent misleading results. This test is consistent since it yields both standard and adjusted SH estimations. Outcomes for SH and corrected SH can be obtained as follows:

$$\tilde{\Delta}_{SH}= (N)^{\frac{1}{2}}(2K)^{-\frac{1}{2}}\left(\frac{1}{N}\tilde{S}-K\right) \quad (4)$$

$$\tilde{\Delta}_{ASH}= (N)^{\frac{1}{2}}\left(\frac{2K(T-K-1}{T+1}\right)^{-\frac{1}{2}}\left(\frac{1}{N}\tilde{S}-2k\right) \quad (5)$$

The test statistics for explanatory variables k were expressed using S and N states for cross-sectional units.

4.3.3.2. Cross-sectional dependency

In recent studies, cross-sectional dependence (CSD) has been widely used when performing panel data estimations. Nations are highly interconnected due to the cooperation of the economies worldwide. Neglecting the CSD can result in inaccurate statistical estimates, leading to erroneous policy consequences (Pesaran, 2007). The CSD test provides reliable results while addressing panel data concerns. Equation (1) describes the CSD test used.

$$CSD_{TM} = \left[\frac{TN(N-1)}{2}\right]^{\frac{1}{2}} \eth N \quad (6)$$

$\eth N$Represents the pair-wise correlations, N shows cross-sectional entities, and T signifies time.

4.3.3.3. Unit Root/ Stationarity

First-generation stationarity tests can yield erroneous outcomes in the presence of cross-sectional dependence (CSD) and slope homogeneity (SCH). Therefore, it is compulsory to choose the proper stationarity test considering CSD and SCH. The current study employed Pesaran's (2007) CIPS test to determine the stationarity properties of the related variables. Both CSD and SCH issues are tackled in this test. As a result, CIPS is more appropriate than the traditional unit root test of the first generation. The CIPS test equation is mentioned as follows:

$$\widehat{CIPS} = \frac{1}{N}\sum_{i=1}^{n} CADF_i \quad (7)$$

4.3.3.4. Panel Cointegration

Next, the study used the Westerlund (2007) cointegration test to check the long-term relationship between dependent and independent variables. The equations below use this test, with Ga and Gt representing group statistics and Pa and Pt reflecting panel statistics.

$$G_t = \frac{1}{N}\sum_{i=1}^{N}\frac{\varphi_i}{SE\ (\varphi_i)} \qquad G_a = \frac{1}{N}\sum_{i=1}^{N}\frac{T\varphi_i}{\varphi_i(1)} \tag{8}$$

$$P_t = \frac{\varphi}{SE\ (\varphi)} \qquad P_a = T\varphi_i \tag{9}$$

4.3.4 Method of Moment Quantile Regression

The MMQR (Method of Moments Quantile Regression) introduced by Machado and Silva (2019) was employed to examine the distributional and heterogeneous variations between dependent and independent variables across the various quantiles. This approach directly supports the research objective by uncovering the asymmetric and distributional dynamics of the drivers of environmental quality. The MMQR outperforms the conventional quantile regression due to its better performance when unobserved heterogeneity is present in the dataset (Anwar et al., 2021). This approach is more vigorous than traditional means and PQR estimation. Because mean-based estimators only capture the average effect, they ignore important distributional heterogeneity across different environmental quality levels. Similarly, the PQR has substantial limitations, including incidental parameters and potential bias issues. However, MMQR addresses these issues by providing consistent and efficient estimates without requiring the estimation of individual-specific effects (Machado and Silva, 2019), allowing for a more accurate and comprehensive understanding of how independent variables influence the entire distribution, rather than just the average outcome. Furthermore, it may assess the conditional heterogeneous covariance impact of primary and explanatory variables while considering individual fixed effects. The MMQR's capacity to account for the covariance effect in the overall distribution makes it preferable to other models, including the conventional quantile regression model. The MMQR can reliably address endogeneity and deliver results even when the dataset is neither linear nor normal.

However, the diversified sample of EU27 economies suggests using a technique that can produce estimators for the endogenous conditional distribution variables. As a result, the MMQR has been employed to achieve the goal. A fascinating characteristic of the MMQR is its ability to have an impact on the dependent variable's conditional distribution. Eq. 10 shows the conditional quantile for a random variable QY[X], as Machado and Silva (2019) described. The mathematical equation for the conditional location scale variation Qy(σ|R) is as follows:

$$Y_{it} = \vartheta_i + \mathfrak{X}_{it}\phi + (\Upsilon_i + \mathcal{B}_{it}\Omega)\mu_{it} \tag{10}$$

Where; $\text{þ}\{\Upsilon_i + \text{K}_{it} > 0\}$, This signifies that the probability equals one, and the model's parameter is represented as $(\phi, \Upsilon_i \mathcal{B}_{it} \Omega)$; i= 1, . . . , n denotes the discrete fixed effects, then the selected elements of X's k-vector are represented as Z, which undergo distinct modifications with element l defined by $\check{Z}_j = \check{Z}_j(\mathfrak{X}), j = 1,2, \ldots, k$.

$\mathfrak{X}_{it}$ is invariant concerning time, equally distributed, and operates independently for every constant i. Furthermore, the term μ_{it} is time redistributed across individuals i and perpendicularly to X_{it}, So permitting Machado and Silva's instant requirements as follows:

$$Qy(\sigma|R) = \vartheta_i + (\lambda_i \rho_i q(\sigma) + \mathfrak{X}_{it}\phi + \mathcal{B}_{it}\Omega q(\sigma) \quad (11)$$

where independent vector parameters are covered by $\mathfrak{X}_{it}$; Qy(σ|R) represents Y_{it} quantile distribution. The following equation accommodates the optimization.

$$Min_q \sum_i \sum t\chi(Rit - [(\Lambda Z)_i + Z_{it}\Upsilon)q] \quad (12)$$

Where $\chi(R)$=(ʒ-1)RI {R≤0}+TRI{R>0} denoted the checked function

Furthermore, to ensure robustness and to address econometric issues such as cross-sectional dependence (CSD), non-stationarity, and potential endogeneity, we complement the MMQR estimates with advanced long-run estimators, including the CUP-FMOLS and BA-OLS methods, as well as the Two-Stage Least Squares (2SLS) technique. These approaches validate the stability and reliability of our findings, offering more credible policy implications consistent with the study's theoretical and empirical framework.

4.3.5 Panel Granger Causality

The concluding stage evaluates the causal association linking CO_2 emissions and other explanatory variables. The previously identified methods, such as Dynamic OLS, FMOLS, Fixed Effect-OLS, and MMQR methods, provide the specific influence of the individual factors on the dependent variable while ignoring the causal relationship between the variables. This study used Dumitrescu and Hurlin's (2012) pairwise panel Granger causality test. This causality test accounts for the CSD and SCH concerns and yields reliable outcomes even when the panel is uneven (Banday and Aneja, 2020). The general formulation of this test is given as follows:

$$Z_{i,t} = \vartheta + \sum_{k=1}^{p} \sigma_i^k Z_{i,t-k} + \sum_{k=1}^{p} \omega_i^k T_{i,t-k} \quad (13)$$

Where i denote the lag length. The autoregressive coefficients are represented by $\sigma^k(K)$, The cross-section is denoted by i, and the temporal dimension of the data is denoted by t.

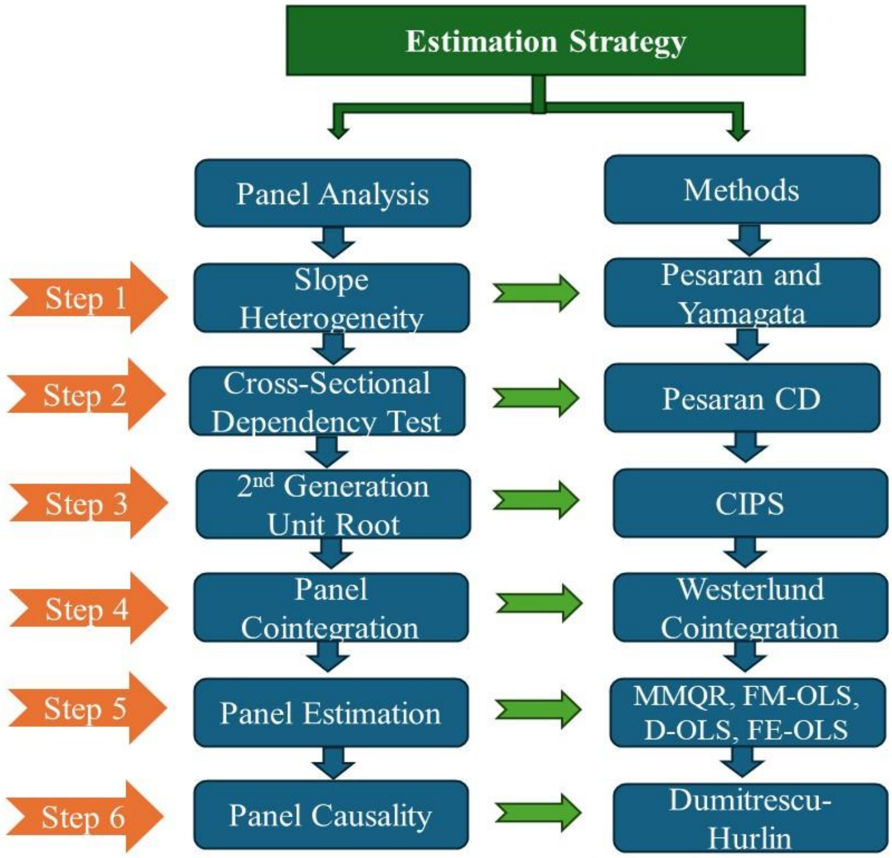

Figure 4.2: Estimation Strategy

4. 4. Results

Before starting the empirical analysis, Table 3 comprehensively overviews all variables, including CO_2 emissions, DIGIT, GOV, REN, GDP, and TNRR. The mean value of CO2 is 7.386, ranging from 2.927 to 25.610, DIGIT is 4.039, ranging from 1.284 to 4.593, followed by GOV, with a mean of 2.879, ranging from 0.182 to 3.330. REN has a mean of 2.571 and ranges from -2.303 to 4.060. GDP has a mean of 10.067, ranging from 8.222 to 11.630, and TNRR has a mean of 0.544, ranging from 0.001 to 5.714. The Jarque-Bera result suggests that the data follows a non-normal distribution. It indicates that the use of linear approaches may produce misleading findings. For this reason, we used the novel MMQR to analyse the heterogeneous effects across different points of the CO_2 emissions distribution. Before executing any other econometric model, it is crucial to determine the probability of multicollinearity in the dataset. When independent variables are correlated, they lead to an incorrect outcome. However, Table 3 (B) presents the correlation matrix between the dependent and independent variables, indicating a positive association of DIGIT, GOV, REN, GDP, and TNRR with CO_2 emissions. Since all correlation coefficients are below the critical threshold of 0.80, we reject the presence of multicollinearity, confirming that multicollinearity is not a concern in the dataset.

Table 4.3 (A) Summary Statistics

Variables	CO_2	DIGIT	GOV	REN	GDP	TNRR
Mean	7.386	4.039	2.879	2.571	10.067	0.544
Median	6.719	4.255	2.969	2.754	10.056	0.288
Maximum	25.610	4.593	3.330	4.060	11.630	5.714
Minimum	2.927	1.284	0.182	-2.303	8.222	0.001
Std. Dev.	3.445	0.581	0.539	0.945	0.688	0.699
Skewness	2.038	-1.893	-4.317	-1.715	-0.072	2.465
Kurtosis	9.439	6.732	21.409	8.419	2.544	11.737
Jarque-Bera	1502.783	731.588	10698.150	1064.319	5.905	2604.389
Probability	0.000	0.000	0.000	0.000	0.000	0.000
Observations	621	621	621	621	621	621

Table 4.3 (B) Correlation Matrix

Variables	CO_2	DIGIT	GOV	REN	GDP	TNRR
CO_2	1.000					
DIGIT	0.069	1.000				
GOV	-0.250	-0.004	1.000			
REN	-0.369	0.276	-0.071	1.000		
GDP	0.500	0.496	0.165	-0.094	1.000	
TNRR	-0.078	-0.168	-0.373	0.252	-0.464	1.000

Furthermore, the current research utilizes the Pesaran and Yamagata (2008) test to investigate slope heterogeneity. Table 4 presents the estimated results, indicating that our model has a problem with SCH. The Δ and adjusted Δ values are substantially significant, demonstrating heterogeneity in the slope coefficients and supporting H1.

Table 4.4 Slope heterogeneity outcomes (Pesaran, Yamagata. 2008)

Test	**Statistics**	**Prob.**
Delta	15.956***	0.000
Adj. Delta	19.131***	0.000

Note: *** specifies a significant level of 1 %

The most common issue in panel data analysis is cross-sectional dependence, which must be addressed before examining relationships among variables. We used the CSD test to get around this issue (Pesaran's, 2007); the results are shown in Table 5. The results reject the null hypothesis of validating the CSD in the data. As a result, any changes in DIGIT, GOV, REN, GDP, TNRR, and CO_2 emissions in one EU country will be conveyed to the other EU27 nations. Consequently, the EU27 countries are highly interconnected.

Table 4.5. Cross-sectional dependence outcomes

Variable	**Pesaran CSD**	**P-Value**
CO_2	50.653 ***	0.000
DIGIT	81.713 ***	0.000
GOV	23.243***	0.000
REN	80.41 ***	0.000
GDP	63.841***	0.000
TNRR	27.472***	0.000

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

The findings of the cross-sectional dependence and slope heterogeneity tests verified the existence of SCH (Slope coefficient heterogeneity) and CSD. The conventional stationarity tests proposed by Levin et al. (2002) and Im et al. (2003) may yield inaccurate results due to CSD and SCH obstacles; hence, second-generation stationarity tests are required. The CIPS unit root test, established by Pesaran (2007), and Pesaran's Cross-Sectionally Augmented Dickey-Fuller (CADF) were utilized in this study. This test yields effective estimates even with CSD and SCH problems. Table 6(A) summarizes the results of the CIPS test, and Table(B) summarizes the results of the CADF test. The findings indicate that all underlined variables are stationary at I (1). These findings reject the H_0 of a unit root in support of the null hypothesis.

Table 4.6 (A). CIPS unit root test outcomes (Pesaran, 2007)

Variable	**Intercept and trend**	
	I (0)	**I (1)**
CO_2	-2.056	-4.752***
DIGIT	-2.211	-4.857***
GOV	-1.701	-4.031***
REN	-1.543	-2.746***
GDP	-1.708	-2.986***
TNRR	-1.456	-2.665 ***

Table 4.6 (B). CADF unit root test outcomes

Variable	Intercept and trend	
	I (0)	**I (1)**
CO_2	-1.819	-3.468 ***
DIGIT	-3.685	-4.638***
GOV	-1.582	-2.859***
REN	-2.753	-3.840***
GDP	-1.505	-2.597***
TNRR	-2.347	-3.555 ***

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

The current study also used Westerlund's (2007) cointegration technique to confirm long-term relationships between the investigated variables. Table 7(A) presents the cointegration test results. The estimated results reject the null hypothesis that there is no "long-term cointegration" in contrast to the alternative hypothesis that there is "long-term cointegration." These outcomes show that GDP, REN, GOV, TNRR, and DIGIT in the EU27 nations has a long-term cointegrating connection with CO_2 emissions.

Table 4.7 (A). Cointegration results (Westerlund, 2007)

Test	**Values**	**Z-Values**	**Robust P-Value**
Gt	-3.977***	-9.084	0.000
Ga	-3.572***	5.516	0.000
Pt	-17.988***	-6.719	0.000
Pa	-10.393***	-1.543	0.000

Note: *** p<0.01, ** p<0.05, * p<0.1, *Gt=Group-Mean Test, Individual-Specific Adjustment, Ga=Group-Mean Test, Panel-Aggregate Adjustment, Pt=Panel Test, Pooled Adjustment, Pa=Panel Test, Panel-Aggregate Adjustment.*

The Variance Inflation Factor (VIF) was used to assess multicollinearity among the explanatory variables. As shown in Table 7(B), the VIF values for all variables are below the critical value, with a mean VIF of 1.28. These values are substantially below the commonly accepted threshold of 5 (and even the more lenient cutoff of 10), indicating that multicollinearity is not a concern in the estimated model. Thus, each independent variable contributes uniquely to explaining variations in the dependent variable without excessive overlap.

Table 4.7(B). Multicollinearity Variance Inflation Factors (VIF)		
Variables	**VIF**	**1/VIF**
DIGIT	1.23	0.810
GOV	1.13	0.882
REN	1.15	0.867
TNRR	1.46	0.686
GDP	1.43	0.701
Mean VIF	**1.28**	

Turning to the main analysis, this study uses a novel technique, MMQR, to deal with non-normal errors in the dataset. However, this study presents the results of MMQR in Table 8 to investigate the effects of explanatory and control variables on the CO_2 emissions at lower (τ = from 0.10 to 0.30), medium (τ = from 0.40 to 0.60), and higher order quantiles (τ = from 0.70 to 0.90) make it easier to interpret the findings. Firstly, it is found that the impact of digitalization on CO_2 emissions is negative and significant in all quantiles. The results demonstrate that the negative effect of digitalization on CO_2 emissions rises from 0.160 to 1.243, which is significant at 5% as the quantile increases. Similarly, the results support the idea that digitization helps EU27 economies by reducing their CO_2 emissions. Comparably, although the magnitudes of the coefficients vary, digitalization has a significant negative impact on preventing climate degradation. However, as Fig. 3 illustrates that the effect differs for each quantile.

Furthermore, findings demonstrate the clear relationship between GOV and CO2 emissions. This indicates that a 1% increase in GOV will result in a decrease in CO2 emissions in all quantiles (0.10 to 0.90). However, the magnitude of the coefficient is increasing as we go from lower to upper quantiles (see Fig. 3). Additionally, the findings observed that REN reduces CO2 emissions across all quantiles (0.10 to 0.90). In addition, the estimated outcomes discovered the significant positive impact of GDP on CO_2 emissions across quantiles. Initial output increases slowly in the initial stages of economic growth and more quickly in the latter stages. Our findings indicate that increased economic activity reduces environmental quality. Finally, the results demonstrate that TNRR tends to raise the CO_2 emissions by a greater amount within lower, medium, and higher-order quantiles. More precisely, the magnitude of the relationship has an upward trend from the 10^{th} to the 90^{th} quantiles.

Table 4.8: Effect of Digitalization and GOV on CO_2 Emissions

			Lower Quantiles			Middle Quantiles			Higher Quantiles		
Variables	Location	Scale	0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90
DIGIT	-0.601**	-0.299	-0.160	-0.275	-0.383*	-0.484**	-0.563**	-0.630**	-0.722**	-0.885**	-1.243**
	(0.267)	(0.198)	(0.258)	(0.227)	(0.219)	(0.232)	(0.253)	(0.278)	(0.320)	(0.408)	(0.620)
GOV	-2.017***	-0.498**	-1.284***	-1.476***	-1.655***	-1.823***	-1.955***	-2.066***	-2.220***	-2.492***	-3.087***
	(0.270)	(0.200)	(0.261)	(0.230)	(0.223)	(0.235)	(0.256)	(0.280)	(0.324)	(0.416)	(0.632)
REN	-1.268***	-0.467***	-0.580***	-0.760***	-0.928***	-1.085***	-1.209***	-1.313***	-1.458***	-1.712***	-2.270***
	(0.182)	(0.135)	(0.176)	(0.155)	(0.152)	(0.158)	(0.171)	(0.187)	(0.218)	(0.284)	(0.431)
GDP	3.260***	0.925***	1.898***	2.254***	2.588***	2.898***	3.143***	3.350***	3.636***	4.140***	5.246***
	(0.237)	(0.175)	(0.231)	(0.203)	(0.201)	(0.207)	(0.221)	(0.241)	(0.284)	(0.379)	(0.574)
TNRR	0.875***	0.138	0.672***	0.725***	0.775***	0.821***	0.858***	0.888***	0.931***	1.006***	1.170***
	(0.172)	(0.127)	(0.166)	(0.146)	(0.141)	(0.149)	(0.163)	(0.179)	(0.206)	(0.262)	(0.399)
Constant	-14.41***	-3.880**	-8.704***	-10.20***	-11.60***	-12.90***	-13.93***	-14.79***	-15.99***	-18.11***	-22.74***
	(2.075)	(1.535)	(2.005)	(1.764)	(1.713)	(1.801)	(1.960)	(2.151)	(2.486)	(3.193)	(4.855)
Observations	621	621	621	621	621	621	621	621	621	621	621

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

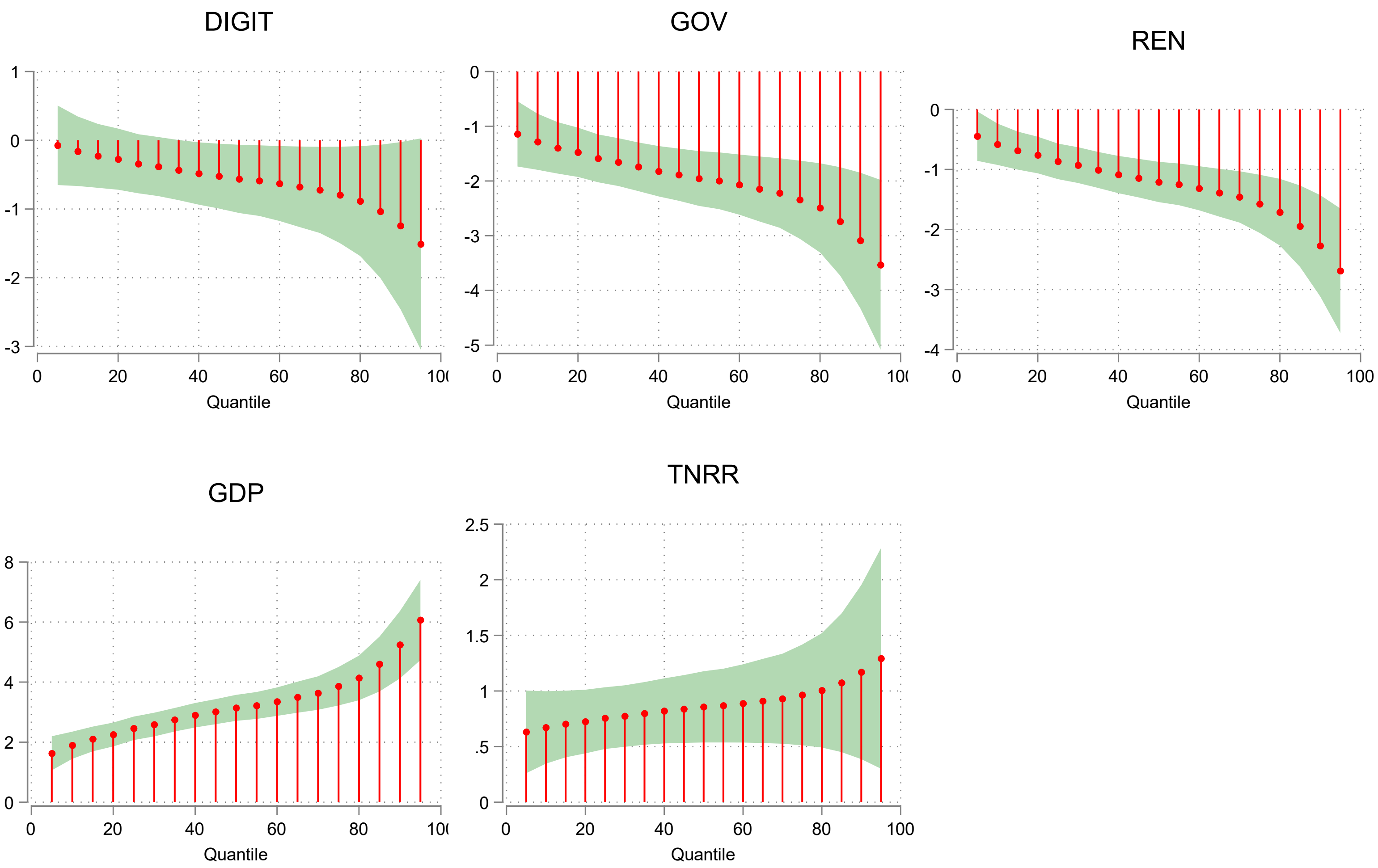

Figure 4.3: Method of Moment Quantile-Regression (MMQR) Estimates

Table 4.9: Moderating Role of IND and GOV

			Lower Quantiles			Middle Quantiles			Higher Quantiles		
Variables	Location	Scale	0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90
DIGIT	-0.769**	-0.0612	-0.680**	-0.703***	-0.725***	-0.746***	-0.762***	-0.776**	-0.795**	-0.826*	-0.900*
	(0.299)	(0.222)	(0.290)	(0.255)	(0.246)	(0.261)	(0.286)	(0.315)	(0.361)	(0.450)	(0.693)
GOV	-3.017***	-0.098**	-1.981***	-1.271***	-1.312***	-1.423***	-1.753***	-1.966***	-2.020***	-2.291***	-2.787***
	(0.370)	(0.210)	(0.231)	(0.220)	(0.219)	(0.221)	(0.222)	(0.223)	(0.322)	(0.326)	(0.362)
REN	-1.266***	-0.464***	-0.588***	-0.766***	-0.930***	-1.092***	-1.213***	-1.318***	-1.461***	-1.694***	-2.259***
	(0.181)	(0.134)	(0.175)	(0.155)	(0.151)	(0.158)	(0.171)	(0.187)	(0.218)	(0.278)	(0.428)
GDP	3.294***	0.912***	1.960***	2.310***	2.633***	2.953***	3.190***	3.397***	3.679***	4.136***	5.248***
	(0.233)	(0.173)	(0.226)	(0.201)	(0.198)	(0.204)	(0.218)	(0.238)	(0.280)	(0.368)	(0.565)
TNRR	0.904***	0.128	0.717***	0.766***	0.811***	0.856***	0.889***	0.918***	0.957***	1.021***	1.177***
	(0.168)	(0.125)	(0.163)	(0.143)	(0.138)	(0.147)	(0.160)	(0.177)	(0.203)	(0.253)	(0.390)
DIGIT*GOV	-0.480***	-0.119**	-0.306***	-0.352***	-0.394***	-0.435***	-0.466***	-0.493***	-0.530***	-0.590***	-0.735***
	(0.0637)	(0.0473)	(0.0617)	(0.0544)	(0.0527)	(0.0556)	(0.0605)	(0.0665)	(0.0769)	(0.0969)	(0.149)
Constant	-20.54***	-5.267***	-12.84***	-14.86***	-16.72***	-18.57***	-19.94***	-21.14***	-22.76***	-25.40***	-31.82***
	(1.964)	(1.457)	(1.903)	(1.683)	(1.640)	(1.716)	(1.855)	(2.035)	(2.368)	(3.028)	(4.655)
Observations	621	621	621	621	621	621	621	621	621	621	621

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

This research advances current literature by analyzing the moderating influence of digitalization and government expenditure on transforming environmental degradation. Due to this moderating variable, we can investigate whether and how the impact of one independent variable (such as digitalization) on the dependent variable CO_2 emissions varies based on the level of another independent variable (such as government expenditure) by employing a moderating relationship between digitalization and government expenditures on CO_2 emissions. Furthermore, the influence of digitalization on CO_2 emissions always depends on government expenditure because as the government increases investment in digitalization, digitalization will increase, and CO_2 emissions will decrease. In other words, government expenditure affects CO_2 emissions directly and indirectly through investments in digital infrastructure. However, it is important to check the moderate effects of digitalization and government expenditure on CO_2 emissions. Table 9 presents the outcome of the interaction effects which indicate that DIGIT*GOV reduces CO_2 emissions by 0.306 (10^{th} quantile), 0.352 (20th quantile), 0.394 (30th quantile), 0.435 (40th quantile), 0.466 (under 50^{th} quantile), 0.493 (under 60th quantile), 0.530 (under 70^{th} quantile), 0.590 (under 80th quantile), and 0.735 (under 90th quantile), respectively. The combined effect of DIGIT*GOV has a significant environmental impact at 1% significance. Typically, the coefficient of the moderating variable is smaller than the individual since it measures the change in the relationship's slope under different moderator levels. Because it works indirectly through interaction, it is frequently smaller by nature (Smithson, 2012). Secondly, the constituent variables and interaction terms often have a strong correlation. However, this finding is highly novel and may be put into scientific literature. Digitalization, public awareness of climate change, and administrative leadership present new chances to use digital technology to improve governance in the EU27 countries.

Table 4.10: Dumitrescu and Hurlin Panel Granger Causality

Null Hypothesis	Wald Statistics	Z-Value	P-Value
DIGIT $\longrightarrow$ CO_2 emissions	4.342***	12.048	0.000
CO_2 DIGIT	0.740	-0.938	0.348
GOV $\longrightarrow$ CO_2 emissions	1.943***	3.401	0.000
CO_2 GOV	1.167	0.602	0.547

REN →	CO_2 emissions	7.043***	21.787	0.000
CO_2	REN	2.834***	6.614	0.000
GDP →	CO_2 emissions	5.140***	14.926	0.000
CO_2	GDP	1.521*	1.877	0.060
TNRR →	CO_2 emissions	2.178***	4.247	0.000
CO_2	TNRR	1.880***	3.174	0.001

Note: *** indicates significance level at 1 %, ** at 5%, and * at 10%.

Finally, to explore the direction of causality among the study variables, this research employed the Dumitrescu and Hurlin (2012) panel Granger causality test, which accounts for heterogeneity across cross-sections and explicitly incorporates cross-sectional dependence (CSD). This approach extends the traditional Granger causality framework by capturing interdependencies among EU countries, thereby providing more reliable and unbiased causal inferences. The results, presented in Table 10, reveal that the Wald statistics and Z-scores are statistically significant for most causal relationships. Specifically, the findings confirm bidirectional causality between GDP and CO_2 emissions, TNRR and CO_2 emissions, and REN and CO_2, suggesting feedback effects between these variables. In addition, unidirectional causality is observed from DIGIT and GOV to CO_2 emissions, indicating that these factors play a moderating and mitigating role in enhancing environmental quality. Overall, the causality results imply that any policy changes in DIGIT, government expenditure, renewable energy adoption, economic growth, or natural resource utilization will have a significant and reciprocal impact on environmental outcomes across the EU-27 economies.

In addition to the baseline estimations, we employed second-generation estimators, including Continuously Updated Fully Modified OLS (CUP-FMOLS) and the Bias-Adjusted OLS (BA-OLS) methods, to explicitly account for cross-sectional dependence. These estimators are designed to produce consistent and efficient results under CSD, thereby strengthening the reliability of the empirical analysis. The results derived from CUP-FMOLS and BA-OLS were in line with those from MMQR, providing additional validation and ensuring that our key findings are robust across different estimation techniques. Table 11 presents the results of two models. Based on the calculated results, the estimated DIGIT value in all regression models shows a negative association between DIGIT and CO2 emissions. According to DIGIT, the

CO_2 emissions decrease is 0.018 (CUP-FMOLS), and 0.278 (BA-OLS) for every 1% increase. Furthermore, GOV significantly reduces CO_2 emissions, such as a 1% increase in GOV lowers CO_2 emissions levels by 1.861 (CUP-FMOLS), and 3.008 (BA-OLS) correspondingly. Turning to the REN, the estimated values indicate that a 1% increase in REN corresponds to 1.621 (CUP-FMOLS), and 1.801 (BA-OLS. Regarding the GDP, the results show a significant positive impact on CO_2 across all regression models. This means that a 1% increase in GDP is inclined to increase CO_2 emissions by 2.538 (CUP-FMOLS), and 2.136 (BA-OLS), respectively. Finally, TNRR, the computed parameter, indicates that a 1% rise in total natural resource rent increases ecological deprivation by 0.260 (CUP-FMOLS), 0.552 (BA-OLS) while holding the other variables constant.

Furthermore, to further validate the collective importance of the explanatory variables, a Wald test was performed for DIGIT, GOV, REN, GDP, and TNRR. The null hypothesis that all slope coefficients are jointly equal to zero was decisively rejected ($F\ (5{,}615) = 129.31$, $p = 0.000$). This confirms that the selected explanatory variables, taken together, have strong explanatory power in determining CO_2 emissions.

Table 4.11: CUP-FMOLS and BA-OLS

	CUP-FMOLS		**BA-OLS**	
VARIABLES	Coefficients	Std. errors	Coefficient	Std. errors
DIGIT	-0.018***	0.003	-0.278***	0.108
GOV	-1.861***	0.500	-3.008***	0.371
REN	-1.621***	0.099	-1.805***	0.205
GDP	2.538***	0.350	2.136***	0.181
TNRR	0.260***	0.103	0.552***	0.243

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

To ensure the robustness of the quantile regression results, a Two-Stage Least Squares (2SLS) estimation was conducted to account for potential endogeneity in GDP and TNRR. Based on theoretical reasoning and the evidence of bidirectional causality from the Granger causality tests, GDP and TNRR were identified as potentially endogenous variables. This was further confirmed by the Durbin–Wu–Hausman test, which strongly rejected the null hypothesis of exogeneity (p-value = 0.000). Accordingly, GDP and TNRR were instrumented using one-period lagged values of all five explanatory variables (excluded instruments: L. DIGIT, L. GOV, L.REN, L.GDP, and L. TNRR). The validity of these instruments was confirmed by the Sargan–Hansen test (see Table 12(B)), which failed to reject the null hypothesis of instrument exogeneity. The 2SLS results presented in Table 12(A) are consistent with the MMQR estimates in both sign and statistical significance. Specifically, DIGIT continues to exhibit a negative and statistically significant effect on CO_2 emissions, GOV remains negatively associated with CO_2, and REN further mitigates emissions. Conversely, GDP and TNRR maintain their positive and significant relationship with CO_2 emissions. The consistency of findings across both MMQR and 2SLS estimates demonstrates the robustness of the results to distributional heterogeneity and potential endogeneity.

Table 4.12 (A). Two-Stage Least Squares (2SLS) regression

Variables	Coefficient	Robust Std. Errors
DIGIT	-1.451***	0.298
GOV	-2.037***	0.230
REN	-1.179***	0.867
GDP	3.520***	0.293
TNRR	0.987***	0.131

Table 4.12 (B). Sargan-Hansen test of overidentifying restrictions

Test	Value	P-Value
Sargan-Hansen	2.648	0.449

Note: Standard errors are in parentheses. ∗∗∗p<0.01, ∗∗p<0.05, ∗p<0.10.

4.4.1 Discussion of Results

This section discusses the relationship between CO_2 emissions and the explanatory variables (DIGIT, GOV, REN, GDP, and TNRR). The relationship between DIGIT and CO_2 is negative and statistically significant. This negative relationship indicates that digitalization leads to decreased CO_2 emissions. The negative association can be justified by the fact that more digitalization in society decreases the necessity for physical travel, or using modern technologies to reduce energy consumption in numerous sectors. Further, virtual meetings and purchasing goods online can reduce the need for actual travel. Reducing travel can lead to lower CO_2 emissions by using fewer vehicles and reducing exhaust emissions. Overall, research on digitalization shows how adopting technology might help lessen its negative effects on the environment. This finding aligns with the European Union's strategic initiatives, such as the "European Green Deal and the Digital Strategy for Europe", which focus on using digital transformation to attain carbon neutrality by 2050 (European Commission, 2020). Besides, our results are consistent with Yasmeen et al. (2024), who explored the influence of internet usage on carbon emissions in G-seven countries. Similarly, Ulussever et al. (2024) validated that internet users reduced environmental deprivation in GCC countries. These findings were also supported by numerous other studies, including those conducted on Chinese cities by Xu et al. (2024), Edquist and Bergmark (2024) in 181 countries, and Higón et al. (2017) in 141 countries. Overall, the growth and adoption of internet use considerably minimize environmental degradation and preserve environmental equilibrium. From the perspective of Ecological Modernization Theory, these findings illustrate how technological advancement and digital innovation serve as crucial mechanisms for decoupling economic activity from environmental harm. EMT posits that modern societies can achieve ecological sustainability through the integration of technology, innovation, and institutional reforms. Hence, the negative impact of digitalization on CO_2 emissions confirms that technological modernization within the EU contributes to achieving sustainable development without compromising economic growth. To that purpose, the government, private entities, corporations, and universities must expand their spending to support the advancement of online services. As a result, the empirical findings support the hypothesis that digital transformation serves as a fundamental driver of improved environmental quality across EU27 economies. Furthermore, governments should enact laws encouraging such technology's development and widespread adoption.

CO_2 emissions and GOV are negatively correlated; this relationship is statistically significant at the 1% level. This implies that higher government investment in environmental protection programs or green infrastructure is linked to reduced CO_2 emissions. The EU has been actively pursuing carbon reduction goals through smart government spending on green initiatives and sustainable projects. Notably, efforts such as the European Green Deal and the EU Emissions Trading System (ETS) aim to steer public funding toward low-carbon technologies, renewable energy infrastructure, and energy-saving solutions (European Commission, 2020). Our findings are consistent with earlier research, such as Mohammed Saud et al. (2019), who discovered that the Venezuelan government ignored the environmental implications of its expenditures, resulting in a crisis that harmed the country's environmental quality. Furthermore, Wang et al. (2024) in African countries found that government expenditures and financial development promote ecological quality. On the other hand, research has shown that government expenditure on green growth, education, and research & development has greatly improved environmental quality (Wang et al., 2024; Yasmeen et al., 2024). From the standpoint of Ecological Modernization Theory, these findings highlight the essential role of proactive state intervention and policy innovation in promoting sustainable development. EMT asserts that governments can drive ecological transformation by redirecting fiscal resources toward cleaner technologies, institutional reforms, and environmentally responsible investments.

Thus, the negative association between government expenditure and CO_2 emissions empirically supports the theoretical view that modernization, guided by strong environmental governance, can reconcile economic progress with ecological sustainability.

Turning to renewable energy consumption, we found that REN and CO_2 emissions have a negative relation across all quantiles. This implies that switching to clean energy from fossil fuels improves environmental quality. Energy transition can lower energy prices, enhance air quality, provide new job prospects, and mitigate the adverse impacts of climate change. This finding is consistent with EU climate regulations, such as the Renewable Energy Directive (RED II), which requires member states to derive at least 32% of their energy from renewables by 2030 (European Commission, 2020). In terms of prior literature, the findings coincide with Anwar et al. (2021), who found that renewable energy mitigates CO_2 emissions in all quantiles of MMQR in the case of ASEAN nations. Furthermore, Javed et al. (2023) proposed that transitioning from non-renewable energy to green energy sources is essential to achieve sustainable growth. Further, the findings are also supported by other researchers (Javed et al., 2025; Fuinhas et al., 2017; Marques et al., 2018; Ali et al., 2024; Wang et al., 2024; Banday and Aneja, 2020). Furthermore, GDP has a statistically significant impact on CO2 emissions at the 1% level. This suggests that economic growth hurts the environment. According to the coefficients, CO_2 emissions tend to rise in line with GDP growth. However, as economies expand and technology advances, the quality of the environment improves. In addition, economic expansion may eventually result in a decline in environmental quality. The literature can validate the findings (Silva et al., 2023; Javed et al., 2024; Qayyum et al., 2024).

On the other hand, total natural resource rents positively correlate with CO_2 emissions, emphasizing their negative environmental consequences. The positive relationship between CO_2 emissions and TNRR suggests that income generated from exploiting natural resources leads to a harmful impact on environmental quality. This aligns with the Resource Curse Theory, which posits that economies heavily reliant on natural resource revenues often experience slower progress in sustainable development due to inefficient resource management, weak institutional structures, and environmental degradation. The findings affirm the results of Raihan et al. (2024), who explored the positive effect of TNRR on CO_2 emissions. Over time, increasing demand for products and services drives industrial expansion, often relying on energy-intensive processes that consume fossil fuels such as coal and natural gas. Furthermore, greater energy demand stimulates extraction and mining activities, ultimately worsening environmental degradation. The study results are also consistent with those of

Elmassah and Hassanein (2023). However, Özkan et al. (2024) suggested that financial institutions should enact immediate regulations and channel natural resource rents effectively across sectors to promote economic diversification and mitigate environmental harm. The summary of MMQR estimations for each research variable is shown in Table 12.

Furthermore, the study explores the moderating effect of GOV on the relationship between DIGIT and CO_2 emissions by introducing an interaction term (DIGIT × GOV). The inclusion of this moderator captures how fiscal policy can enhance or weaken the environmental benefits of digitalization. The results show that the interaction coefficient is negative and statistically significant at the 1% level, suggesting that higher government spending strengthens the negative impact of digitalization on CO_2 emissions. In other words, when public investment complements digital transformation through funding digital infrastructure, smart governance systems, and green technologies, the environmental gains from digitalization are amplified. This finding is well aligned with the Ecological Modernization Theory (EMT), which posits that environmental improvement can be achieved through technological innovation supported by proactive governmental and institutional reforms. From this perspective, government expenditure acts as an enabling mechanism that channels digital advancements toward eco-efficient outcomes, fostering the development of low-carbon technologies, sustainable public services, and green innovation ecosystems. Hence, greater fiscal support for digital initiatives not only accelerates technological diffusion but also reinforces environmental sustainability. These results are consistent with Yasmeen et al. (2024), who examined the moderating role of regulatory quality and digitalization in G7 countries, as well as Qayyum et al. (2024) and Li et al. (2023), who confirmed that institutional and technological synergies significantly enhance environmental quality.

Table 4.13: Summary of MMQR outcomes

Variables	Lower quantile (τ = from 10^{th} to 30^{th})	Middle quantile (τ = from 40^{th} to 60^{th})	Upper quantile (τ = from 70^{th} to 90^{th})
REN	-	-	-
GDP	+	+	+
TNRR	+	+	+
GOV	-	-	-
DIGIT	-	-	-

Note: (+) and (-) signs show that the dependent and independent variables have significant positive and negative relationships, respectively.

4.5 Conclusion and Policy Recommendations

The main objective of this empirical study is to investigate the impact of DIGIT, GOV, REN, and TNRR on CO_2 emissions in EU27 countries from 2000 to 2022. Before empirical analysis, this study conducts a series of diagnostic tests to examine the panel data's features. Based on the outcomes of these tests, the most suitable econometric model was selected to empirically explore the relationships among the study variables. Specifically, this study applies MMQR alongside several long-run mean estimation methods, including FMOLS, DOLS, and FE-OLS, to ensure the robustness of the findings. Compared with traditional mean-based estimation techniques, MMQR offers a more comprehensive analysis by capturing heterogeneous effects across different points in the conditional distribution of the dependent variable. The MMQR results indicate that DIGIT and GOV have a significant negative relation with CO_2 emissions across all quantiles, suggesting that both factors consistently enhance environmental quality. Additionally, REN demonstrates a significant ecological protection in all quantiles. Furthermore, GDP and TNRR exhibit a significant positive influence on CO_2 emissions across all quantiles, indicating that GDP and TNRR are associated with increased environmental degradation. The results from the mean estimators (FMOLS, DOLS, and FE-OLS) indicate that increases in DIGIT, GOV, and REN improve environmental quality by reducing CO_2 emissions. Conversely, higher levels of GDP and TNRR are associated with increased CO_2 emissions, thereby exacerbating environmental degradation. Finally, the Dumitrescu and Hurlin (2012) causality test was applied to explore the causal relationships among the variables.

The findings of this study offer concrete guidance for EU policymakers aiming to achieve sustainability goals. First, promoting digitalization through investments in smart technologies and digital infrastructure can significantly reduce CO_2 emissions by improving energy efficiency and enabling low-carbon innovation. Second, strategic government expenditure is a key driver of environmental quality in the EU-27. Targeted spending on green technologies, renewable energy, sustainable infrastructure, and R&D can amplify the benefits of digitalization and accelerate the shift to a low-carbon economy. At the same time, investments in institutional reforms and the digitalization of public services strengthen governance, while stricter regulation of resource-based industries reduces ecological risks. By prioritizing these areas, governments can foster innovation, improve efficiency, and build the foundations for long-term sustainability. Third, a fundamental overhaul of the energy sector is required, mandating an accelerated transition to renewable energy sources coupled with stringent conservation policies. This entails implementing a dual strategy that rapidly phases out fossil fuels through massive public and private investment in green energy infrastructure, while simultaneously enforcing rigorous regulations to curb the overexploitation of natural resources. Concurrently, governments must drive efficient gains by incentivizing the retirement of obsolete, energy-intensive technologies and promoting the widespread adoption of economical and efficient energy use practices across all sectors of the economy. Finally, EU-27 policymakers should adopt stricter regulations on natural resource extraction to prevent overexploitation and environmental degradation. At the same time, revenues from resource-based industries should be redirected toward renewable energy, eco-innovation, and sustainable infrastructure to ensure long-term ecological and economic sustainability. Collectively, these measures support the EU's climate and sustainability targets, including the European Green Deal, and provide policymakers with actionable insights to inform the design of integrated, evidence-based environmental strategies.

This study provides important insights into the relationship between digitalization, renewable energy, natural resources, government expenditure, and environmental quality. However, several limitations should be acknowledged, which open avenues for future research. First, the analysis employs CO_2 emissions as the sole proxy for environmental quality. Future studies could broaden this perspective by incorporating alternative indicators such as the ecological footprint and load capacity factors, which may capture environmental sustainability more comprehensively. Second, while the present study focuses on domestic determinants, external factors such as political instability, geopolitical risks, trade dynamics, and global economic conditions could also shape environmental outcomes. Moreover, incorporating the roles of green investment and green trade would provide deeper insights into how sustainable financial flows and environmentally friendly trade policies influence environmental quality, particularly amid evolving global challenges. Third, although the study applies the Method of Moments Quantile Regression (MMQR) to capture heterogeneous long-run effects across the distribution of CO_2 emissions, future research could benefit from employing dynamic panel approaches, such as the Cross-Sectionally Augmented ARDL and the Pooled Mean Group ARDL models. These methods would allow for the exploration of both short-run and long-run dynamics while addressing cross-sectional dependence. Finally, future research should consider sectoral-level analyses (e.g., energy, transportation, and manufacturing) and explore the role of emerging technologies such as artificial intelligence and blockchain in reducing carbon footprints. Such extensions would enrich understanding of how digital transformation, sustainable policies, and technological innovation can jointly support the EU's climate neutrality targets and contribute to achieving the UN SDGs.

5. The Role of E-Government, Government Fiscal Expenditure, Natural Resources Rents, and Energy Transition in Achieving Sustainable Development in Selected European Union Countries

5.1 Introduction

A broad spectrum of human activities causes global climate change and biodiversity loss worldwide (Cramer et al., 2018). As environmental concerns, policymakers in developed countries have increasingly prioritized sustainable development, supported by advancements in green technologies and institutional reforms (Zhao et al., 2023). In response, the pursuit of sustainable development has become a central focus for European Union (EU) nations, particularly in alignment with the United Nations Sustainable Development Goals (SDGs) and the EU's strategic agendas. Among these, SDG 7 (Affordable and Clean Energy), SDG 13 (Climate Action), and SDG 16 (Peace, Justice, and Strong Institutions) are especially relevant to the intersection of environmental responsibility, resource governance, and institutional effectiveness. The EU's European Green Deal and RE-Power-EU plan aim to accelerate the transition toward climate neutrality by 2050 and reduce reliance on fossil fuels, directly reinforcing SDG 7 through the expansion of renewable energy infrastructure. This energy transition not only helps lower the ecological footprint contributing to SDG 13 but also supports the EU's broader climate objectives, including a 55% reduction in greenhouse gas emissions by 2030. Simultaneously, initiatives under the Digital Decade Policy Program target the full digitization of public services by 2030, aligning with SDG 16 by promoting transparency, enhancing governance, and enabling more effective management of public resources, including natural resource rents. Together, these international and regional frameworks offer a comprehensive pathway for EU countries to align digital governance, environmental performance, and sustainable development goals in a mutually reinforcing manner.

The adverse impacts of ecological degradation and natural resource depletion, such as rising temperatures, sea levels, ocean acidification, droughts, land degradation, and biodiversity loss, pose serious threats to ecological and human survival (Wang et al., 2023). Therefore, it is crucial to effectively identify the indicators that reflect the full spectrum of environmental impacts to address ecological degradation. While CO_2 emissions are commonly used in environmental studies (Awan et al., 2025; Li & Yan, 2024), they only capture the consumption and production emissions. It overlooks other essential components, including built-up land, cropland, fishing grounds, forest resources, and grazing areas. In contrast, EFP provides a more holistic assessment, unlike a single-pollutant measure; the EFP accounts for the biologically productive land and sea area required to sustain human consumption and absorb waste (Javed et al., 2024). This metric captures broader sustainability dynamics by evaluating the balance between human demand on nature and the Earth's regenerative capacity. Ultimately, it reveals the extent to which natural resource use exceeds biocapacity, underscoring the urgent need for systemic environmental management (Liu et al., 2023).

The Declaration on Green and Digital Transformation of the EU has significantly advanced efforts toward sustainable development by integrating green priorities with digital innovation. Investment in green digital technologies is now considered essential for achieving Europe's climate neutrality targets and fostering long-term sustainable growth (Bianchini et al., 2023). In this context, the deployment of digital public services plays a critical role in enhancing environmental sustainability by reducing resource depletion and streamlining service delivery. Electronic government (EGOVT) has emerged as a central pillar in this transition, reshaping traditional governance structures through the adoption of advanced technologies such as artificial intelligence (AI), cloud computing, the Internet of Things (IoT), and machine learning (Roy, 2017). Within the EU countries, where digital infrastructure is relatively advanced, governments are better positioned to implement comprehensive e-governance systems (Pérez-Morote et al., 2020). By improving transparency, minimizing bureaucratic procedures, and reducing the need for physical documentation, e-government not only enhances administrative efficiency but also contributes to lowering EFP (Zioło et al., 2022). Furthermore, digital governance fosters two-way communication between citizens and public institutions through applications and online platforms, thereby promoting participatory decision-making (Tran Pham et al., 2024). Prior studies have shown that EGOVT can play a pivotal role in reducing environmental degradation by facilitating paperless processes, enabling remote work, optimizing public resource allocation, and curbing emissions associated with transportation and administrative infrastructure (Shahbaz et al., 2022).

During the green and digital transition, government fiscal expenditure plays a crucial role in shaping environmental outcomes (Ahmad & Satrovic, 2023), particularly through its influence on public investment priorities and regulatory frameworks (Azam et al., 2023). Public spending directed toward environmental protection, clean energy infrastructure, sustainable transport, and technological innovation can significantly mitigate ecological degradation (Wang et al., 2024). Conversely, unbalanced or misallocated fiscal expenditures, especially those favoring fossil fuel subsidies or resource-intensive sectors, may exacerbate environmental stress and increase environmental degradation (Coady et al., 2017). Within the context of the EU, fiscal policy is being increasingly aligned with climate objectives under the European Green Deal, which encourages member states to integrate sustainability into their national budgetary frameworks (European Commission, 2019). By strategically channeling government expenditure into green innovation, energy efficiency, and sustainable public services, EU nations can reduce pressure on biocapacity and foster a transition toward ecological resilience (Caglar et al., 2023). Moreover, responsible fiscal management enhances institutional capacity to respond to climate risks and supports the long-term resilience of environmental systems. Understanding the nuanced impact of fiscal decisions on EFP is therefore crucial for designing coherent policies that strike a balance between economic growth and ecological preservation.

The transition toward renewable energy is a cornerstone of global efforts to control ecological degradation and achieve long-term environmental sustainability (Javed et al., 2025). According to IPCC (2018), the energy sector accounts for 47% of EFP, followed by industry (30%), transportation (11%), and building (3%). However, the energy, production, and transportation sectors contribute the most to EFP (Appiah et al., 2021). Thus, the energy sector remains a primary contributor to greenhouse gas emissions and resource depletion. Shifting from fossil fuels to clean energy sources such as wind, solar, and hydropower has the potential to significantly reduce the EFP (Liu et al., 2025). The EU countries are prominent consumers of renewable energy and are making efforts to make their economic growth more sustainable and ecologically conscious (Ahmad et al., 2024). However, this transition is supported by ambitious policy frameworks such as the EU Green Deal, RE-Power-EU, and national climate laws that prioritize carbon neutrality and sustainable energy use (European Commission, 2019). ET not only improves energy efficiency and lowers environmental costs but also supports green innovation and job creation. By decoupling energy consumption from environmental harm, ET plays a vital role in reshaping production-consumption patterns and enhancing the ecological resilience of advanced economies (Wang et al., 2023).

The causal linkage between NRR and EFP continues to be a critical area of inquiry in environmental policy, particularly within the EU context. Despite their varying levels of resource endowment, EU member states must navigate the delicate balance between resource-based economic gains and environmental sustainability (Li & Yan, 2024). The interaction between NRR and EFP is multifaceted, shaped by institutional quality, environmental regulations, technological advancements, and consumption behaviors (Bashir et al., 2023). In resource-rich EU countries, ineffective governance or weak environmental safeguards may lead to the over-exploitation of natural capital, contributing to increased ecological pressure. Conversely, channeling resource revenues into sustainable initiatives such as investments in renewable energy, environmental innovation, and conservation can reduce the ecological burden. Thus, the effective management of natural resource rents is central to supporting the EU's broader sustainability agenda and achieving long-term environmental goals.

Several scholars have investigated the factors that influence EFP in different countries. Such as Li & Yan (2024) explore the effect of EGOVT on environmental quality in 5 "Shanghai Cooperation Organization" countries; Silal & Sharma (2024) in a global cross-country; and Zhao et al. (2023) in 125 Chinese cities. In the context of the EU, the European Commission has made substantial progress in reducing the EFP over recent decades. Strategic investments through initiatives such as the "European Green Deal" and the "RE-Power-EU Plan" have accelerated the adoption of renewable energy (target to at least 45% by 2030), energy-efficient infrastructure, and green technologies, all aimed at achieving carbon neutrality by 2050 (European Commission, 2019). Furthermore, "The Digital Europe Program (2021–2027)" is also a €7.6 billion EU initiative aimed at boosting digital transformation through investments in AI, supercomputing, cybersecurity, digital skills, and technology adoption (European Commission, 2020). Despite these initiatives, significant challenges remain, particularly in completely decarbonizing and spreading digitalization across the EU countries. This highlights the importance of examining key drivers such as EGOVT, GFE, NRR, ET, and GDP in shaping the EFP across EU nations, offering critical insights for sustainable policy design.

Given the EU's prominent role in sustainable development and its commitment to initiatives such as the "Green Deal" and the SDGs, assessing ecological sustainability in the region is crucial. Despite strong environmental governance, EU countries face growing ecological pressures from public spending, digital expansion, resource dependence, and uneven energy transition factors that may significantly shape their EFP. However, this study presents several key contributions to the growing literature on environmental sustainability and governance. First, this study adopts the EFP as a more comprehensive and multidimensional metric of environmental degradation for the EU-26 context, moving beyond the conventional reliance on carbon emissions alone. This broader measure encompasses a comprehensive range of environmental pressures and resource demands, providing a more holistic understanding of sustainability challenges. Second, in line with the dynamic structural and ecological characteristics of EU economies, this study incorporates a broader and more diverse set of explanatory variables as potential drivers of the EFP. These include EGOVT, GFE, NRR, ET, and GDP. Unlike previous studies that often focus on a narrow range of environmental determinants, this research offers a more nuanced and comprehensive framework for evaluating the multidimensional factors that influence ecological sustainability in EU-26 countries. By incorporating EGOVT as a central explanatory factor, the study brings novel insights into how digital governance and public sector modernization can influence ecological outcomes, an area still underexplored in environmental economics. Furthermore, grounded in Public Value Theory, the research highlights how digital governance and public resource allocation can promote environmental value and sustainable outcomes. By conceptualizing EGOVT as a vehicle for public value creation, the study offers a novel theoretical lens through which governance mechanisms are linked to ecological sustainability. Methodologically, this study advances the literature by employing the Method of Moments Quantile Regression (MMQR) technique, which captures the heterogeneous effects of these variables across the distribution of EFP, offering nuanced policy implications tailored to different environmental contexts within the EU bloc. These contributions collectively enrich the theoretical and empirical understanding of sustainable development governance in advanced economies.

The remaining section of the article is structured as follows. The "Literature review" section presents an overview of empirical research, with a particular emphasis on EU countries. The "Data and Methodology" section introduces the data and specifies the spatial econometric models used to test the occurrence of EGOVT. The "Empirical results" section shows the outcomes of the estimates. Finally, the "Conclusion" and "Policy Implications" sections present concluding remarks and policy recommendations based on empirical findings.

5.2 Literature Review

5.2.1 E-government – EFP Nexus

E-government (EGOVT) refers to the application of information and communication technologies (ICTs) in public administration to enhance efficiency, transparency, and service delivery. It also encompasses the use of ICTs by governments to improve leadership, communication, and collaboration (Khan et al., 2021; Senadheera et al., 2024; Silal & Sharma, 2024). Beyond administrative efficiency, EGOVT facilitates information gathering, communication, decision-making, and self-reflection, thereby creating deliberative spaces that encourage discussions on sustainability and public participation in environmental governance (Adamo and Willis, 2022). Moreover, EGOVT plays a vital role in mobilizing and shaping public opinion on global environmental challenges that are often intangible or abstract (Geels, 2010). Prior literature has shown growing interest in exploring how EGOVT, the digital economy, and ICT contribute to reducing energy consumption and mitigating carbon emissions (Yan et al., 2023; Li & Yan, 2024). The adoption of EGOVT facilitates remote work and digital platforms for citizen engagement and public services, effectively decreasing the need for office energy use and physical travel. Convenient digital alternatives, such as electronic tax filing and virtual consultations, further help reduce transportation-related emissions (Zhao et al., 2023). In addition, the streamlining of administrative processes and improvements in data management enhance resource efficiency and help prevent wasteful practices, thereby reducing carbon emissions. Some scholars argue that digital technologies positively influence carbon reduction through dematerialization and substitution effects (Yang et al., 2022). For instance, Ge et al. (2022) found that the digital economy can alleviate factor misallocation, particularly in labour and capital, thus improving carbon emission efficiency, based on empirical evidence from 30 provincial-level regions in China between 2011 and 2019. Similarly, Zhong et al. (2022) reported that ICT contributes to carbon reduction by substituting fossil fuels and promoting the use of non-fossil energy sources. The positive impacts of EGOVT stem mainly from its efficiency effect and optimization effect, both of which contribute to reducing carbon emissions. The efficiency effect arises as digital government transforms traditional administrative structures and workflows into paperless, online, and intelligent systems, improving interdepartmental coordination and service delivery while saving resources and energy (Bertot et al., 2010). The optimization effect enhances the quality of governmental carbon regulation and the business environment, fostering the green transformation of traditional industries and the growth of environmentally friendly enterprises (Le, 2022), thereby further lowering carbon emissions. Furthermore, Li et al. (2025), using data from 159 countries spanning 2003 to 2022, found that EGOVT exerts a non-linear impact on carbon emissions, characterized by an inverted “U”-shaped relationship initially promoting, and subsequently inhibiting, carbon emissions.

5.2.2 Government Fiscal Expenditure – EFP Nexus

The research reveals that government fiscal expenditure (GFE) is a crucial factor affecting the demand side of the economy. It exerts its effect globally through government spending, revenue collection, and taxes. A substantial body of research has explored the relationship between government expenditure and environmental sustainability, yielding mixed results. For instance, Bekhet and Lojuntin (2020), in their analysis of Malaysia from 1971 to 2019, found no direct effect of government spending on reducing carbon emissions. Similarly, Khan et al. (2022) reported that government expenditure worsened environmental sustainability when examining its interaction with nuclear energy from 1981 to 2016. Redonda (2016) highlighted the implications of tax expenditures for sustainability, emphasizing the necessity of thoroughly assessing their consistency with sustainability objectives. In addition, studies by Costantini and Martini (2010) and Feng et al. (2023) have investigated how government spending can support renewable energy development and contribute to lowering carbon emissions. Meanwhile, findings by Azam et al. (2023) on natural resources, government expenditure, nuclear energy, and carbon emissions revealed a negative association between government expenditure and carbon emissions. Similarly, in Belt and Road Initiative countries, several studies have shown that government expenditure is positively associated with adverse climate outcomes. Likewise, Ullah et al. (2023) and Yuelan et al. (2022) reported that tax revenue plays a significant role in reducing CO_2 emissions in these economies. In contrast, other empirical evidence suggests that government spending can have a significant negative direct and indirect effect on per capita pollution emissions. Using dynamic ordinary least squares for a panel of 77 countries, Halkos and Paizanos (2013) demonstrated such effects in the case of China, while Zeraibi (2021) found similar results for Korea using the ARDL approach (Bulus & Koc, 2021).

5.2.3 Energy Transition- EFP Nexus

Energy transition plays a vital role in transforming how nations consume energy to achieve their zero-carbon goals, promote environmental sustainability, and decarbonize the energy sector. Furthermore, shifting to clean energy fosters sustainable development, decreases pollution, and mitigates the ecological impact of human activities. For instance, Bashir et al. (2023) examined the impact of the energy transition and found that it had a mitigating effect on environmental degradation in the top ten manufacturing countries and within the BRICS group. Likewise, Wang et al. (2024) analyzed the impacts of the energy transition on the environment in the top ten carbon-emitting countries and found that the energy transition contributed to lowering CO_2 emissions. In a similar vein, Ahmad et al. (2024) analyzed the influence of energy transition on CO_2 emissions, concluding that the energy transition effectively reduced CO_2 emissions and helped curb environmental degradation. Similarly, Wang et al. (2024) found that renewable energy contributed to lowering CO_2 emissions. Further, Yin et al. (2025) examined the effect of green energy transition on EFP in the case of G-7 countries and found that energy transition significantly decreased the EFP level. Similarly, Kartal et al. (2025) found that energy transition efforts are ineffective in all BRICS countries, having the undesired effect of increasing EFP. Likewise, Nathaniel et al. (2025) investigated the impact of energy transition on EFP for Emerging countries, and empirical findings revealed that energy transition was adversely related to EFP in all countries.

5.2.4 Natural Resources – EFP Nexus

Natural resources are limited and vital for sustaining life, and their depletion can cause significant economic and social disruptions. (He et al., 2024; Wei et al., 2023). The relationship between natural resources (NRR) and the ecological footprint (EFP) has attracted considerable scholarly interest over the past few decades. Many studies have examined the complex links between resource availability, usage patterns, and the resulting environmental effects. Several of these studies have identified the negative impact of NRR exploitation on the EFP. Prior empirical literature reveals a heterogeneous impact of NRR on environmental outcomes. On the one hand, several studies suggest that NRR can help reduce environmental degradation. For instance, Shittu et al. (2021) find a negative relationship between natural resource rents and environmental degradation across 45 resource-rich Asian countries. Similarly, Khan et al. (2020) report that NRR contributes to environmental sustainability in BRICS countries. These findings are further supported by Kongbuamai et al. (2020) for ASEAN nations and Tufail et al. (2021) for OECD countries. Conversely, a number of studies document that natural resource rents exacerbate environmental degradation, as measured by EFP. Positive associations have been observed in various contexts, including five selected African countries (Aladejare, 2022), sixteen EU countries (Bekun et al., 2019), MINT economies (Faisal et al., 2023), G7 countries (Gyamfi and Adebayo, 2022), Southeast Asian nations (Lei et al., 2022), BRICS countries (Nathaniel et al., 2020), and the top fifteen renewable energy-consuming economies (Ullah et al., 2021). Further, Emir and Karlılar (2023) found that natural resource rents contribute to an increase in Turkey's ecological footprint. Similarly, Onifade et al. (2023), in their analysis of nine MENA countries between 1990 and 2018, revealed that the exploitation of natural resources adversely affects environmental quality. Ma et al. (2024) showed that in the United States, higher levels of natural resource use are associated with increased CO_2 emissions, while reductions in resource use correspond to declines in emissions. Likewise, Guan et al. (2025), examining 60 countries from 1996 to 2018, reported a positive relationship between natural resource rents and environmental degradation.

5.3. Theoretical Mechanism, Data, and Methods

5. 3.1 Theoretical Unrepining

This study draws on Public Value Theory (PVT) as a guiding framework to understand how governance mechanisms contribute to environmental outcomes, particularly the EFP. Public Value Theory, as introduced by Moore (1995), emphasizes that public sector actions should aim to create value for society by enhancing well-being, promoting sustainability, and upholding democratic accountability. As acknowledged in the public values literature, public organizations and their managers can contribute to the creation of public values (Silal and Sharma, 2024). The public value scholarly landscape emphasizes the importance of public managers aligning their strategies with legitimate powers, current capabilities, and citizen preferences (Hartley et al., 2017). The public manager's position becomes more difficult as they seek common ground and manage the authorities' expectations. Moore (1995)'s "strategic triangle" tool defines their scope. Considering the growing emphasis on "restoring the public dimension in public values," contemporary public managers are increasingly situated in complex deliberative environments, where conflicting ideologies and diverse stakeholder expectations converge, making the pursuit of broadly acceptable solutions a challenging process of negotiation and consensus-building. In this context, e-government initiatives are seen not only as tools for administrative efficiency but also as platforms for delivering environmental value through increased transparency, citizen engagement, and smart policy implementation (Jørgensen & Bozeman, 2007). Silal and Sharma (2024) support the argument by claiming that EGOVT is crucial for enhancing global environmental performance through institutional modernization and sustainable transitions. Their findings demonstrate how digital governance may help align public administration priorities with environmental goals, resulting in new types of sustainable government through PVT. Moreover, the allocation of government fiscal expenditure, management of natural resource rents, and promotion of renewable energy reflect the state's capacity to shape public outcomes aligned with sustainability goals. Economic activity, proxied by GDP, can either support or undermine these efforts depending on how it interacts with environmental regulation and governance structures. By integrating these variables, PVT offers a comprehensive perspective on how institutional strategies and public resource allocation can mitigate ecological degradation and promote sustainable development.

Considering the theoretical foundation outlined above, the following model has been constructed for this study:

$$EFP_{it} = f(EGOVT_{it} + GFE_{it} + NRR_{it} + ET_{it} + GDP_{it}) \quad (1)$$

Based on the established model, the corresponding regression expression is given below:

$$EFP_{it} = \alpha_o + \beta_1 EGOVT_{it} + \beta_2 GFE_{it} + \beta_3 NRR_{it} + \beta_4 ET_{it} + \beta_5 GDP_{it} + \mu_{it} \quad (2)$$

5.3.2 Data

This study empirically examines how E-government (EGOVT), government fiscal expenditure (GFE), natural resource rent (NRR), energy transition (ET), and gross domestic product (GDP) influence the ecological footprint (EFP) across 26 EU countries. For the analysis, a panel dataset covering the period from 2001 to 2023 is utilized for the selected 26 EU countries, depending on data availability. It is significant to highlight that the data was only available up to 2022; as a result, the study was limited to a similar time frame. The dependent variable in this study is the Ecological Footprint (EFP), which is measured in global hectares per capita. The exploratory variables include the E-Government Development Index (EGOVT) from the UN E-Government Knowledgebase to demonstrate the e-government development levels of various nations. This is a comprehensive combination of multiple indices, such as the E-Participation Index, Online Service Index, Telecommunication Infrastructure Index, and Human Capital Index; Government fiscal expenditure measured by total govt. expenditure % of GDP; Natural resources rent calculated by % of GDP; Energy transition measured by renewable energy consumption % of total final energy consumption; GDP as gross domestic product per capita, constant 2022 US$. The data for EFP is obtained from the Global Footprint Network, EGOVT is sourced from the UN E-Government Knowledge Base, while GFE, NRR, ET, and GDP are retrieved from the World Bank database. The data description for the variables obtained is presented in Table 1.

Table 5. 1: Data Description

Variables	Measurement Unit	Sources
EFP	Ecological Footprint	EFN
EGOVT	E-Government Development Index, which has core content related to website development patterns	UN E-Govt Knowledge base
GFE	Government Fiscal Expenditure is measured by Total Government expenditure (% of GDP)	WDI
NRR	Total natural resources rents (% of GDP)	WDI
ET	Energy Transition is measured by Renewable energy consumption (% of total final energy consumption)	WDI
GDP	Per Capita Gross Domestic Product	WDI

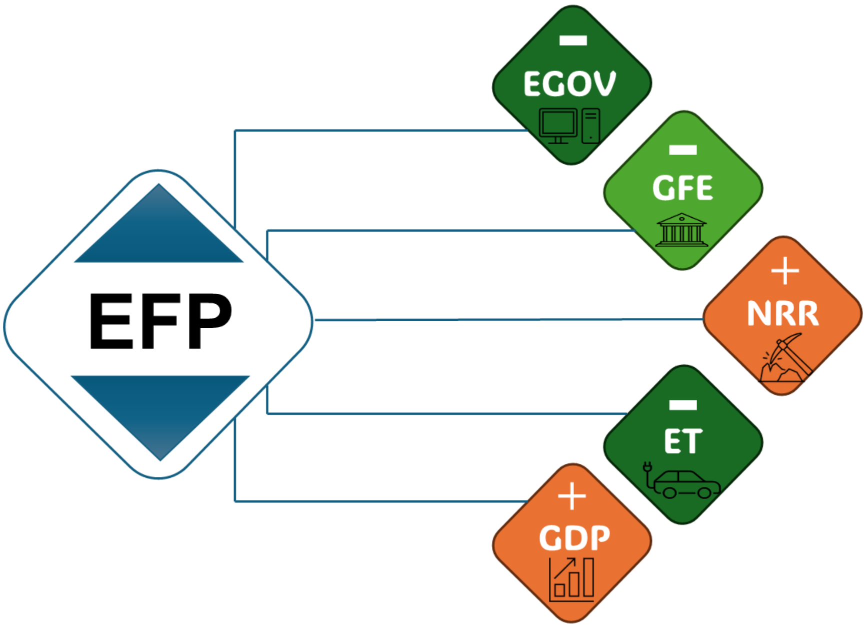

Figure 5.1: Expected outcomes of MMQR, FMOLS, DOLS, FE-OLS

5.3.3 Estimation Strategies

5. 3.3.1 Cross-Sectional Dependence

Given the structure of the panel data, the initial step involves addressing cross-sectional dependence. To this end, the current study employs the Lagrange Multiplier (LM) test, as proposed by Breusch and Pagan (1980), along with the Cross-Sectional Dependence (CD) test developed by Pesaran et al. (2004), to identify and account for any interdependencies among cross-sectional units. The test supports the obtaining of reliable outcomes because it is required to investigate the presence of CD in panel data. Specifically, the equation for the Pesaran et al. (2004) test is as follows:

$$CSD = \sqrt{\frac{2T}{N(N-1)} \sum_{i=1}^{N-1} \sum_{j=1+i}^{N} \widehat{\rho_{ij}}} \rightarrow N(O,1) \tag{3}$$

Where T denotes the period, N indicates the pair-wise parameters, and $\widehat{\rho_{ij}}$ Reflects the cross-sectional correlation of errors.

5.3.3.2 Slope Heterogeneity

The issue of slope heterogeneity (SH) must be investigated in advance, as it can significantly impact the interpretation of panel data regression outcomes. Accordingly, this research employs the Pesaran and Yamagata (2008) test to examine whether the slope coefficients are consistent across cross-sectional units. To evaluate SH, the study uses delta and adjusted delta test statistics, and their formulations are presented below:

$$\Delta_{SH} = (N)^{\frac{1}{2}}(2K)^{\frac{1}{2}}\left(\frac{1}{N}S - K\right) \tag{4}$$

$$\Delta_{ASH} = (N)^{\frac{1}{2}}\left(\frac{2K(T-K-1}{T+K}\right)^{-\frac{1}{2}}\left(\frac{1}{N}S - 2K\right) \tag{5}$$

Δ_{ASH} refers to the delta-adjusted slope heterogeneity measure, while Δ_{SH} stands for the standard delta value, as indicated in the formulas above.

5.3.3.3 Unit Root/ Stationarity

The presence of CSD and SH in the data first-generation stationarity test provides insufficient results. This necessitates the use of a second-generation unit root test, specifically the Cross-sectionally Augmented IPS (CIPS) test developed by Pesaran (2007). This approach is preferred because conventional first-generation unit root tests are not capable of handling the complications introduced by CSD and SH. The test accounts for both CSD and SCH issues in panel data analysis. The CIPS test statistics are formulated as follows:

$$\Delta C_{i,t} = \varphi_i + \varphi_i Y_{i,t-1} + \varphi_i \overline{C_{t-1}} + \sum_{I=0}^{p} \varphi_{il} \Delta \overline{C_{t-1}} + \sum_{I=0}^{p} \varphi_{il} \Delta C_{it-1} + \mu_{it} \tag{6}$$

Equation (4) demonstrates that $\overline{C_{t-1}}$ and $\overline{C_{t-1}}$ represent the cross-sectional averages. The CIPS test is formulated and presented using Equation (5), as shown below

$$\widehat{CIPS} = N^{-1} \sum_{i=0}^{n} CDF_i \tag{7}$$

In the above equation, CDF represents the cross-sectionally augmented Dickey-Fuller statistic.

5.3.3.4 Panel Cointegration

Once the stationarity of the variables is established, the subsequent step involves examining the existence of a long-run cointegration relationship among EGOVT, GFE, NRR, ET, and GDP across the EU27 countries. To examine the long-term cointegration relationship among the variables, the study applies the panel cointegration test proposed by Westerlund (2007). In contrast to the conventional cointegration test, Kao (1999) and Pedroni (2004), this test accounts for various forms of cross-sectional dependence (CSD) and slope heterogeneity (SH) test (Javed et al., 2024). The null hypothesis is "no presence of long-run cointegration." The following equations outline the mathematical structure of the model.

$$G_t = N^{-1}\sum_{i=1}^{N}\frac{\partial_i}{ZE(\partial_i)} \qquad G_a = N^{-1}\sum_{i=1}^{N}\frac{T\partial_i}{ZE(\partial_{ij})} \tag{8}$$

$$P_t = \frac{\hat{\vartheta}_i}{ZE(\hat{\partial}_i)} \qquad P_a = T\hat{\partial} \tag{9}$$

Eq. 8 defines the group-level statistics (Ga, Gt), while Eq. 9. Describe the panel-level metrics (Pa, Pt).

5.3.3.5 Method of Moment Quantile Regression

Following the assessment of the stationarity properties of the data series, the long-run elasticities are estimated using the Method of Moments Quantile Regression (MMQR) framework introduced by Machado and Silva (2019). This approach is particularly well-suited for capturing distributional heterogeneity, as it allows the analysis to uncover how the effects of explanatory variables on EFP vary across different points of its conditional distribution. Unlike traditional mean-based models, MMQR enables a deeper understanding of the asymmetric and heterogeneous relationships between the independent variables and EFP across quantiles. Furthermore, compared to standard quantile regression, the MMQR technique demonstrates enhanced performance under conditions of unobserved heterogeneity. This method also accommodates individual fixed effects and evaluates the conditionally heterogeneous covariance between the dependent and independent variables (Machado & Silva, 2019). Conversely, standard quantile regression approaches are less effective, as the MMQR framework accounts for covariance structures throughout the entire distribution. It effectively handles endogeneity concerns and generates consistent results even when the assumptions of linearity and normality are not met. Finally, given the heterogeneity among the selected EU economies, it is essential to adopt an estimation technique that can capture the full conditional distribution of the dependent variable. Accordingly, the MMQR effectively accommodates distributional differences across countries and quantiles, thereby aligning with the objective of the study. This estimation of the conditional quantile for the random variable $Uy(\mathcal{T}|Q)$ is conducted per the procedures demonstrated by (Awan et al., 2025).

$$y_{it} = a_i + Q'_{it}\lambda + (\delta_i + P'_{it}\upsilon)X_{it} \tag{10}$$

The probability $P\{\delta_i + P'_{it}\upsilon > 0\}$ represents the collection of parameters to be assessed. Including the values of a, λ, δ, and υ. The individual fixed effects (a_i , δ_i), where i = 1. . ., n are explicitly identified. Moreover, P denotes a k-vector composed of elements of Q that are expressed through differentiable transformations. Each element in P, indexed by I, is calculated through a specific functional representation.

$$P_I = P_I(Q), I = 1, \dots k \tag{11}$$

Where Q_{it} is assumed to follow an identical and independent distribution for each cross-sectional unit i and is also independent over periods t. In contrast, X_{it} exhibits an independent and identical distribution over both the cross-sectional units and time, and is uncorrelated with Q_{it}. Moreover, X_{it} is standardized in a way that meets the moment conditions, without requiring the assumption of strict exogeneity, as illustrated below.

$$Uy(\mathcal{T}|Q_{it}) = \left(a_i + \delta_i q(\mathcal{T})\right) + Q'_{it}\lambda + P'_{it}\upsilon q(\mathcal{T}) \tag{12}$$

Hence, Equation (10) defines the vector Q_{it}, which includes various independent variables. The key variables under investigation include EGOVT, GFE, NRR, ET, and GDP. Moreover, $Uy(\mathcal{T}|Q_{it})$ utilized to examine its association with the dependent variable y_{it} , where y_{it} denotes the EFP. Notably, the quantile behavior of y_{it} is determined based on the value of the independent variable Q_{it}. Additionally, the fixed effect for the quantile $\mathcal{T}$of individual i is captured by the scalar coefficient a_i ($\mathcal{T}$) = a_i + $\delta_i q$ ($\mathcal{T}$). The individual effect, unlike traditional fixed effects, does not signify a modification of the intercept. The parameters underlying these effects are time-invariant, yet their influence differs across quantiles. Here, q($\mathcal{T}$) identifies the $\mathcal{T} - th$ quantile in the sample distribution, calculated via a specific optimization criterion. Through this optimization approach, the corresponding value of the sample quantile is determined.

$$min_q \sum_i \sum_t \psi_{\mathcal{T}}(M_{it} - (\delta_i + P'_{it}\upsilon)q) \tag{13}$$

The given expression $\psi_{\mathcal{T}}(W) = \mathcal{T} - 1)WI\{W \leq 0\} + TWI\{W > 0\}$ reflects the check function.

5.3.3.6 Granger Causality

The final phase of the empirical analysis involves assessing the causal dynamics between EFP and the associated explanatory factors. Although FE-OLS, FM-OLS, D-OLS, and MMQR are robust estimators, they overlook the causal links and directionality among variables. Therefore, this study uses the Dumitrescu and Hurlin (2012) panel Granger causality method. The mathematical expression for the test is presented below:

$$y_{i,t} = \psi_i + \sum_{i=1}^{p} \gamma_i^{(p)} y_{i,t-n} + \sum_{i=1}^{p} \eta_i^{(p)} y_{i,t-n} + \mu_{i,t} \tag{14}$$

Here, $\eta_i^{(p)}$ corresponds to the regression coefficient parameters, while $\gamma_i^{(p)}$ represents those of the autoregressive component.

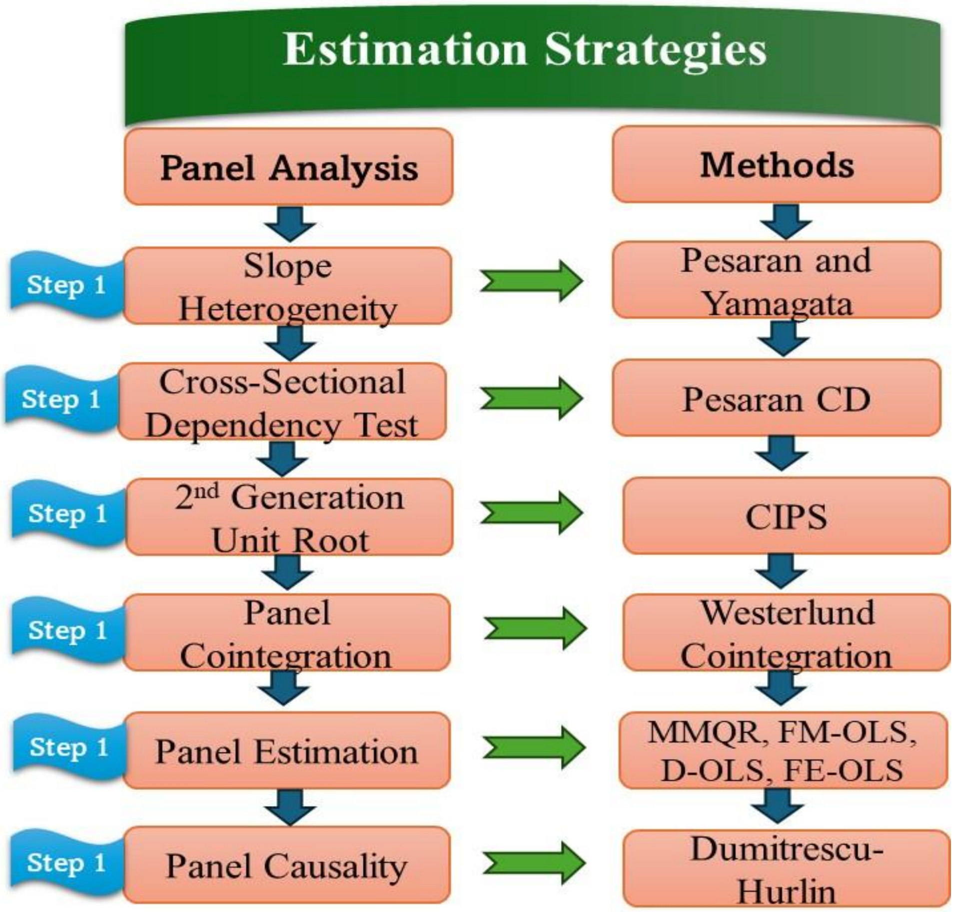

Figure 5.2: Estimation Strategies

5.4 Results and Discussion

Prior to carrying out the empirical estimations, we first investigated the descriptive statistics to acquire a full grasp of the distributional features of the underlying variables. According to the statistics reported in Table 1, GDP has the highest mean value (10.674), followed by REN (3.418), GFE (2.980), EFP (1.800), E-GOV (0.782), and NRR (0.162). Upon examination of the skewness values, it is evident that the EFP, GFE, and NRR exhibit a positive skewness, whilst the E-GOV, GDP, and REN exhibit a negative skewness. In addition, the findings of the kurtosis analysis show that the GFE follows a leptokurtic distribution, whilst the EFP, E-GOV, NRR, GDP, and REN all follow platykurtic distributions. Moreover, the Jarque–Bera test statistics are significant for all variables, indicating a clear violation of the normality assumption. This suggests that relying exclusively on linear estimators may lead to inefficient or biased inferences. Therefore, to more accurately capture the heterogeneous effects across the conditional distribution of the dependent variable, the study employs the Method of Moments Quantile Regression (MMQR) technique.

Table 5.2: Descriptive Statistics

Variables	EFP	E-GOV	GFE	NRR	GDP	ET
Mean	1.800	0.782	2.980	0.162	10.674	3.418
Median	1.799	0.783	2.969	0.154	10.696	3.453
Maximum	1.894	0.891	3.081	0.258	10.751	3.589
Minimum	1.697	0.667	2.930	0.070	10.567	3.117
Std. Dev.	0.053	0.064	0.037	0.048	0.053	0.153
Skewness	0.169	-0.087	0.964	0.311	-0.623	-0.615
Kurtosis	2.042	2.216	3.360	2.238	2.285	1.910
Jarque-Bera	25.703	16.070	95.868	24.163	51.466	67.360
Probability	0.000	0.000	0.000	0.000	0.000	0.000
Observations	598	598	598	598	598	598

Additionally, Table 2 presents the structure of the correlation relationship between all the underlying variables. According to the findings of the correlation analysis, E-GOV has a negative association with EFP. This suggests that enhancements in the performance of e-government relate to an improvement in environmental quality, as higher e-government lowers the EFP level. Additionally, results show a negative linkage between renewable energy and ecological footprint, LNEFP, which suggests that greater utilization of renewable energy contributes to a reduction in the ecological footprint. On the other hand, natural resource rents have a high and positive correlation with EFP, which indicates that a larger reliance on the extraction of natural resources leads to an increase in environmental deterioration in the underlying countries. Finally, the results explain that economic growth (GDP) has a slight negative connection with the EFP, which gives the impression that the sample's countries' economic expansion is only marginally associated with reductions in ecological footprint.

Table 5.3: Correlation Matrix

Variables	LNEFP	E-GOV	GFE	NRR	ET	GDP
LNEFP	**1**	-0.604	-0.434	0.814	-0.450	-0.195
E-GOV	-0.605	**1**	0.362	-0.564	0.595	0.583
GFE	-0.434	0.362	**1**	-0.229	0.668	0.448
NRR	0.814	-0.564	-0.229	**1**	-0.115	-0.018
REN	-0.450	0.595	0.668	-0.115	**1**	0.854
GDP	-0.195	0.582	0.448	-0.018	0.854	**1**

At the initial phase of the estimation process, we comprehensively evaluated the slope heterogeneity. We conducted the slope heterogeneity test developed by Pesaran and Yamagata (2008), and the estimated results are presented in Table 3. These outcomes provide evidence that the research model demonstrates slope heterogeneity (SH), as seen by the significant values of delta and adjusted delta. As a result of the findings, the alternative hypothesis is supported, and the null hypothesis that there is no heterogeneity is rejected at the 1% significance level.

Table 5.4: Slope heterogeneity test

SCH Test	Statistics
$\Delta_{\text{ŠĤ}}$	14.006***
$\Delta_{\text{ĄŠĤ}}$	16.793***

Note: *** indicates a 0.01 significance level.

Next, one of the most common issues that arises while conducting panel data analysis is the presence of cross-sectional dependency. This issue must be resolved before examining the relationship between the variables, as potential spillover effects from interdependencies among economies within a panel can bias the outcomes. To address this issue, we applied the Breusch-Pagan LM and Pesaran's (2007) CSD tests, and the results of these tests are reported in Table 5. The findings indicate that the null hypothesis of "cross-sectional independence" is rejected in favor of the alternative, confirming the presence of "cross-sectional dependence". Given evidence of CSD and SH, it is more appropriate to apply second-generation unit root tests and a cointegration approach to determine the order of integration and the long-term cointegration relationship among the study variables.

Table 5.5: Cross-sectional dependence

Variables	Breusch-Pagan LM	Pesaran CD
EFP	1519.472***	30.18***
E-GOV	1473.394***	66.30***
GFE	1576.714***	22.15***
NRR	1584.213***	28.01***
ET	1743.025***	77.63***
GDP	1518.272***	61.10***

Note: ***, ** & * indicate 0.01, 0.05, and 0.10 significance levels.

Upon verifying the existence of cross-sectional dependence and slope heterogeneity, it is essential to implement a panel non-stationarity test that accommodates both characteristics of

CSD and SH. For this purpose, the present study utilizes second-generation unit root tests, notably the CIPS and CADF tests, to guarantee the stationarity of the study. These unit root tests are suitable for CSD and heterogeneity situations. Table 3 reveals that all the underlying variables display unit roots at their levels but attain stationarity following the first difference. Consequently, all variables are integrated of first order, I(1).

Table 5.6: Second-generation unit root outcomes

Variables	CIPS		CADF	
	I (0)	I (1)	I (0)	I(I)
EFP	-2.463***	-5.323***	-1.759	-3.486***
E-GOV	-2.352***	-4.128***	-2.324***	-3.931***
GFE	-1.636	-3.926***	-1.581	-2.803***
NRR	-2.697***	-4.130***	-2.357***	-3.556***
ET	-2.698***	-4.650***	-2.441***	-3.555***
GDP	-1.504	-2.595***	-1.530	-2.616***

Note: ***, ** & * indicate 0.01, 0.05, and 0.10 significance level.

Before performing the empirical analysis, it is essential to verify the existence of a long-term cointegration connection among the variables under investigation. To accomplish this, we utilized the second-generation cointegration approach suggested by Westerlund (2007). This cointegration approach is more suitable in comparison to the traditional cointegration techniques in the presence of SH and CSD. The findings of the cointegration test are reported in Table 1. These results support the presence of a long-term cointegration relationship among the studied variables by rejecting the null hypothesis of no cointegration.

Table 5.7: Westerlund cointegration results

Statistics	Value	Z-value	P-value
Gt	-3.840***	-6.388	0.000
Ga	-8.334***	4.108	0.000
Pt	-18.565***	-5.981	0.000
Pa	-8.302***	1.844	0.000

Note: *** indicates a 0.01 significance level.

After confirming that the dependent variable (EFP) and the explanatory variables (E-GOV, GFE, REN, NRR, and GDP) demonstrate long-term cointegration, the subsequent step is to analyze the response of the ecological footprint to shocks from these explanatory variables. To achieve this, we employ the Method of Moments Quantile Regression (MMQR) approach, which provides robust coefficient estimates across different points of the conditional distribution. This technique enables us to uncover the heterogeneous and dynamic relationships between EFP and its determinants across various quantile levels rather than relying on average effects alone. The empirical results obtained from the MMQR estimations are reported in Table 7. For illustrative purposes, the table presents coefficient estimates from the 10th through the 90th quantiles, highlighting how the effects of E-GOV, GFE, REN, NRR, and GDP on EFP vary across the distribution of EFP.

According to the outcomes given in Table 3, E-GOV has a significant negative relationship with EFP across all quantiles. The negative coefficient size of E-GOV increases as it proceeds from the lower quantiles to the upper quantiles, which indicates that the influence of E-GOV on EFP varies as it passes from lower to higher quantiles (see Fig. 1). More precisely, a one percent increase in E-GOV results in a rise in EFP that is equal to 0.339% to 0.665% over nine quantiles. These findings are consistent with prior empirical research, which has highlighted the importance of digital governance in improving institutional performance and environmental quality. Roy (2017) highlights how digital public services enhance administrative efficiency; Pérez-Morote et al. (2020) demonstrate that E-GOV contributes to improved public management outcomes; Zioło et al. (2022) provide evidence of the contribution of digitalization to sustainable development; and Shahbaz et al. (2022) report that advancements in digital technologies support environmental improvements by promoting responsible resource use. Furthermore, the findings are consistent with the goals of the Digital Decade Policy Program, which aims to fully digitize public services across the EU by 2030. These projects enhance the ability of e-government to promote transparency, better governance, and assure more effective management of public resources, particularly natural resource rents. These activities directly promote the SDG 16 goal by increasing institutional accountability and developing digitally integrated public administrations.

Furthermore, the MMQR outcomes given in Table 1 exhibit a significant negative association between GFE and the EFP at all quantiles. The magnitude of negative coefficient values of GFE for EFP increases from the lower 0.123% to the upper quantiles 0.148%. This adverse impact of GFE on EFP suggests that effective and well-targeted fiscal policies can play a crucial role in improving environmental quality. These findings are closely aligned with the objectives of the European Green Deal, which emphasize the necessity of strategic public investment in achieving climate neutrality, increasing resource efficiency, and facilitating a sustainable economic transition. Governments can alleviate environmental constraints while encouraging long-term sustainability by allocating fiscal resources to clean technologies, renewable energy, and ecologically appropriate infrastructure. The findings are also consistent with preceding empirical literature. Ahmad and Satrovic (2023) and Azam et al. (2023) emphasize the positive environmental impact of public spending directed toward green sectors. Wang et al. (2024)

demonstrate that financial interventions can reduce environmental degradation by investing in sustainable technology. Coady et al. (2017) emphasize the significance of government spending in rectifying environmental externalities, whereas Caglar et al. (2023) show how fiscal policies help the transition to low-carbon development.

Next, the findings demonstrate that NRR exerts a positive and significant influence on EFP across all quantiles. More specifically, a 1% increase in NRR raises EFP by approximately 0.049% to 0.139% across the examined quantiles. Notably, the magnitude of this positive association strengthens progressively from the lower to the upper quantiles, indicating that the adverse impact of natural resource rents on environmental quality becomes more pronounced at higher quantiles. This implies that as countries intensify natural resource extraction, environmental quality deteriorates at an increasing rate. In the case of energy transitions, the MMQR results given in Table 1 suggest that ET has a significant negative influence on EFP at all quantiles. However, the magnitude of this negative effect is heterogeneous (see Fig. 1). Specifically, the outcomes demonstrate that a 1% increase in ET results in a decrease in EFP that ranges from 0.061% to 0.055% over nine quantiles. This outcome suggests that the transition from traditional to renewable energy improves the environmental quality in the underlying countries by lowering the ecological footprint. These findings are consistent with significant European policy initiatives, such as the EU Green Deal, REPowerEU, and other national climate laws, which prioritize expediting the clean energy transition, reaching carbon neutrality, and promoting sustainable energy consumption (European Commission, 2019). These frameworks provide the institutional support required to amplify the environmental benefits of energy transition by emphasizing renewable energy deployment, energy efficiency, and reduced reliance on high-emission fuels. The findings are also aligned with previous empirical literature. Javed et al. (2025) and Appiah et al. (2021) demonstrate that increasing renewable energy use greatly reduces environmental damage. Liu et al. (2025) and Ahmad et al. (2024) emphasize the environmental benefits of shifting to clean energy systems. Wang et al. (2023) also confirm that ET policies help to reduce long-term ecological footprints. Finally, the outcomes given in Table 2 suggest that economic growth is significantly positively linked with EFP at all quantiles. The positive influence of GDP on EFP is heterogeneous across all quantiles (see Fig. 1). This demonstrates that an increase in economic activity leads to a decline in environmental quality, as evidenced by the increase in EFP.

Table 5. 8: MMQR Outcomes

			Lower Quantile			Middle Quantile			Higher Quantile		
Variables	**Location**	**Scale**	**0.10**	**0.20**	**0.30**	**0.40**	**0.50**	**0.60**	**0.70**	**0.80**	**0.90**
E-GOV	-0.499***	-0.099	-0.339**	-0.405***	-0.442***	-0.467***	-0.493***	-0.526***	-0.567***	-0.605**	-0.655***
	(0.105)	(0.066)	(0.146)	(0.120)	(0.110)	(0.106)	(0.105)	(0.108)	(0.117)	(0.130)	(0.152)
GFE	-0.136***	-0.007	-0.123***	-0.128***	-0.131***	-0.133***	-0.135***	-0.138***	-0.141***	-0.144***	-0.148***
	(0.020)	(0.012)	(0.027)	(0.022)	(0.020)	(0.020)	(0.020)	(0.020)	(0.022)	(0.024)	(0.029)
NRR	0.094***	0.028*	0.049*	0.067***	0.078***	0.085***	0.092***	0.102***	0.113***	0.124***	0.139***
	(0.018)	(0.011)	(0.026)	(0.021)	(0.019)	(0.018)	(0.018)	(0.019)	(0.020)	(0.023)	(0.027)
ET	-0.058***	0.005	-0.061***	-0.060***	-0.059***	-0.058***	-0.058***	-0.057***	-0.057***	-0.056***	-0.055***
	(0.013)	(0.008)	(0.018)	(0.015)	(0.0138)	(0.013)	(0.013)	(0.013)	(0.014)	(0.016)	(0.019)
GDP	0.423***	0.037***	0.364***	0.388***	0.402***	0.411***	0.421***	0.433***	0.448***	0.463***	0.482***
	(0.019)	(0.012)	(0.363)	(0.022)	(0.020)	(0.019)	(0.019)	(0.019)	(0.021)	(0.023)	(0.027)

Note: ***, ** & * indicate 1%, 5%, and 10% significance levels.

These findings are also consistent with Public Value Theory, which suggests that governments generate public value when their activities improve social well-being and institutional performance, and promote long-term outcomes. The observed negative relationship between e-government and government fiscal expenditure with the ecological footprint highlights how investments in digital governance, transparency, and targeted public spending provide environmental public value. Similarly, the contributions of ET and responsible natural resource management strengthen the notion that public institutions play a critical role in providing long-term environmental gains.

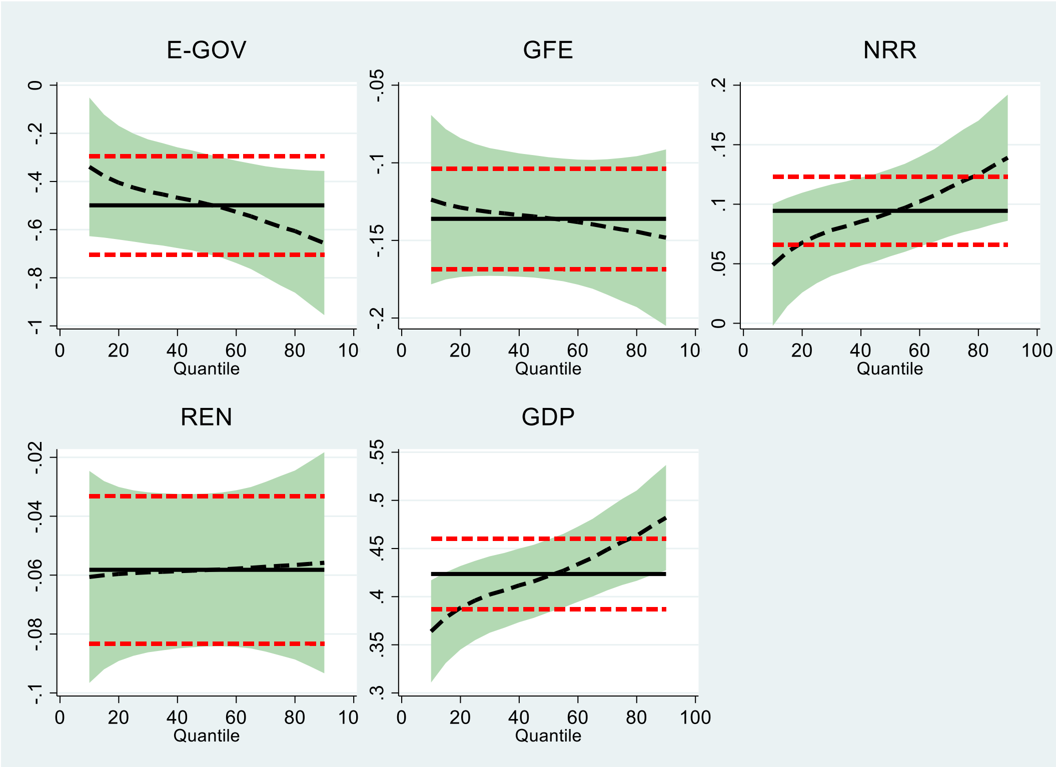

Figure 5.3: MMQR outcomes

This study further evaluates whether and how the explanatory factors under investigation are linked to the ecological footprint, thereby validating the robustness of the MMQR results. In this instance, the PCSEs model, which stands for Prais–Winsten regression with Panels Corrected Standard Errors, is utilized as a robustness test to confirm the outcomes of the MMQR model. This model takes into consideration the assumption that the panel data contains correlated errors. Table 5 presents the results of the PCSEs model. The results demonstrate that E-GOV, GFE, and ET are negatively linked with the EFP. This implies that E-GOV, GFE, and ET improve the environmental quality by lowering the level of EFP. On the other hand, NRR and GDP have a positive association with EFP. This implies that higher economic growth and the extraction of natural resources deteriorate the environmental quality. These outcomes validate the findings of the MMQR approach.

Table 5.9: Prais-Winsten regression with Panel-Corrected Standard Errors (PCSEs)

Variables	**Coef.**	**Std. Err.**	**P-value**
E-Gov	-0.236	0.107	0.028
GFE	-0.165	0.032	0.000
NRR	0.059	0.012	0.000
ET	-0.087	0.022	0.000
GDP	0.388	0.030	0.000

In the last step of our estimation, we evaluate the causal relationships between the ecological footprint and the explanatory variables of the study. Although the MMQR and PSCEs approaches provide robust parameter estimates, they do not capture the direction of causality among the variables. Therefore, this study applies to the Dumitrescu and Hurlin (2012) panel Granger causality test, with the results presented in Table 10. The Wald and Z-bar statistics are used to test the null hypothesis of no causal relationship. The results show that the test statistics are highly significant for all relationships, leading to the rejection of the null hypothesis of no causality. The findings indicate both unidirectional and bidirectional causal relationships among the variables.

Table 5.10: Dumitrescu Hurlin Panel Causality Results

Null Hypothesis	Wald statistics	ZBAR-statistics	P-value
E-GOV ≠ EFP	4.638***	4.538	0.000
EFP ≠ E-GOV	9.243***	13.440	0.000
GFE ≠ EFP	0.399***	-3.646	0.000
EFP ≠ GFE	0.175***	-4.079	0.000
NRR ≠ EFP	1.552***	-1.417	0.000
EFP ≠ NRR	4.565***	4.404	0.000
ET ≠ EFP	6.959***	9.029	0.000
EFP ≠ ET	9.334***	13.617	0.000
GDP ≠ EFP	3.812***	2.949	0.003
EFP ≠ GDP	1.404*	-1.702	0.086

Note: ***, ** & * indicate 1%, 5%, and 10% significance levels.

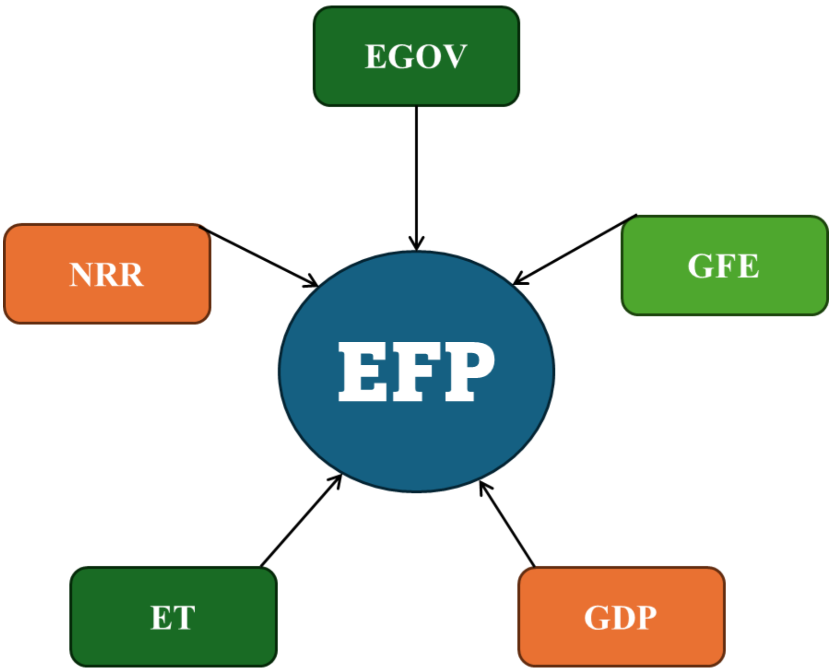

Figure 5.4: Causal links of exploratory variables with green EFP

5.5 Conclusion and Policy Recommendations

This study provides comprehensive empirical evidence on the relationship between EFP, EGOVT, GFE, NRR, ET, and GDP across 26 EU countries from 2000 to 2022. Prior to empirical analysis, this study first conducts a series of preliminary tests to examine the underlying characteristics of the panel data. For this purpose, we applied the SCH by Pesaran and Yamagata (2008), the CSD by Pesaran (2007), and the second-generation panel unit root test (Pesaran, 2007) to evaluate the fundamental statistical features of the dataset. In addition, the Westerlund (2007) panel cointegration test was conducted to explore the existence of a long-term cointegration between the EFP and the explanatory variables. The results of these diagnostic evaluations lead to the adoption of the most appropriate econometric strategy for reliable empirical investigation. However, this study utilizes the MMQR to capture the heterogeneous effects of these drivers across different quantiles of EFP. The results highlight that while EGOVT and ET significantly contribute to reducing the EFP, higher GDP and reliance on NRR tend to exacerbate environmental degradation, particularly at the upper quantiles of the distribution. GFE shows mixed impacts, reflecting the dual role of public spending in either supporting environmental initiatives or intensifying ecological stress, depending on its composition and effectiveness.

The empirical findings of this study yield several important policy implications. First, strengthening EGOVT systems can enhance transparency, improve public service efficiency, and facilitate the implementation of environmentally responsible policies. Governments should invest in digital infrastructure to better monitor environmental data and streamline green public services. Second, public expenditure must be strategically reallocated toward sustainability goals, particularly by increasing investments in renewable energy, green infrastructure, and environmental protection programs. Third, effective governance of natural resource rents is crucial; revenues derived from resource extraction should be reinvested into long-term ecological preservation, clean technologies, and education. Additionally, accelerating the transition to clean energy remains a vital policy priority. This includes phasing out fossil fuel subsidies, supporting renewable energy expansion, and ensuring a just transition that safeguards vulnerable populations. Finally, economic growth strategies should integrate environmental considerations, encouraging low-carbon development pathways that align with both ecological preservation and economic stability. Regional cooperation and cross-sectoral coordination will further enhance the effectiveness of these policies, particularly in multi-country contexts such as the European Union. These recommendations aim to guide policymakers toward balancing economic advancement with ecological sustainability.

This study provides valuable insights into the influence of EGOVT, GFE, NRR, ET, and GDP on EFP in EU countries. Despite its contributions, this study possesses certain limitations that warrant further exploration in future academic research. First, Future research should explore emerging drivers such as green growth, sustainable finance, and digitalization, which hold potential for shaping innovative sustainability policies. Second, in terms of EGOVT, future research should examine the specific mechanisms through which digital governance affects environmental sustainability, such as digital service delivery, online environmental reporting systems, open data platforms, or citizen engagement tools. Exploring the interaction between e-government and smart city initiatives, as well as the role of digital literacy and access disparities, could also offer critical insights. Methodologically, while this study employs MMQR to capture heterogeneous influence across EFP distribution, future work could utilize dynamic spatial panel regressions or nonlinear ARDL techniques to account for regional spillovers and long-term asymmetries. Additionally, integrating machine learning models or high-frequency environmental indicators, such as satellite-based emissions data, could significantly enhance the accuracy and policy relevance of empirical analysis. Finally, comparative studies across developed and developing economies or within digital governance maturity levels would further contribute to a broader understanding of sustainable digital governance strategies.

6. Conclusion of Thesis

This thesis aims to investigate the evolving dynamics of governance performance, management control systems, change management, and digital transition within public administration, with a particular focus on how these factors collectively enhance institutional efficiency and contribute to broader sustainable development goals. Through four peer-reviewed empirical studies, the research provides an integrated and multifaceted understanding of how governance systems can adapt, innovate, and generate public value in an era characterized by rapid technological change, complex societal needs, and sustainability issues. The first empirical study conducted a systematic literature review of Total Quality Management and Quality Function Deployment in higher education institutions. The analysis revealed that structured quality tools traditionally rooted in industrial management hold significant transformative potential for modernizing academic governance. By identifying key research themes, conceptual trends, and theoretical gaps, this study demonstrates how QFD can enhance teaching quality, institutional responsiveness, and evidence-based decision-making. It highlights that strengthening management control systems in educational settings enhances accountability, transparency, and continuous quality improvement.

The second study advanced these insights through a comprehensive bibliometric analysis of the Plan-Do-Check-Act framework within higher education. This chapter mapped intellectual structures, leading authors, and thematic research clusters to illustrate how PDCA has evolved as a core mechanism for quality enhancement. The findings confirm that PDCA supports organizational learning and systematic performance monitoring, reinforcing its relevance for public sector institutions seeking to promote sustained quality assurance. Together, the first two studies underscore that continuous improvement methodologies are vital components of effective governance performance in public administration, particularly in the context of higher education.

The third empirical study expanded the analytical lens to the macro-level, investigating how digitalization and government expenditure influence sustainable development across EU27 countries. Using advanced Method of Moments Quantile Regression and 2-Stage Least Squares techniques, the findings indicate that digital transformation improves environmental quality when accompanied by strategic public spending. The results also emphasize the need for coherent fiscal policies that align with digital governance initiatives, revealing important implications for governments aiming to accelerate environmental progress through digital means. This study demonstrates that digital transformation is not only a technological shift but also a structural governance reform that strengthens institutional performance and supports environmental outcomes.

The fourth study further deepened this perspective by examining the combined effects of e-government development, government fiscal expenditure, natural resource rents, and the energy transition on ecological sustainability in selected EU countries. Employing the Method of Moments Quantile Regression alongside robust long-run estimators, the study found that e-government, public expenditure, and clean energy transitions consistently reduce ecological footprints. In contrast, natural resource rents and economic expansion increase ecological pressures. These results affirm the importance of digital governance, sustainable fiscal strategies, and responsible resource management in shaping long-term environmental performance across the EU.

Therefore, by integrating these four studies, this thesis makes an original and integrated contribution to the literature, linking governance performance, management control systems, digital transformation, and sustainability outcomes within a unified analytical framework. The findings reveal several overarching insights. First, high-performing governance systems require more than compliance and administrative control; they depend on innovative strategies, data-driven tools, and organizational cultures that embrace continuous improvement. Second, digital transformation is not merely a technological shift but a governance reform that enhances public value creation, strengthens institutional performance, and improves environmental outcomes. Third, public financial management, particularly the strategic use of government expenditure, remains a critical mechanism for enabling digitalization, supporting energy transition, and managing natural resources responsibly. Finally, sustainable development in modern public administration is achievable only when governance reforms, technological innovations, and environmental policies are aligned. However, this thesis contributes to the literature by offering an integrated analytical perspective that links management control, governance performance, technological innovation, and sustainability outcomes. It provides valuable implications for policymakers, public managers, and researchers seeking to enhance institutional effectiveness and public value creation in the digital era. By demonstrating how governance tools, technological reforms, and sustainability strategies intersect, the research affirms that the transformation of public administration is both necessary and achievable, offering actionable insights to address the pressing societal challenges of the twenty-first century.

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