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The Impact of Green Patents, Fintech and Digitalization on Resource Efficiency: Moderating Effects of Regulatory Framework and Policy Uncertainty

by

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CERTIFICATE OF APPROVAL

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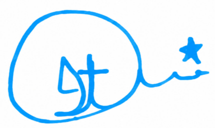

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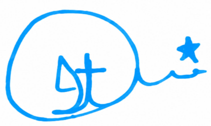

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(Iqra Toheed)

Abstract

Benefiting from greater efficiency in the use of resources is now a key macro economic goal of all nations as they attempt to build a sustainable economy that is not based on dependence on natural resources or environmental damage. While the volume of literature is growing in the field of sustainability studies, the knowledge on the interplay between innovation and digital processes with the macro institutional factors is still limited.

The aim of this Study is to address this gap and develop a detailed framework to assess the impact of FinTech, green patents and digitalisation on resource efficiency at the national level. Most importantly, the main idea of the research is to analyse the structural impact of the environment in which these key factors function: how they are regulated by national institutions and how much Economic Policy Uncertainty they experience. The positive and stable coefficients of all these variables with national resource efficiency show the use of the data in the panel composed of 21 countries; nonetheless, digitalization works best, followed by FinTech and green patents. More importantly, the analysis of external institutions is key in this regard, since the tight regulation from national regulators plays an important role in increasing the effect of resource efficiency as it ensures external environment stability, environmental disclosure transparency and rules enforcement.

However, high Economic Policy Uncertainty is a strong institutional destabilizer as it leads to strategic friction, lowering capital flow and making capital investments risky, which impacts technological innovation sustainability. It is important to emphasize that these research findings provide the background for practical policies that should be adopted by the relevant authorities in regulating cross border technology transfer or implementing separate technologies, without which the process will not be possible; and in the absence of a stable and highly transparent regulatory environment, it is impossible to prevent macroeconomic policy shocks. The study has distinctive features since it adopts the dependance of the internal capabilities vis-à-vis the external regulatory processes in the frame of the Institutional Theory and Resource Based View (RBV).

Keywords: Green patents, Fin Tech, Digitization, Resource efficiency, Regulatory environment, Economic policy uncertainty, System GMM, Panel data,Green Innovation,Financial Technology,Digital Transformation,Energy Efficiency,Carbon Emissions,Environmental Policy, Economic Growth,Sustainable Development

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Abbreviations

DI	Digitalization
EPU	Economic Policy Uncertainty
ER	Environmental Regulation
FDI	Foreign Direct Investment
FT	FinTech
GDP	Gross Domestic Product
GMM	Generalized Method of Moments
GP	Green Patents
IMF	International Monetary Fund
INF	Inflation
IPS	Im, Pesaran & Shin
LLC	Levin, Lin & Chu
RE	Resource Efficiency
WDI	World Development Indicators
WIPO	World Intellectual Property Organization

Chapter 1

Introduction

1.1 Background of the Study

For hundreds of years before the rise of systematic industrialization, the economy of humanity was in a relative balance, being symbiotic with the environment (Polanyi, 1944). All production processes were highly local relied solely on biological energies and were strictly limited by nature itself, resulting in no negative impact (Sieferle, 2001). However, a set of historical industrial revolutions radically changed the world as we knew, it creating an economy characterized by its movement from the agricultural stage towards industrialization (Wrigley, 2010).

Mechanization, specialization, factory structures and intensive use of fossil fuels permitted the nations to greatly boost the level of production capacity establish trade connections globally and gain economic prosperity as never before (Clark, 2007). Nevertheless, such global breakthroughs carried along another significant drawback: anthropogenic accumulation of carbon dioxide emissions and environmental pollution became a serious problem (Malm, 2016). As for economic paradigms established during industrial times, there was always a priority to increase raw production volumes and expand the scope of capital investments at any cost and both natural resources and industrial waste were considered inexhaustible and therefore unlimited (Meadows et al., 1972).

Given the inevitable consequences of industrial expansion throughout the late 20th century and into the early 21st, the world community faced a dramatic rise in environmental instability, ecosystem failures and erratic climate change (Rockström et al., 2009). A considerable body of empirical evidence in environmental economics has confirmed that there exists a clear cause-and-effect relationship between past emissions of carbon dioxide by industry and the phenomenon of global warming resulting in unpredictable weather conditions, climate-based disasters and resource shortages around the world (Stern, 2007).

These environmental problems have made it necessary for global authorities and macroeconomics specialists to acknowledge the obvious fact that the current pattern of development judging the success of a country purely on GDP growth with no regard for its ecological footprint is ultimately unsustainable and doomed to global ecological disaster (Stiglitz et al., 2009).

To ensure planetary health conserve biodiversity and address such environmental risks the system of macroeconomics had to make a dramatic shift in its approach to industrial practices and switch towards international environmental regulation (Biermann, 2014).

As a result of this transition in history, international environmental councils, transnational commissions and international climate change treaties were established with the intent to effectively control global carbon emissions ensure sustainable policies and coordinate green efforts between different countries (Keohane and Victor, 2011).

Strict protocols were laid out by these international organizations which included active observation of environmental degradation, setting up specific targets for reducing emissions and protection of global ecosystems from the adverse effects of industry (Bodansky, 2010).In such a highly regulated global atmosphere technological advances have been the key strategic approaches through which these goals could be achieved (Keohane and Victor, 2011; Bodansky, 2010).

Modern technological developments are being made in the form of combining FinTech, green patents and digitalization, which is the key strategy currently for decoupling growth from environmental issues and ensuring that production systems are optimized for achieving environmental protection objectives globally (Block et al., 2025; Song et al., 2023; Chen et al., 2023b).

Just as the global finance system does, the modern world is run by the evolutionary law. Traditionally, finance has been used to allocate capital efficiently, until now. As no consideration was given to ecological impacts from industrial production cycles, the goal was to maximize shareholder value (Meadows et al., 1972).

The three main types of money used for financing in the past decades were commercial loans, equity and venture capital. All of these are examples of linear economic instruments (take, make, throw away). Natural resources have been viewed as "infinite externalities," as opposed to finite assets, under this model (Polanyi, 1944; Sieferle, 2001).

As we enter the second decade of the 21st century, the problems associated with the traditional financial model have become apparent. There was only one metric of success for conventional finance: return on investment (ROI). So, ecological debt was not calculated or taken into account. With global warming and biodiversity spiraling out of control, the very fundamentals of sustainable economics are being broken down (Stern, 2007; Rockström et al., 2009).

Over the past few years, the term 'Green' has been introduced in various contexts in the fields of Research and Business, for example in the context of Green Finance, Green Patents and Green Innovation. However, the question is still open have these terms ideas in fact stimulated Resource Efficiency, or are they really just an extension of "Greenwashing"? (Ozili, 2022). For instance, logging in the forest has two impacts: one on the GDP side as a sale of wood (Traditional Finance); and one on the side of a very negative reduction in the potential for carbon sequestering and the potential for future Resources (Traditional Resource Use) (Stiglitz et al., 2009). Can the current "Green" technology, in combination with the capacities of FinTech and Digitalization, close that gap and offer "resource efficiency" through more economic output per dollar spent without cutting down the trees? For most developing and emerging economies, resource efficiency, defined as a situation in which economic output is achieved using the least amount of resources, is not a reality (Khan et al., 2023; Li et al., 2024a).

Though the world has committed itself to sustainability, the consumption of resources is still high in comparison to GDP and inefficient production structures, and environmental degradation is increasing in most countries of the world. This has been corroborated by various reports from OECD (2021) and UNEP (2023), and others.

The trends indicate a clear divergence between economic growth and sustainable use of resources, thus reducing long-term development perspectives and increasing environmental and economic vulnerability (Biermann, 2014). Investment in green innovation is still low and access to sustainable finance is very unevenly distributed, while several institutional shortcomings hinder the use of modern technologies on a wide scale and to their full effect (Ansari et al., 2024; Kwilinski et al., 2025). Indeed, increasing resource efficiency at the macro level is one of the most pressing challenges for policy makers today to address in order to increase productivity while also decreasing ecological pressures (Sadiq and Kofi, 2023; Hsieh and Lin, 2024).

Though the world has committed itself to sustainability, the consumption of resources is still high in comparison to GDP and inefficient production structures, and environmental degradation is increasing in most countries of the world. This has been corroborated by various reports from OECD (2021) and UNEP (2023), and others. The trends indicate a clear divergence between economic growth and sustainable use of resources, thus reducing long-term development perspectives and increasing environmental and economic vulnerability (Biermann, 2014). Investment in green innovation is still low and access to sustainable finance is very unevenly distributed, while several institutional shortcomings hinder the use of modern technologies on a wide scale and to their full effect (Ansari et al., 2024; Kwilinski et al., 2025). Indeed, increasing resource efficiency at the macro level is one of the most pressing challenges for policy makers today to address in order to increase productivity while also decreasing ecological pressures (Sadiq and Kofi, 2023; Hsieh and Lin, 2024).

Recent literature points out that financial innovation and technological development, as well as the shift towards green economies, have a great impact on the improvement of resource efficiency at the macro level. One of the key factors is green innovations which can be represented by the number of green patents, indicating a country's transition to cleaner technologies and more productive processes (Block et al., 2025). The advent of FinTech has since changed the financial systems, by providing better access to finance, lower transaction costs and better transparency. The empirical evidence shows that digital financial inclusion, as enabled by FinTech, has a positive impact on sustainable investment flows and the environmental performance in developing countries (Chen et al., 2023b).

Moreover, digitalization is a catalyst for structural change, which facilitated countries to implement sophisticated monitoring systems, to automate industrial processes and to create methods for enhanced diffusion of green financial products. Digital economies are more likely to improve the efficiency of resources, energy productivity and to embed the natural environment in the financial decision-making of firms and households.

Digitalization complements green innovation and FinTech development as a complementary solution to enhance the national resource efficiency. Furthermore, resource efficiency has become a major indicator of the efficiency with which economies are using their productive inputs to generate maximum economic output, making it an important indicator in contemporary economic research. Financial tools that can support structural transformation have gained traction in developing economies due to the need to ensure the continuation of economic growth without increasing dependence on resources (Rahman and Alam, 2022). Green finance, Fintech and Digitalization are helping to create an ecosystem in which companies can follow sustainable business practices, improve their operational efficiency and switch to low carbon production systems (Yu and Li, 2024).

These transitions are particularly relevant in the context of environmental disclosures, carbon footprints and innovation capacity being linked to the availability of capital by global financial institutions (Ahmed et al., 2023). From this perspective, green finance acts as a catalyst for sustainable investment decisions, by attracting financial capital to projects that result in efficiency, prevent waste and promote sustainable output (Wang et al., 2023).

Financial products like green bonds, sustainability linked loans and environmental screening investment funds reorient capital flows towards areas that are considered to have a higher environmental value and long-term productive potential (Nguyen et al., 2022).

Empirical studies of recent years indicate that green finance markets are related to better progress in resource-efficient production, better environmental quality, and higher innovation capacity (Khan et al., 2023). Beyond just finance and digital advances, green patents explicitly contribute to resource efficiency by achieving improved energy mixes, lowering waste and driving sustainable production processes (Zhou and Zhang, 2023).

In addition to finance and digital innovations, green patents play a clear role in resource efficiency, through the improvement of energy mixes, reduction in waste and sustainable production processes (Zhou and Zhang, 2023). A recent study shows that economies with high levels of R&D and eco innovation and clean technologies experience higher productivity with lower resource development (Kraus et al., 2022). Green tech arenas also develop strong resilience to reduce operating uncertainty and implement environmentally friendly production systems (Li and Huang, 2023).

Thus, the convergence of green finance, Fintech and green patents provides a profound avenue to achieve resource efficiency at a macro level. However, the longevity of this relationship is greatly affected by relational and structural conditions (especially regulatory conditions). A robust governance framework comprising robust financial governance, environmental disclosure and effective enforcement could significantly amplify the impact of green finance and Fintech on positive sustainable outcomes (Kumar and Dixit, 2023).

Robust regulatory frameworks reduce uncertainty, encourage companies and investors to adopt sustainable practices aligned with long-term economic interests, and promote trans-inclusive policies and practices (Usman et al., 2023). The importance of digitalization is also undeniable as technologically advanced economies can better connect technological innovation into financial activities and encourage more adoption of green and resource efficient options (Song et al., 2023).

Digitalization improves the dissemination of information, boosts utilization efficiency and strengthens the channels of green and environmentally efficient financial products (Khan and Yousaf, 2024).

The other side of the coin, however, is that increasing Economic Policy Uncertainty (EPU) is a significant threat to sustainable financing. EPU increases the investment risks, restricts the capital flow and prevents firms from adopting innovative or green patents.

A high degree of uncertainty may reduce long term investment in environmental projects, which might undermine the positive effect of green finance and FinTech on resources efficiently (Li et al., 2022). Thus, EPU is a destabilizing factor that might hinder and distort sustainable financial outcome.

These dynamics highlight the need to consider the direct impact of green finance, FinTech and green patents not only on resource efficiency, but also on the economy as a whole. However, the situational influences that impact their effectiveness as well. This relationship is critical to understanding for policy-makers, financial regulators and institutional investors seeking to foster sustainable economic transition.

1.2 Problem Statement

In spite of the rapid development of green finance, the development of FinTech and the innovation of digital technology, resource efficiency and digitalization in the financial sector remain very low. Economies have not achieved high levels of efficiency to date, especially in developing economies. Green patents, FinTech development and digitalization are considered to be broadly perceived phenomena. Together and in combination, they can be seen as potential drivers of sustainable growth, The lack of understanding of on resource efficiency is limited. The current literature looks at these. factors in isolation focusing either on financial mechanisms, technological These pathways were ignored in the advancement or environmental outcomes, which is a synergistic pathway. The intersection of finance and technology that influences national productivity of resources.

Building on this disparity, three key enabling factors exist: regulatory environment, process technology, and organizational skills. The combined effects of digitalization and economic policy uncertainty have been studied little, if at all.

In a single empirical framework. Weak regulatory governance, inadequate digitalization and policy uncertainty can have a major impact on financial flows, and restrict the take-up of innovation and jeopardize the benefits of efficiency from green finance and FinTech.

In addition, the majority of the studies conducted so far are cross-sectional or static estimations that do not take into account endogeneity, reverse causality and The lack of country-level heterogeneity limited the scope of the findings that could be drawn from this research.

This means that the most fundamental issue that this study seeks to solve is that of the lack of an integrated, a theoretically sound and empirically validated model of how green patents are explained, The impact of FinTech and digitalisation on resource efficiency and how this relationship works together. The relationship is subject to regulatory quality and uncertainty on the economic policy. across countries.

1.3 Research Gap

Although the field of finance research is expanding rapidly, there are a few. income and other factors on poverty.There are also substantive gaps that prevent us from understanding the combined effect of financial income and other factors on poverty and macro level mechanisms to boost resource efficiency.

First, the literature focuses on the development of FinTech and green patents, dividing these developments into two broad categories.Literature first focuses on the development of FinTech and green patents, which are split into two main categories. separately. The literature on green finance focuses on emissions reduction or green financial risk management. FinTech sector is thriving in sunny spots.In contrast, the FinTech sector is booming in sunny areas. The literature mainly focuses on financial inclusion or transaction efficiency. few studies that integrate these drivers in a unified empirical model. A combined empirical model to evaluate their combined effect on resource efficiency (Ozili, 2022). This breakdown is problematic for scholars to grasp the complementarities of financial innovation, digitalization and green patents and hinders the development of the theory in sustainable financial economics. (Kwilinski et al., 2025). In contrast, resource efficiency has been given only scant It is a more comprehensive measure than sustainability indicators such as and arises from empirical consideration. The carbon dioxide emissions or pollution levels (Li et al., 2024a; Sadiq and Kofi, 2023). Moreover, few studies Consider resource efficiency as an economic outcome in macro-level, either because to green finance or due to green innovation (Zhou and Zhang, 2023; Fu et al., 2023).

Although the The correlation of FinTech with sustainability results is relatively It is considered a gamechanger in the global finance sector and is under-researched. (Nasir et al., 2023).

The majority of FinTech studies are related to financial access, payments or only emerging research is addressing financial stability (Demir et al., 2024; Qamruzzaman and Wei, 2021). Economics and investment avenues in green finance and environmental protection.Connects digital finance with investment avenues in green sector or environmental protection. transparency (Chen et al., 2024a; Li et al., 2022). the teacher and the student.The evidence of interaction between teacher and student. FinTech, green innovation and green finance and their impact on resource efficiency is almost entirely missing and therefore a significant lack of thought and research. (Block et al., 2025; Tan et al., 2022).

The effect of regulatory uncertainty and economic policy uncertainty (EPU) are There is still limited research into sustainability finance in sustainability frameworks (Chang and Gupta, 2023). While The quality of governance has been determined as a determinant of financial behavior. Few studies evaluate the and environmental outcomes (Lopes et al., 2023; Kumar and Dixit, 2023). The positive or negative influence of regulation on the impact of green The study focuses on finance and FinTech development from the point of view of macroeconomic sustainability indicators. (Ansari et al., 2024). Similarly, EPU, a known factor impacting investment, The perception of risk and the innovation processes (Baker et al., 2016; Bloom, 2009) is rarely considered. They were explored as a moderator in resources efficiency models (Li et al., 2022; Gulen and Ion, 2016).

This means that there is little understanding of the impact of policy. The volatility in terms of green financing, technology development and sustainable economic growth. outcomes (Leduc and Liu, 2016; He et al., 2025). Typically, empirical evidence is constrained by country-specific designs, that are not dynamic (i.e., cross-sectional / static country-specific designs).

Interactions and long-term impacts of financial, technological and institutional variables (Spyromitros, 2023). Typical regression methods fail to take into consideration endogeneity, reverse causality and Arising unobserved heterogeneity that is often found in macro-financial and environmental contexts. studies (Blundell and Bond, 1998; Arellano and Bover, 1995). The development of theory about "it".

sustainable finance remains in disarray. Most of the research is dedicated to either of the above. environmental economics or innovation theories but there is limited research that adopts an institutional approach and the Resource Based View (DiMaggio and Powell, 1983; Barney, 1991). There is a lack of a combined theoretical perspective which limits Understanding of internal resources, including innovation, and digital skills. readiness, external institutional pressures such as regulatory, Uncertainty about quality and policy uncertainty, which affects the growth of resources efficiently (North, 1990).

Together these gaps indicate the need for an integrated analysis at the macro-level, which can reflect the interconnection between green innovation (green patents), and FinTech development and digitalization, its impact on the efficiency of financial services, As a product of the regulatory framework and EPU, the use of resources. (Usman et al., 2023; Bui, 2024). The research is conducted according to a general framework which integrates Institutional theory and RBV to give creditable and policy relevant conclusions To address these gaps (DiMaggio and Powell, 1983) explains about sustainable economic performance.

1.4 Theoretical Background

1.4.1 Resource Based View

Barney (1991) advanced a new organizational theory, dubbed the Resource Based View (RBV), which focuses on how well an organization possesses and leverages valuable, rare, inimitable and non-sustainable (VRIN) resources to drive their performance. They cover technological capacities, financial capital, human skills, knowledge and innovation capacities.

According to RBV, the competitive advantage of a firm and its long-term achievement of performance is dependent on its internal capabilities.

Green patents represents a critical intangible resource that improves production efficiency, reduces waste and increases output with fewer environmental inputs.

Fintech capability acts as an innovation driven financial resource that enhances transparency, reduces transaction costs and improves resource allocation efficiency.

Green finance availability provides the necessary financial capital for adopting green patents, upgrading infrastructure and supporting cleaner and more efficient production systems.

This research examines how green innovation (GI) and Fintech capability and availability of green financial resources are strategic assets that give economies and firms the ability to improve the efficiency of using their resources. Green patents is a key intangible factor which enhances the efficiency of production, lowers waste and boosts the output while utilizing fewer environmental inputs. Fintech capability is a financial innovation tool that boosts transparency, cuts down on transactional expenses and optimises the allocation of resources. Green finance availability offers financial resources that can be utilized for the adoption of green technologies, infrastructure development, and cleaner and efficient production systems. These resources are also firm and economies to convert restricted natural inputs into economic value, which directly translates to resource efficiency, according to RBV. The ability to create competitive advantages through enhanced productivity and cost reduction, and sustainable performance, is enhanced by having a stronger green innovation ecosystem, more advanced financial innovations and higher green financial capacity. Therefore, RBV supports the relationship between your independent variable and the dependent variable (resource efficiency), reasoning that internal financial and technological capacities are strategic resources which will enhance productive efficiency at the macro level.

1.4.2 Institutional Theory

This research is based mainly on institutional theory that focuses on the influence of external institutional factors like governance, norms, policy framework, structures and regulations over organizational behavior and economic outcomes. DiMaggio and Powell (1983) suggest that institutions put pressures on firms in three ways: coercive, normative and mimetic.

In the financial sense, institutions play a critical role in the creation of the incentives, constraints and opportunities available to financial actors and market participants (North, 1990). In the context of the study, it is the principles of Institutional Theory that help to understand the impact of the regulatory environment, digitalization infrastructure and economic policy uncertainty on the relationship between sustainable finance mechanisms and resource efficiency.

A strong regulatory environment including green financial regulations, environmental disclosure policy and sustainable investment guidelines create a coercive institutional pressure that encourages firms and financial institutions to channel funds toward environmentally efficient projects. National digitalization level reflects normative and technological institutional support that accelerates the adoption of Fintech, enhances financial transparency and fosters innovation in sustainable finance. Economic policy uncertainty (EPU) represents an institutional instability that generates risk, undermines investor confidence and influences strategic responses to financial and technological change.

A robust regulatory framework, such as green financial regulations, environmental disclosure policy and sustainable investment guidelines, exerts a regulatory influence that forces companies and financial institutions to invest in environmentally friendly projects. National digitalization level is the indicator of the normative and technological institutional support to foster the adoption of Fintech, strengthen financial transparency and innovation in sustainable finance. Economic policy uncertainty (EPU) is an institutional instability that introduces risk and erodes investor confidence and shapes strategic responses to financial and technological change.

Based on this, the institutional theory helps to understand the regional differences of the effectiveness of green finance, Fintech and green innovation in relation to the quality and stability of its institutional structures. Nations with robust governance, regulations and an advanced digital economy are more likely to experience positive financial technology synergies that can improve the use of resources.

However, low regulatory standards or increased policy uncertainty has the potential to limit the availability of green investment, delay the uptake of technologies and dampen the overall efficiency effect. The institutional theory has been included as a moderating variable, as it is suggested that the sustainability outcomes are influenced by the regulatory environment as well as the digitalization and EPU.

1.5 Research Questions

1.5.1 Research Question 1

How does the Green Patents influence Resource Efficiency?

1.5.2 Research Question 2

How does FinTech development contributes to improving Resource Efficiency?

1.5.3 Research Question 3

How does the Digitalization influence the Resource Efficiency?

1.5.4 Research Question 4

Does the Regulatory Environment moderate the relationship between Green Patents and Resource Efficiency?

1.5.5 Research Question 5

Does the Regulatory Environment moderate the relationship between FinTech and Resource Efficiency?

1.5.6 Research Question 6

Does the Regulatory Environment moderate the relationship between Digitalization and Resource Efficiency?

1.5.7 Research Question 7

Does the EPU Index moderate the relationship between Digitalization and Resource Efficiency?

1.5.8 Research Question 8

Does the EPU Index moderate the relationship between Green Patents and Resource Efficiency?

1.5.9 Research Question 9

Does the EPU Index moderate the relationship between FinTech and Resource Efficiency?

1.6 Research Objectives

1.6.1 Objective 1

To examine the impact of Green Patents towards Resource Efficiency.

1.6.2 Objective 2

To evaluate how FinTech development contributes towards improving Resource Efficiency.

1.6.3 Objective 3

To evaluate the impact of Digitalization towards Resource Efficiency.

1.6.4 Objective 4

To analyze whether Economic Policy Uncertainty moderates the relationship between Green Patents and Resource Efficiency.

1.6.5 Objective 5

To examine whether Economic Policy Uncertainty moderates the relationship between FinTech development and Resource Efficiency.

1.6.6 Objective 6

To evaluate whether Economic Policy Uncertainty moderates the relationship between Digitalization and Resource Efficiency.

1.6.7 Objective 7

To assess whether the Regulatory Environment moderates the relationship between Green Patents and Resource Efficiency.

1.6.8 Objective 8

To examine whether the Regulatory Environment moderates the relationship between FinTech development and Resource Efficiency.

1.6.9 Objective 9

To assess whether the Regulatory Environment moderates the relationship between Digitalization and Resource Efficiency.

1.7 Significance of the Study

The study is of great significance to policy makers, financial institutions, regulatory bodies, scholars in the field of finance, sustainability and technological innovation. Given the growing global pressures on economies to boost productivity and reduce risks associated with environmental changes and resource use, a growing awareness of the financial and technological variables that drive resource efficiency are of great relevance.

The report integrates green finance with Fintech and technological innovation under one analytical framework to provide useful insights into the potential of the financial system to support sustainable and resource efficient economic growth. The study adds to the financial policy and sustainable development planning. In this context, as the Governments of the world are introducing green financing instruments, building digital financial ecosystems and encouraging eco innovation, there is still very little empirical evidence on the effectiveness of the financial instruments.

This study provides solid and tangible evidence of the ways in which green finance can direct capital towards more resource efficient sectors, reduce the financing constraints for green projects and directly improve productive efficiency through green innovation itself. This result offers policy makers some evidence-based advice on where incentives, subsidies and regulatory focus should be aimed to maximize sustainability outcomes.

It also represents research which will be important for financial institutions, investors and the banking sector as there is growing pressure on coherent investment decisions with environmental and technological priorities. The evaluation of financial instruments and digital platforms' impact on macroeconomic resource efficiency provides financial institutions with knowledge to create more effective green financial products, strengthen risk assessment and adopt disclosure-based investment strategies.

The study also helps investors understand the long-term economic benefits of investing in green technologies and from digital financial ecosystems. The moderating variables of the regulatory environment, digitalization and economic uncertainty (EPU) provide valuable practical relevance. All factors are essential elements of the functioning of modern financial markets but remain unexamined when it comes to sustainability oriented financial research. This study shows how high regulatory quality strongly enhances the impact of financial mechanisms, how digitalization speeds up the adoption of sustainable financial technologies and how economic policy uncertainty disrupts capital flow and shrinks resource efficient investment. The advantage of these insights can be leveraged by policy makers and regulators in the quest for more stable and transparent financial environments, which are also conducive to innovation.

The paper will advance theory on sustainable finance through institutional theory and the Research Based view. This dual theoretical lens shall provide an explanation for both external pressures on institutional systems and the internal resources of firms explaining the external pressure and the internal capability which makes a contribution to explain resource efficient outcomes at the macroeconomic level, such as an integrated approach, which will lead to a deeper academic understanding of how institutional systems and the resources of a firm interact.

The study has methodological value in the sense that it employs sophisticated estimation methods for dynamic panel data: the generalized method of moments. This method is more effective than the standard regression models in the endogeneity and omitted variable bias and heterogeneity problems. This increases the strength and stability of the results. The addition of multi-country panel data enhances the generalizability and offers cross national evidence that is applicable to both developed and emerging economies. The proposed research is important because it offers a finance-focused explanation for the effect of financial innovation and green technologies and institutional conditions on resource efficiency, a key component of the construction of sustainable, resilient and productive economic systems. The output of these will help to inform decision making by policy makers, financial regulators, institutional investors, banks and technology drive enterprises in developing strategies aligned to the global sustainability goals.

1.8 Structure Scheme of Research

The structure of the research proceeds in a logical manner from a theoretical base to an empirical validation of the hypotheses put forth.

The first chapter provides an overview of the reasons for the shift from traditional financial tools to new 'green' financial instruments.

The second chapter contains a full review of the literature available from 2022 to 2026 and includes a discussion that compares so-called 'buzz words' with actual empirical evidence of the decoupling of natural resources from all economic activity.

The third chapter reviews the methodology and justifies the use of a 'system GMM' (Generalized Method of Moments) model to accommodate the dynamic nature of resource productivity.

The fourth chapter provides the empirical results obtained from EViews including all the robustness checks and moderation analyses.

The fifth chapter provides overall policy recommendations that look beyond the 'green' designations of financial instruments and provides ways to implement sustainable and structural transformations in economies.

Chapter 2

Literature Review

2.1 Green Patents

Green Patents, which are beginning to be used increasingly, are becoming a vital tool to finance missing environmental protection funding and to further advance sustainable development projects (Wang et al., 2023; Lee et al., 2022).

In general, green finance involves all kinds of financial instruments and mechanisms designed to offer investment and financing activities with an environmental benefit in the context of a more general framework of sustainable development. Involves people, businesses and governments (Huang et al., 2019; Reboredo, 2018)to take part in low carbon and green efforts. The primary aim is to invest in activities in the environment that will create a greener economy.

According to the aforementioned, Green finance enhances the transparency of the information, thereby reducing information asymmetry (Lee et al., 2022), consolidates social capital, provides monetary support for green development (as identified by the study of (Dikau and Volz, 2021), and alleviates financing pressure effectively and promotes sustainable practices in an intrinsic way that motivates to improve ESG performance (Ozili, 2022; Soundarrajan and Vivek, 2016). Supporting green innovation is a very important aspect of green finance's influence. Green innovation, which is essential for sustainable national development, refers to the creation and implementation of new knowledge, materials, processes, products or technologies that either decrease negative environmental impact or result in positive effects on the environment.

(?)indicated that this form of innovation will be facilitated by green finance as this finance has channeled money from high polluting industries to low polluting industries, provided favorable conditions for green innovation activities, lowered financing costs and thus promoted the development of green patents. This can enhance the effectiveness and potentiality of such sustainable innovation in improving efficiency of the allocation of resources, reducing the destruction of natural resources or improving the competitiveness of sustainable development. The experience demonstrates that green finance has a positive impact on the national ESG performance.

Consistent findings from cross national data analyses show that green finance has a significant impact on the national ESG performance Zheng et al. (2025). Green finance has a more positive impact on ESG performance in countries that have greater financial development, higher institutional quality and quicker ICT development. Zheng et al. (2025)found that the most significant transmission pathway of green finance to ESG performance is speeding up green technology development. Green finance has been found to significantly improve green productivity (Fu et al., 2023; Jjiakui et al., 2023)and clean energy efficiency, further demonstrating the very important role of green finance in sustainable development promotion. Industrial structural upgrading is not regarded as a key policy instrument for green finance to enhance ESG performance, although green finance plays a role in raising the thresholds for financing of polluting enterprises, increasing financing costs, and driving the transformation of these enterprises into eco-friendly enterprises. Previous studies have shown huge potential for green finance to achieve sustainable growth (Zhou and Zhang, 2023). In addition, some scholars also studied the influence of green finance pilot zone policy on ESG results, finding that green finance has a positive impact on ESG results (Zhang et al., 2022b; Shen et al., 2025).

Recent empirical evidence further supports the role of green finance in promoting sustainable environmental outcomes. Tariq and Hassan (2023), using panel data from 70 countries over the period 2012–2020, examined the effects of green finance, renewable energy, environmental regulations and carbon finance on environmental sustainability. Their findings indicate that green finance significantly contributes to environmental sustainability, highlighting the importance of directing financial resources toward environmentally sustainable activities. The study further demonstrates that the effectiveness of green finance is not independent of the institutional environment, suggesting that financial mechanisms can produce stronger sustainability outcomes when supported by appropriate regulatory conditions.

H1: Green finance has a positive and significant impact on resource efficiency.

2.2 FinTech

The traditional financial services have been shaken by a wave of digital innovations, known as fintech, which significantly enhance the transparency, availability and efficiency of financial services. Combining the blockchain, AI, algorithmic lending, digital payments and big data analytics, Fintech helps reduce transaction costs, information asymmetry and capital mobility towards the most environmentally and productive sectors (Saeedi and Ashraf, 2024). Such technologies allow for savings to be better redirected to green and high productivity projects that are not necessarily well financed by traditional finance sources. The evidence around Fintech and sustainability is increasing.

In particular, Fintech based platforms enable green loans with the improvement of credit evaluation, automated underwriting based on AI or machine learning, and real-time environmental risk monitoring capabilities (Li and Chen, 2024). This is because the flow of investment to ”green” investments, such as renewable energy or energy efficient infrastructure, is less friction intensive and clearer.

Secondly, the Fintech industry can help to facilitate and democratize P2P investment in sustainable projects, giving small investors the ability to invest in environmentally friendly projects that are aligned with ESG principles (Khan and Wahab, 2025). Moreover, Fintech fosters the use of energy efficient consumption patterns, which enhances the efficiency of resources. Digital finance driven mobile systems and smart metering systems enable consumers to track their energy consumption in real time, to get digital incentives for being 'green', as well as to track their carbon footprints using systems supported by tokens or blockchain. This type of environmental responsibility puts the user in a state of active participation rather than being a mere consumer, creating a more dynamic and participatory approach to sustainability.

The influence of Fintech in emerging economies is even stronger, as the traditional banking system is not particularly inclusive and financial services access is generally low. In this regard, Fintech can contribute to going beyond the traditional models, through digital financial inclusion, credit access and environmental finance for the unserved population. For instance, Bakri et al. (2025) have stated that ease of entry and accessibility of financial products is an important factor in financial development and results in resource efficiency within sectors essential for long-term sustainability.

Furthermore, the paper proves that green finance also has a positive impact on the performance of financial institutions through the introduction of Fintech. For example, sophisticated Fintech solutions lower costs, enhance the management of risk and boost the reputation of banks which in turn magnify the proceeds of green lending activities significantly (Li and Chen, 2024).

This synergy underscores the true meaning of Fintech: it is not a tool to facilitate green finance, but rather a player that is reshaping the way environmental and financial objectives can work together in the financial system. In general, Fintech contributes to sustainable development through digital innovation: it accelerates capital to projects that have environmental value, it makes resources more efficient by smart consumption and it promotes financial inclusion in emerging markets. Thus, Fintech transforms economic reality into finance and strengthens financial systems in ecological sustainability.

Ibrahim et al. (2024) examined the relationship between green finance, digital economy, and FinTech, finding that these three variables are closely interrelated, providing helpful knowledge regarding the development of environmental sustainability in Middle Eastern countries.

Similarly, Xu et al. (2025) examined the impact of FinTech on green finance using panel data from 30 provinces in China for the period 2011–2021, revealing that FinTech facilitates the development of green finance through financial efficiency and green innovation as significant channels, with the influence being more pronounced in regions with higher financial development levels.

Furthermore, Afjal (2023) conducted a bibliometric analysis on the role of digital financial services within FinTech, highlighting a growing interdisciplinary interest since 2016 and emphasizing the significance of digital financial services in addressing the limitations of traditional financial institutions. In this regard, Li et al. (2024c) further established that financial technology can significantly enhance the resource allocation efficiency of enterprises by promoting the breadth and depth of digital technology application.

H2: Fintech development positively influences resource efficiency.

2.3 Digitalization

Digitalization, also closely referred to as the digital economy, plays a transformative role in both economic and environmental landscapes. As a new economic form derived from digital technology, it can influence energy and ecological industries by reducing production costs, advocating enterprise innovation and improving energy utilization efficiency. This contributes to achieving carbon reduction goals.

Evidence shows that the digital economy significantly restrains regional carbon emissions. For example, using data for China, researchers estimated that with a 1% increase in digital economy development, total carbon emissions decreased by approximately 1.09% (Chen et al., 2023a). This inhibiting effect is more pronounced in eastern regions and areas with higher levels of digital economy development, suggesting heterogeneity. According to(Chen et al., 2023a), the mechanisms involved in digitalization reducing carbon emissions are related to the improvements of energy efficiency and optimization of energy structures. Moreover, the digital economy has a spatial spillover effect on carbon emission reduction, which means its benefits may extend to nearby regions (Chen et al., 2023a).

The concept of a digital economy, first put forward by Don Tapscott in 1996 (Tapscott, 1996), now encompasses not only the development of information and communication technology but also all economic activities that promote the adjustment of the whole social and economic structure, the improvement of production efficiency and the integration and innovation of traditional industries through modern information and communication technology (UNCTAD, 2019). On the economic level, the digital economy greatly enhances the total factor productivity by promoting industrial structure upgrading (Tai et al., 2025)and technological progress (Bai et al., 2024). It also influences corporate governance and thus leads to a higher level and efficiency of governance within enterprises (Zhang et al., 2022a) and promotes the transformation of resident's consumption (Ma and Lin, 2023). Socially, a digital economy can facilitate integrated urban and rural development(Xia et al., 2025), promote rural revitalization and help achieve common prosperity(Tai et al., 2025), and increase labor demand and improve the employment and occupational status of women (Lu et al., 2025).

The measurement of the digital economy normally needs the comprehensive index system. One classifies metrics into four main parts: digital infrastructure, industrial structure, digital industrial scale and technological innovation of the digital economy. According to(Chen et al., 2023a), all are specific measures: digital infrastructure refers to per capita internet access traffic, ports, optical cable length and computers per capita.

Metrics in industrial structure show the proportion of the software and information technology service industry both in GDP and employment and also in digital financial inclusion. Digital industrial scale involves metrics related to technology market turnover, revenue gained due to software products and e commerce activities.

Technological innovation is assessed via R&D funding, number of R&D projects and patents concerning the digital economy. Several scholars also take objective weighting methods for assessment that include principal component analysis, the entropy method and the vertical and horizontal pull off method. The digital economy significantly lowers regional carbon emissions. In addition, for every percent that increases in the development of a digital economy, there is a significant decline in the total carbon emissions(Chen et al., 2023a). The effect is stronger in the more developed digital economies and eastern regions. Digitalization can inhibit carbon emissions through enhancing energy efficiency and optimization of energy structures by (Chen et al., 2023a).

The digital economy causes a spatial spillover effect in carbon emission reduction, meaning that adjacent areas also benefit from it. More broadly, the digital economy promotes higher total factor productivity(Tai et al., 2025), industrial structure upgrade(Bai et al., 2024), corporate governance improvement(Zhang et al., 2022a), consumption pattern transformation (Ma and Lin, 2023) and urban and rural integration (Xia et al., 2025) and enhances women's employment opportunities.

H3: Digitalization has a positive effect on resource efficiency

2.4 Regulatory Environment as Moderator

The regulatory environment, often assessed through various governance indicators, plays a critical role in shaping economic outcomes and influences the effectiveness of diverse policies. There is broad consensus among economists that a country's governance and the quality of its institutions have a significantly positive impact on growth performance. This view was shared by(Acemoglu et al., 2001; Kaufmann and Kraay, 2002; Han et al., 2014; Mira and Hammadache, 2017; Samarasinghe, 2018).

According to the World Bank (1994), good governance is characterized by transparent processes, professional bureaucracy, governmental accountability and a strong civil society operating under the rule of law. Governance is defined by the World Bank as the way power is exercised in the management of a country's economic and social resources for development(World Bank, 1994).

One of the six WGIs is RQ, developed by (Kaufmann and Kraay, 2002) which has been found in Lopes et al. (2023)to be positively related to real GDP growth consistently and statistically significantly. In fact, according toLopes et al. (2023), this positive relationship is stronger for the emerging market economies than for developed economies.

A sound regulatory environment therefore acts as a potent stimulant for economic growth in developing contexts. On the other hand, another WGI, RL, has been found to bear a statistically significant negative relationship with economic growth in some analyses, even though the finding does not hold up consistently across all tests, partly because of low within country variation in this indicator.

This ambiguity could arise because the established elites in some contexts benefit from low-quality institutions and hence have little incentive to demand better governance.

Institutional quality, which encapsulates the regulatory environment, among other elements, is the general level of a country's governance system. Good institutional quality facilitates conditions that are promotive of innovation, technological progress and new methods of organization of economic and social activities; in turn, advances social and economic development. According to World Bank (2020), a strong institutional framework means lower instability in economic policies and more complete intellectual property protection systems.

These conditions can strongly increase the enthusiasm and effectiveness of green finance activities, implying a moderating role here, with a strong regulatory environment amplifying the positive impacts of green finance and digitalization on resource efficiency. Countries with good quality institutions also face smaller negative growth shocks (Kaufmann and Kraay, 2002).

In the series, the impact of Regulatory Quality is positive, stable and statistically significant with regard to real GDP growth, with higher magnitude in emerging marketsLopes et al. (2023). Good governance which shall be proxies by transparent processes for accountability-is an important determinant of economic growth(Kaufmann and Kraay, 2002).

A country's governance system is regarded as the level of institutional quality. It therefore encourages innovation and technological progress through the development of economic activities.

According to World Bank, (2020) it is one of the top components of growth friendly environment. Better institutional quality implies more stable economic policies and stronger intellectual property protection, which can favors engagement in green finance activities and also improve the positive impact that digitalization may have on resource efficiency.

The importance of regulatory institutions is also supported by Tariq and Hassan (2023), who examined the moderating role of environmental regulations in the relationship between green finance and environmental sustainability using a cross-country panel framework.

Their findings demonstrate that regulatory policies can strengthen the contribution of green finance to environmental sustainability, indicating that financial resources alone may not be sufficient to achieve sustainable outcomes.

Effective environmental regulations can create incentives for firms and investors to direct financial resources toward environmentally responsible activities and can improve the effectiveness of green-finance initiatives.

This evidence supports the argument that the institutional environment conditions the effectiveness of sustainable financial and technological mechanisms.

Accordingly, the present study extends this perspective by examining whether regulatory quality strengthens the relationships between green patents, FinTech, digitalization and resource efficiency.

H4: The regulatory environment positively moderates the relationship between green Patents and resource efficiency.

H5: The regulatory environment positively moderates the relationship between FinTech and resource efficiency.

H6: The regulatory environment positively moderates the relationship between Digitalization and resource efficiency.

2.5 Economic Policy Uncertainty EPU

EPU is defined as uncertainty about the direction, stability and scope of government policies that shape business expectations, financial markets and economic activities. For instance, in situations of frequent macroeconomic policy changes, political instability, or poor regulatory frameworks affecting firm operations and outputs, such uncertainties may arise, as shown by Bloom (2009). The EPU Index, one of the most common measures of policy uncertainty, was developed by Baker et al. (2016). It is constructed using three weighted components: (1) the frequency of newspaper coverage of policy related uncertainty, (2) the number of federal tax code provisions set to expire in coming years and (3) the degree of disagreement among economic forecasters. This index thus becomes a very robust proxy to capture fluctuations in the overall level of policy uncertainty in an economy.

High levels of EPU have been shown to significantly impact economic activities by reducing investment, employment and output. Empirical studies show that under uncertainty in policy, firms delay or scale back investments, in a manner consistent with real options theory ((Dixit and Pindyck, 1994)Bloom (2009) further illustrates that uncertainty shocks make firms postpone hiring and production decisions. Increased EPU also leads households to raise precautionary savings, which further weakens aggregate demand and slows down economic growth (Leduc and Liu, 2016).

In fact, the relationship between EPU and green patents has been empirically supported. Greater uncertainty tends to dampen the willingness of firms to invest in a long term, capital intensive and irreversible innovation project such as green innovation. Gulen and Ion (2016) explain that increasing EPU exacerbates information asymmetry, making it challenging for external financiers to assess the firm's prospects. This increases financing constraints and reduces available funds for research and development. Pastor and Veronesi (2012) consequently reduce their environmentally oriented R and D investments owing to increased risk and limited external financing. However, some researchers have argued that EPU may encourage innovation in some contexts. The underlying reason is that uncertainty amplifies competitive pressure, which drives firms to innovate to maintain market share or pursue first mover advantages. For example, (as cited in He et al., 2025) documents a slight positive effect of EPU on the green technology innovation of Chinese listed firms, especially for state owned and high tech enterprises. This incentive effect seems weaker for high polluting firms facing higher environmental scrutiny and regulatory burdens. EPU also moderates the relationship between different economic variables and sustainability outcomes. As such, studies indicate that EPU amplifies negative financial shocks to investment and economic growth (Pastor and Veronesi, 2013). Within environmental contexts, this EPU lowers the effectiveness of green patents initiatives by raising levels of risk and uncertainty. Another way to think about this is that government subsidies for environmental policies may be an effective way to reduce the negative impacts of EPU on firm level green innovations(Qamruzzaman and Wei, 2021). In the context of green finance and digitalization, EPU is therefore expected to have a moderating role in influencing how these tools effectively promote sustainable outcomes.

H7: Economic policy uncertainty negatively moderates the relationship between green Patents and resource efficiency.

H8: Economic policy uncertainty negatively moderates the relationship between FinTech and resource efficiency.

H9: Economic policy uncertainty negatively moderates the relationship between Digitalization and resource efficiency.

2.6 Summary of Hypothesis of the Study

H1: Green Patents has a positive and significant impact on Resource Efficiency.

H2: Fintech development positively influences Resource Efficiency.

H3: Digitalization has a positive effect on Resource Efficiency.

H4: The Regulatory Environment strengthens the relationship between Green Patents and Resource Efficiency.

H5: Regulatory Environment strengthens the relationship between FinTech and Resource Efficiency.

H6: The Regulatory Environment strengthens the relationship between Digitalization and Resource Efficiency.

H7: Economic policy Uncertainty weakens the relationship between Green Patents and Resource Efficiency.

H8: Economic policy Uncertainty weakens the relationship between FinTech and Resource Efficiency.

H9: Economic policy Uncertainty weakens the relationship between Digitalization and Resource Efficiency.

2.7 Theoretical Framework

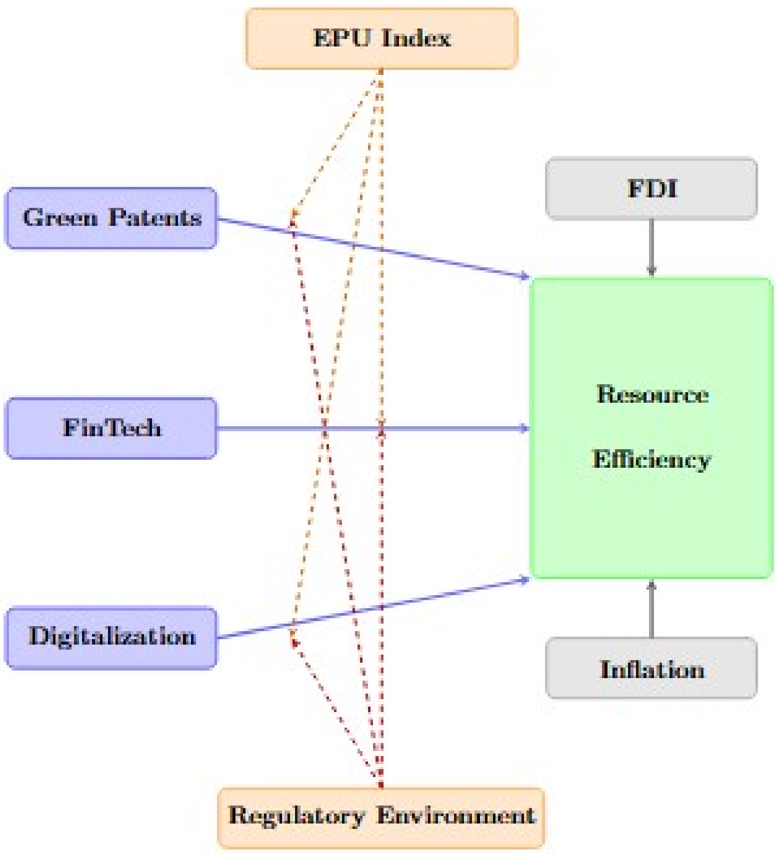

FIGURE 2.1: Theoretical Framework: Impact of Green Patents, Fintech and Digitalization on Resource Efficiency

2.8 Theoretical Framework Explanation

Figure 2.1 above illustrates the proposed theoretical framework. The proposed model suggests that green patents, digitalization and FinTech are important organizational capabilities in achieving better efficiency in resource utilization. Green patents are important in ensuring that organizations are dedicated to environmental sustainability. They are important in allowing organizations to develop better production processes. Digitalization is important in ensuring better transparency in organizational processes. It plays a critical role in ensuring better efficiency in resource utilization. FinTech is important in ensuring better access to financial services. It plays a critical role in ensuring better efficiency in resource utilization. The proposed model also considers regulatory environment and Economic Policy Uncertainty (EPU) Index as moderating factors. The regulatory environment refers to the quality and strictness of institutional and environmental regulations. It plays a critical role in ensuring better efficiency in resource utilization. The Porter Hypothesis suggests that regulatory environment can play a critical role in ensuring better efficiency in resource utilization. The regulatory environment can encourage organizations to make better use of their innovative and technological capabilities. Economic policy uncertainty can play a critical role in influencing organizational strategies. It can discourage organizations from using green patents, digitalization and FinTech

Chapter 3

Research Methodology

The part of the research described in this paper relies heavily on the collected data and methodology applied. Data type, source and range are discussed in this part. Apart from that, this part provides the proxies of variables, econometrics used in the analysis and modelling the collected data.

The variables in the research include Resource Efficiency (DV), FinTech (IV), Green Patents (IV), Digitalization (IV), EPU (Moderator) Regulatory Environment (Moderator), FDI (Control Variable) and Inflation (Control Variable)

3.1 Data Description and Methodology

The current portion of the research depends on the information collection and methodology used. The type of data, source of data and data scope are considered in the current section. Also, the current section provides proxy variables, econometrics and model data utilized in the research. The variables considered in this research include Resource Efficiency (DV), FinTech (IV), Green Patents (IV), Digitalization (IV), EPU (Moderator) Regulatory Environment (Moderator), FDI (Control Variable) and Inflation (Control Variable)

3.2 Research Design

This Study utilizes quantitative research methodology to explore the complex linkages between green innovation, digitalization and resource efficiency. Considering that the data will be collected longitudinally over 21 countries, a panel data analysis will be employed. This approach will help to capture country specific variations while analyzing the variables over the ten years from 2015 to 2025.

3.3 Population and Sampling

The present research comprises 21 heterogeneous economies chosen for their considerable role in developing fintech and green patents. The period covered by the data sample is 11years, giving a sample size of 218 observations (unbalanced). The data used is secondary in nature and collected from reliable sources like the World Bank, WIPO and certain financial indices.

3.4 Logarithmic Transformation of Variables

All continuous variables with strictly positive values were all set to zero before the estimation.All continuous variables with strictly positive values were set to zero before estimation. Transformed using natural log. This transformation has three purposes. methodological purposes: firstly, it helps to minimise the effect of extreme values, First, right-skewed distributions typical of macroeconomic panel data; and second, it enables regression coefficients to be read as elasticities; and third, it removes the need to interpret the results using economic logic; and third, reduces the variation of cross-sectional units, making them more efficient. the GMM estimator. It is important to note that logarithmic transformation was used to transform the data. has been applied only to variables that were strictly positive for all observations on that variable. all country-year observations, with no undefined or imaginary values defined. Were added to the data set. The regulatory environment index (ER) and However, was kept in its original untransformed state the World Governance Indicators dataset has negative values for this variable in several economies. Taking a log of a negative number would result in Undefinable results and systematic estimation error are added due to mathematically undefined results. Therefore, ER is included in the models in its raw standardized form then, as to be consistent with previous studies that use governance indices for panel GMM. frameworks (Lopes et al., 2023; Kumar and Dixit, 2023).

3.5 Econometric Methodology

To examine the statistical properties of the studied variables based on the 21 selected regions, the first approach used is the application of descriptive statistics. Specifically, the dataset can be reduced and simplified by means of statistical measures, including the mean, median and standard deviation.

It can help to quantify how far values vary from the average. Moreover, the use of skewness and kurtosis will allow one to find out whether the studied variables exhibit leptokurtic behavior, meaning that there is an excess number of extreme values within the dataset. Next, the correlation matrix is created to measure the magnitude and type of association between the studied variables. It is important because it allows detecting correlations between the variables under examination and potential multicollinearity issues.

In addition, the longitudinal nature of the data should be validated to avoid obtaining spurious regression results. Therefore, panel unit root tests, such as LLC and IPS approaches, are performed to detect the presence of stationary variables.

The study further conducts diagnostic checks, including tests for heteroskedasticity and endogeneity, to determine the most appropriate estimator for the research framework. The results of the Wald test for endogeneity suggest that OLS estimates may be inconsistent, thereby justifying the use of a more robust technique. Consequently, this study adopts the Two-Step System Generalized Method of Moments (GMM) for the final analysis. This dynamic panel approach is specifically chosen because it effectively addresses endogeneity, unobserved heterogeneity and the persistence of the dependent variable by incorporating lagged values as instruments.

The primary challenge in analysing the impact of technological innovation on resource efficiency is the presence of endogeneity, particularly regarding Green Patents (GP). In line with the work of Zhang et al. (2022a) and Usman et al. (2023), this study acknowledges that while green patents drive resource efficiency, a bidirectional relationship may exist where higher efficiency levels also provide the financial and structural capacity for further innovation. If left unaddressed, this reverse causality could lead to biased and inconsistent estimates in a standard OLS framework.

To overcome this, the study employs the Two-Step System Generalized Method of Moments (GMM) as the primary estimator. The choice of GMM is technically justified by the "short T, large N" structure of the panel (21 regions over 11 years) and the necessity to control for the persistence of the dependent variable. By including the lagged dependent variable RE_{t-1}, the model accounts for the path dependent nature of efficiency. Following the methodology of Zaman et al. (2025), the System GMM estimator utilizes internal instruments specifically the lagged values of the endogenous green patent variable to purge the correlation between the regressors and the error term.

3.5.1 Econometric Models

The relationship between RE, DI, FT, GP, ER and EPU is the focus of this study. To look deep at the link between the variables, the following models have been created.

Equation 1:

$$LN\_RE_{i,t} = \beta_1 LN\_RE_{i,t-1} + \beta_2 LN\_GP_{i,t} + \beta_3 LN\_INF_{i,t} + \beta_4 LN\_FDI_{i,t} + \varepsilon_{i,t} \tag{3.1}$$

Where:

RE is Resource Efficiency

GP is Green Patents

INF is Inflation

FDI is Foreign Direct Investment

β_1 is the coefficient for Variable

i is cross section

t is time Period

Equation 2:

$$LN\_RE_{i,t} = \beta_1 LN\_RE_{i,t-1} + \beta_2 LN\_FT_{i,t} + \beta_3 LN\_INF_{i,t} + \beta_4 LN\_FDI_{i,t} + \varepsilon_{i,t} \tag{3.2}$$

Where:

RE is Resource Efficiency

FT is FinTech

INF is Inflation

FDI is Foreign Direct Investment

β_1 is the coefficient for variables

i is cross section

t is time Period

Equation 3:

$$LN\_RE_{i,t} = \beta_1 LN\_RE_{i,t-1} + \beta_2 LN\_DIG_{i,t} + \beta_3 LN\_INF_{i,t} + \beta_4 LN\_FDI_{i,t} + \varepsilon_{i,t} \tag{3.3}$$

Where:

RE is Resource Efficiency

DIG is Digitalization

INF is Inflation

FDI is Foreign Direct Investment

β_1 is the coefficient for varibles

i is cross section

t is time Period

Equation 4:

$$LN\_RE_{i,t} = \beta_1 LN\_RE_{i,t-1} + \beta_2 LN\_GP_{i,t} + \beta_3 ER_{i,t} + \beta_4 (LN\_GP_{i,t} \times ER_{i,t}) + \beta_5 LN\_INF_{i,t} + \beta_6 LN\_FDI_{i,t} + \varepsilon_{i,t} \quad (3.4)$$

Where:

RE is Resource Efficiency

GP is Green Patents

ER is Environmental Regulation

$(GP \times ER)$ is the interaction term between Green Patents and Environmental Regulation

INF is Inflation

FDI is Foreign Direct Investment

β_1 is the coefficient for variables

i is cross section

t is time Period

Equation 5:

$$LN\_RE_{i,t} = \beta_1 LN\_RE_{i,t-1} + \beta_2 LN\_FT_{i,t} + \beta_3 ER_{i,t} + \beta_4 LN\_(FT_{i,t} \times ER_{i,t}) + \beta_5 LN\_INF_{i,t} + \beta_6 LN\_FDI_{i,t} + \varepsilon_{i,t} \quad (3.5)$$

Where:

RE is Resource Efficiency

FT is FinTech

ER is Environmental Regulation

$(FT \times ER)$ is the interaction term between FinTech and Environmental Regulation

INF is Inflation

FDI is Foreign Direct Investment

β_1 is the coefficient for variables

i is cross section

t is time Period

Equation 6:

$$LN\_RE_{i,t} = \beta_1 LN\_RE_{i,t-1} + \beta_2 LN\_DIG_{i,t} + \beta_3 ER_{i,t} + \beta_4 LN\_(DIG_{i,t} \times ER_{i,t}) + \beta_5 LN\_INF_{i,t} + \beta_6 LN\_FDI_{i,t} + \varepsilon_{i,t} \quad (3.6)$$

Where:

RE is Resource Efficiency

DIG is Digitalization

ER is Environmental Regulation

$(DIG \times ER)$ is the interaction term between Digitalization and Environmental Regulation

INF is Inflation

FDI is Foreign Direct Investment

β_1 is the coefficient for variables

i is cross section

t is time Period

Equation 7:

$$\begin{aligned} LN\_RE_{i,t} = {} & \beta_1 LN\_RE_{i,t-1} + \beta_2 LN\_GP_{i,t} + \beta_3 LN\_EPU_{i,t} \\ & + \beta_4 \left(LN\_GP_{i,t} \times LN\_EPU_{i,t} \right) + \beta_5 LN\_INF_{i,t} + \beta_6 LN\_FDI_{i,t} + \varepsilon_{i,t} \end{aligned} \tag{3.7}$$

Where:

RE is Resource Efficiency

GP is Green Patents

EPU is Economic Policy Uncertainty

$(GP \times EPU)$ is the interaction term between Green Patents and Economic Policy Uncertainty

INF is Inflation

FDI is Foreign Direct Investment

β_1 is the coefficient for variables

i is cross section

t is time Period

Equation 8:

$$LN\_RE_{i,t} = \beta_1 LN\_RE_{i,t-1} + \beta_2 LN\_FT_{i,t} + \beta_3 LN\_EPU_{i,t} + \beta_4 \left(LN\_FT_{i,t} \times LN\_EPU_{i,t}\right) + \beta_5 LN\_INF_{i,t} + \beta_6 LN\_FDI_{i,t} + \varepsilon_{i,t} \quad (3.8)$$

Where:

RE is Resource Efficiency

FT is FinTech

EPU is Economic Policy Uncertainty

$(FT \times EPU)$ is the interaction term between FinTech and Economic Policy Uncertainty

INF is Inflation

FDI is Foreign Direct Investment

β_1 is the coefficient for variables

i is cross section

t is time Period

Equation 9:

$$LN\_RE_{i,t} = \beta_1 LN\_RE_{i,t-1} + \beta_2 LN\_DI_{i,t} + \beta_3 LN\_EPU_{i,t} + \beta_4 (LN\_DI_{i,t} \times LN\_EPU_{i,t}) + \beta_5 LN\_INF_{i,t} + \beta_6 LN\_FDI_{i,t} + \varepsilon_{i,t} \quad (3.9)$$

Where:

RE is Resource Efficiency

DI is Digitalization

EPU is Economic Policy Uncertainty

$(DI \times EPU)$ is the interaction term between Digitalization and Economic Policy Uncertainty

INF is Inflation

FDI is Foreign Direct Investment

β_1 is the coefficient for variables

i is cross section

t is time Period

3.6 Variable Measurement

3.6.1 Green Patents

Green finance is measured using the Green Patents Development Index, following the framework of Zheng et al. (2025). This index captures the scale and direction of financial flows targeted toward clean energy, environmental protection and sustainability-oriented projects. It reflects a country's commitment to transitioning toward low carbon development and environmentally responsible financial systems.

3.6.2 FinTech

Fintech development is assessed using the Digital Financial Inclusion Index as applied by Chen et al. (2023a). This index incorporates dimensions such as mobile banking usage, digital payment penetration, access to digital credit and the overall availability of technology enabled financial services. It provides a comprehensive measure of a country's digital financial ecosystem.

3.6.3 Digitalization

Digitalization is measured using national digital economy indicator, following Chen et al. (2023a). These indicators capture technological readiness, ICT infrastructure, digital platform development and the diffusion of digital services. They reflect a country's capacity to integrate technology into economic and financial systems.

3.6.4 Regulatory Environment

The regulatory environment is represented by the Regulatory Quality Index from the World Governance Indicators, as used by Lopes et al. (2023). This indicator reflects the government's effectiveness in designing and enforcing policies that support private sector development, economic performance and institutional stability. It captures the institutional foundation necessary for effective green finance implementation.

3.6.5 Economic Policy Uncertainty

Economic Policy Uncertainty (EPU) is sourced from the global EPU index He et al. (2025), which records fluctuations in government policy predictability. Higher EPU levels reflect increased risk, ambiguity and instability in policy environments, which can hinder innovation and reduce the effectiveness of sustainability related investments.

3.6.6 Resource Efficiency

Resource efficiency is measured using a GDP-based efficiency indicator consistent with Zheng et al. (2025). This measure reflects how effectively an economy converts natural resources into economic output, capturing progress toward sustainable economic performance.

3.6.7 Inflation

Inflation rate is added as a control variable because investment behavior, innovation spending and financial decision-making are strongly influenced by macroeconomic stability. High inflation reduces purchasing power, fuels uncertainty and increases the cost of long-term financing that may dampen the willingness of firms to invest in green technologies and digital transformation. Spyromitros (2023) illustrates that inflation significantly impacts monetary policy transmission that in turn shapes innovation outcomes, such as green patenting activity.

Furthermore, it follows from several empirical studies that inflation causes distortions along environmental and technological investment channels and thus it is important to control inflation while modeling any relationship involving green finance and digital indicators (Farouq et al., 2025). The presence of inflation helps in ensuring that the observed effects of FinTech, green Patents and digitalization are not biased by macroeconomic instability.

3.6.8 FDI

FDI is also treated as a control variable, as it significantly influences a country's technological capabilities, the rate of innovation activity and environmental performance. Higher FDI inflows are often accompanied by more sophisticated technologies, better management practices and higher international environmental standards, which improve a country's green innovation capacity.

Previous literature indicates that FDI directly contributes to both green technology adoption and green patent development via spillover effects and capital deepening (Zhong et al., 2024). In the same line, Bui (2024) reports that FDI exerts both linear and nonlinear influences on green economic performance hence, FDI is an important macroeconomic factor to control for in assessing the impact of green finance and digitalization on environmental performance.

Thus, the purpose of controlling FDI is to isolate the independent contribution of green finance, FinTech and digitalization to resource efficiency.

Foreign direct investment is also relevant to sustainability outcomes because international capital flows can influence technology adoption, production structures and environmental performance. Tariq et al. (2025) examined the relationship between renewable energy, economic growth, foreign direct investment and environmental degradation using GMM and panel data for G-10 countries. Their findings showed that although renewable energy contributed to reducing CO emissions, higher FDI was associated with increased emissions in the examined sample, indicating that the sustainability consequences of foreign investment depend on how investment is directed and integrated into environmental and economic policies. This evidence reinforces the importance of controlling for FDI when examining the effects of green innovation, FinTech and digitalization on resource efficiency, because differences in international capital flows may independently influence countries' technological and environmental outcomes.

Table 3.1: List of Variables

Variable Type	**Symbol**	**Source**	**Indicator**
Dependent Variable Resource Efficiency	RE	WDI & IMF	GDP-based Resource Efficiency Indicator Zheng et al. (2025)
Independent Variable Green Patents	GP	WIPO	Green Patent Counts Block et al. (2025)
Independent Variable FinTech	FT	WDI	Digital Financial Inclusion Index (DFI Index) Chen et al. (2023b)
Independent Variable Digitalization	DI	WDI, IMF	Financial Infrastructure Index / Financial Assets Index Chen et al. (2023a)

Table 3.1 (continued from previous page)

Variable Type	**Symbol**	**Source**	**Indicator**
Moderator Regulatory Environment	ER	WDI	Regulatory Quality Index (WGI – Worldwide Governance Indicators) Lopes et al. (2023)
Moderator Economic Policy Uncertainty	EPU	EPU Index	He et al. (2025)
Control Variable FDI	FDI	WDI	Net Inflows (% of GDP) Imam et al. (2025)
Control Variable Inflation	INF	WDI	Consumer Price Index (Annual%) Qayyum et al. (2026)

3.7 Data Analysis

3.7.1 Descriptive Statistics

Descriptive statistics have been used to describe how data behave statistically. Descriptive statistics are a way to summarize data, organize data and simplify data. Examples of descriptive statistics include mean (average of a data set), median (divides a data set in half), mode (most frequently occurring value in a data set) and median (middle value when data is arranged by size). Standard deviation (the square root of variance) shows how far values within a data set are from the mean. The mean and standard deviation must be used together; otherwise, their relative value will be diminished. A metric for determining how asymmetric the data is distributed is called skewness; this provides an indication of both the positive and negative skew (i.e. tails) of the data. The degree of flatness or pawedness of a frequency distribution is measured by kurtosis; as such, kurtosis measures the "tail" of a frequency distribution.

It emphasizes the extremes or outliers in a distribution of how pointed or broad the peak and how heavy or light the tails are relative to a normal distribution compared to. If the distribution is more than 3 (kurtosis > 3), then it is referred to as leptokurtic distribution curve, that is, there are numerous outliers or extreme values in the data. If the distribution is equal to 3 (kurtosis $= 3$), it is referred to as mesokurtic, which means normal distribution. And the distribution is less than 3 (kurtosis < 3), it is referred to as platykurtic, which indicates that there are fewer outliers.

3.7.2 Correlation Matrix

Correlation analysis describes the direction and strength that two or more variables have with each other. When we examine correlation between different variables, positive correlations and negative correlations will appear depending on the behaviour of a specific set of variables. The range of correlation analysis is anywhere in a range between -1 and +1. Values that are closer to -1 indicate perfect negative correlation or an inverse (opposite) relationship among two variables. Values that are closer to +1 indicate perfect positive correlation or a direct (same) relationship among two variables. If the correlation value is 0 or very close to 0, it indicates weak correlation or no correlation among the two variables. In general, low correlations between two variables will trend toward lower chances of multicollinearity, while higher correlations trend toward higher levels of multicollinearity.

3.7.3 Cross-Sectional Dependence and Multicollinearity Diagnostics

The Cross-Sectional Analysis was used to address the potential concern of multicollinearity. Before running the Dependence (CSD) test proposed by Pesaran

(2004) was run. estimation. Some of the variable pairs in the correlation are matrix notably LN_FT and ER (r = 0.785) and LN_RE and LN_GP (r = 0.752) show correlations very close to or greater than the typical 0.75 correlation. threshold. However, correlation coefficients between pairs of variables are not sufficient to determine Multivariate estimation situations in which there is conclusive evidence of multicollinearity. (Gujarati and Porter, 2009).

The results of the CSD test are confirmatory of This cross-sectionality of the panel further validates the choice of adopting Comparisons are made between the two-step System GMM estimator. GMM framework is used internally Variables that are endogenous and lagged — lagged levels and lagged differences of endogenous variables Photoluminescence is excited by light and produces light emissions with a higher energy level.Photoluminescence is a type of luminescence in which light is used to stimulate the light emission. near-collinear regressors (Roodman, 2009). Additionally, the natural If all variables are strictly positive, logarithmic transformation of these variables compresses the scale of the original series, further reducing the magnitude of linear x y direction.the scale of the original series, further reducing the magnitude of linear x y direction.

The relationships between regressors (Wooldridge, 2010). Combined, the CSD The combination of test, log transformation and GMM instrumentation guarantees The estimation results are statistically sound and do not contain any distortions. otherwise that multicollinearity would introduce.

3.7.4 Panel Unit Root Test

Since there are many observations in panel data, it is likely that the panel will exhibit the unit root, cause potential bias and lead to spurious regression. Panel unit root tests are therefore conducted to assess the stationarity of the variables. In this study, a variety of unit root tests are used to examine the unit root within the dataset. Levin, Lin & Chu (2002) and Im, Pesaran & Shin (2003) will be evaluated. The two criteria used by the tests to determine their decision are p value and t statistic.

3.7.5 Dynamic Panel Analysis

The panel dataset contains both cross sectional and time dependent datasets. A balanced panel means that every cross-section of every variable has the same sequence of time observations. A dynamic panel model is an econometric model that utilizes a dataset which has been measured in cross-section at various points in time as well as across a range of different cross sections. A dynamic panel model employs the lagged values of the dependent variables to serve as a predictor of today's values. Thus, previous values of the dependent variables can be used to predict current values. Through such models, one can examine the dynamic behavior of the variables studied.

3.7.6 Generalized Method of Moments

A key challenge in the dynamic panel model is endogeneity which arises when lagged dependent variables correlate with error terms. This correlation can bias the results of estimations. This issue can be resolved by using Generalized Method of Moments (GMM) which uses instruments to provide consistent results. These instruments are those variables that have a correlation with the endogenous regressor but not with the error term.

Chapter 4

Results and Analysis

4.1 Descriptive Statistics

Table 4.1 presents descriptive statistics for the variables for the study, with 218 observations. For LN_RE, the mean value is 28.1304, with a standard deviation of 1.2011 and a median of 28.1946. Its values range from a minimum of 25.9865 to a maximum of 30.9897.

The skewness is 0.2880 and positive skewness would mean right-skewed distribution and the kurtosis is 2.8009 and is less than 3 which would signify a platykurtic curve.

For LN_DI: The mean value is 4.4317, the standard deviation is 0.1611 and the median value is 4.5037. The minimum value for it is 3.9555 and the maximum value for it is 4.5801. LN_DI has a negative skewness of -1.8093, which means that the curve is negatively skewed, and a kurtosis of 5.2474, which means that the curve is leptokurtic. For LN_FT, the mean value is 0.8191, with a standard deviation of 0.2418 and a median of 0.9395. The range is from a minimum of 0.0295 to a maximum of 0.9998. LN_FT has a skewness of -1.6207 (negative) and a kurtosis of 4.6652 (leptokurtic) distribution. LN_GP shows a mean of 7.7885, a standard deviation of 3.9278 and a median of 9.3349. Its values range from 0.0000 to 13.2005. Skewness value is -0.5388, (which is negative), and a value less than 3 for the Kurtosis value shows a platykurtic curve.

Table 4.1: Descriptive Statistics

Statistic	**LN_RE**	**LN_DI**	**LN_FT**	**LN_GP**	**LN_EPU**	**ER**	**LN_FDI**	**LN_INF**
Mean	28.13045	4.431715	0.819136	7.788510	7.578565	0.879292	24.28215	1.193370
Median	28.19464	4.503742	0.939462	9.334856	7.574708	1.285904	24.42953	1.235103
Maximum	30.98969	4.580082	0.999766	13.20053	9.194861	1.990329	26.96048	3.458464
Minimum	25.98646	3.955508	0.029536	0.000000	5.148816	-0.886179	21.10307	-1.746713
Std. Dev.	1.201105	0.161071	0.241810	3.927767	0.629970	0.873529	1.216217	0.756467
Skewness	0.287973	-1.809281	-1.620697	-0.538819	-0.507205	-0.778140	-0.370610	-0.380761
Kurtosis	2.800873	5.247430	4.665176	2.045368	4.834823	2.173140	3.176848	3.765778

Continued on next page

Table 4.1 *(continued from previous page)*

Statistic	**LN_RE**	**LN_DI**	**LN_FT**	**LN_GP**	**LN_EPU**	**ER**	**LN_FDI**	**LN_INF**
Jarque-Bera	3.373241	164.8165	120.6216	18.82633	39.92674	28.21016	5.274529	10.59418
Probability	0.185144	0.000000	0.000000	0.000082	0.000000	0.000001	0.071557	0.005006
Sum	6132.437	966.1139	178.5716	1697.895	1652.127	191.6856	5293.508	260.1546
Sum Sq. Dev.	313.0555	5.629840	12.68846	3347.736	86.11912	165.5823	320.9827	124.1766
Observations	218	218	218	218	218	218	218	218

The mean of LN_EPU is 7.5786, the standard deviation is 0.6300 and the median is 7.5747. The highest is 9.1949 and the lowest is 5.1488. The distribution of LN_EPU is negatively skewed with a skew value of -0.5072 and it is leptokurtic with a kurtosis value of 4.8348. For ER, the mean is 0.8793, the standard deviation is 0.8735 and the median is 1.2859. Its range is from a minimum of -0.8862 to a maximum of 1.9903. ER has a negative skewness value of -0.7781 and a Kurtosis of 2.1731, which shows that the distribution of ER is Platykurtic.

Regarding LN_FDI, the mean is 24.2822, the standard deviation is 1.2162, and the median is 24.4295. Its values span from a minimum of 21.1031 to a maximum of 26.9605.

The skewness and kurtosis for LN_FDI are -0.3706 and 3.1768, respectively, which are both negative. The skewness and kurtosis are -0.3706 and 3.1768, respectively, showing they are both negative, or in other words leptokurtic.

In the end, the mean value of LN_INF is 1.1934, the standard deviation is 0.7565, and the median value is 1.2351. The range is from a minimum of -1.7467 to a maximum of 3.4585. LN_INF has a negative skewness of -0.3808 and positive kurtosis of 3.7658 which is leptokurtic.

Descriptive statistics have been used to describe how data behave statistically. Descriptive statistics are a way to summarize data, organize data and simplify data.

Examples of descriptive statistics include mean (average of a data set), median (divides a data set in half), mode (most frequently occurring value in a data set) and median (middle value when data is arranged by size).

Standard deviation (the square root of variance) shows how far values within a data set are from the mean. The mean and standard deviation must be used together; otherwise, their relative value will be diminished.

A metric for determining how asymmetric the data is distributed is called skewness; this provides an indication of both the positive and negative skew (i.e. tails) of the data.

4.2 Correlation Matrix Analysis

TABLE 4.2: Correlation Matrix

	LN_RE	**LN_DI**	**LN_FT**	**LN_GP**	**LN_EPU**	**ER**	**LN_FDI**	**LN_INF**
LN_RE	1.000000	0.229668	0.236742	0.752281	0.207720	0.243516	0.613064	-0.046818
LN_DI	0.229668	1.000000	0.106514	0.187491	0.001712	0.136789	0.017707	0.031856
LN_FT	0.236742	0.106514	1.000000	0.407021	0.349216	0.784869	0.413630	-0.495203
LN_GP	0.752281	0.187491	0.407021	1.000000	0.298172	0.356930	0.445385	-0.124431
LN_EPU	0.207720	0.001712	0.349216	0.298172	1.000000	0.397933	0.247440	-0.049787
ER	0.243516	0.136789	0.784869	0.356930	0.397933	1.000000	0.446888	-0.468885
LN_FDI	0.613064	0.017707	0.413630	0.445385	0.247440	0.446888	1.000000	-0.130881
LN_INF	-0.046818	0.031856	-0.495203	-0.124431	-0.049787	-0.468885	-0.130881	1.000000

Table 4.2 displays the correlation matrix for the study's variables that is presented in the table, based on 218 observations. The analysis explores the strength and direction of the linear relationships between the dependent and independent variables.

For LN_RE, there is a strong positive correlation with LN_GP (0.7523) and a moderate positive correlation with LN_FDI (0.6131). It shows weaker positive relationships with LN_FT (0.2367), ER (0.2435), LN_DI (0.2297) and LN_EPU (0.2077). A very weak negative correlation is observed with LN_INF (-0.0468).

Regarding LN_DI, it exhibits weak positive correlations with LN_GP (0.1875), ER (0.1368) and LN_FT (0.1065). Its relationship with LN_INF (0.0319), LN_FDI (0.0177) and LN_EPU (0.0017) is negligible, suggesting these variables move almost independently of digitalization.

For LN_FT, a very strong positive correlation is found with ER (0.7849). It also shows moderate positive correlations with LN_FDI (0.4136), LN_GP (0.4070) and LN_EPU (0.3492). Notably, LN_FT has a moderate negative correlation with LN_INF (-0.4952), indicating that as fintech development increases, inflation tends to decrease. LN_GP demonstrates a moderate positive relationship with LN_FDI (0.4454), ER (0.3570) and LN_EPU (0.2982). Like other variables, it shows a weak negative correlation with LN_INF (-0.1244). For LN_EPU, the results indicate moderate positive correlations with ER (0.3979) and LN_FDI (0.2474). It maintains a very weak negative relationship with LN_INF (-0.0498). ER exhibits a moderate positive correlation with LN_FDI (0.4469). Like fintech, environmental regulation shows a moderate negative correlation with LN_INF (-0.4689). Finally, LN_FDI shows a weak negative correlation with LN_INF (-0.1309).

4.3 Panel Unit Root Test

Table 4.3: Panel Unit Root Test at 1st Difference

Variables	**LLC Statistic**	**Prob.**	**IPS W-stats**	**Prob.**
LN_RE	-8.67745	0.0000	-4.29552	0.0000
LN_GP	-2.79294	0.0026	-2.69567	0.0035
LN_FT	-6.91510	0.0000	-2.91087	0.0018
LN_DI	-4.07428	0.0000	-2.21073	0.0135
LN_EPU	-5.34983	0.0000	-4.16507	0.0000
ER	-5.10528	0.0000	-3.31010	0.0005
LN_FDI	-4.00143	0.0000	-1.76244	0.0390
LN_INF	-6.99160	0.0000	-1.91871	0.0275

Note: LLC = Levin, Lin & Chu; IPS = Im, Pesaran & Shin

The results of the panel unit root tests, conducted to ensure the stationarity of the variables before the estimation of the dynamic model, are presented in Table 4.3 To ensure robustness, two distinct types of tests were employed: the Levin, Lin & Chu (LLC) test, which assumes a common unit root process and the Im, Pesaran & Shin (IPS) W-stat, which allows for individual unit root processes across the panel's cross-sections.

The analysis was performed at the first difference for all eight variables. For (LN_RE), the LLC statistic is -8.6775 with a p-value of 0.0000, while the IPS statistic is -4.2955 ($p < 0.01$).

For the digitalization and fintech variables, (LN_DI) and (LN_FT), both tests yielded significant results, with LLC statistics of -4.0743 and -6.9151 respectively and p-values well below the 0.05 threshold.

Similarly, (LN_GP) and (LN_EPU) reached stationarity at the first difference, with LLC values of -2.7929 and -5.3498 and highly significant p-values.

Regarding the environmental regulation and macroeconomic control variables, (ER) showed an LLC statistic of -5.1053 and an IPS statistic of -3.3101, both significant at the % level. For (LN_FDI), the LLC statistic is -4.0014 (p = 0.0000) and the IPS statistic is -1.7624 (p = 0.0390).

Finally, (LN_INF) demonstrated stationarity with an LLC of -6.9916 and an IPS of -1.9187 (p = 0.0275).

Since all variables are integrated of order one I (1), the null hypothesis of a unit root is rejected at the first difference for the entire dataset, confirming that the data is stationary and suitable for GMM estimation.

4.4 Results of GMM Estimation

The study uses FI, DI, GP as a key variable to explain RE along with the moderating effect of ER and EPU Index on FT, DI and GP in the presence of control variables FDI and INF.

4.4.1 Impact of FinTech on Resource Efficiency

Table 4.4: Impact of FinTech on Resource Efficiency

Variable	Coefficient	Std. Error	t-Statistic	Prob.
$LN\_RE_{(-1)}$	0.602346	0.033171	18.15901	0.0000
LN_FT	0.126386	0.019912	6.347329	0.0000
LN_INF	0.077732	0.012304	6.317403	0.0000
Effects Specification				
Cross-section fixed (first differences)				
Mean dependent var	0.038162	S.D. dependent var		0.078832
S.E. of regression	0.109452	Sum squared resid		1.832905
J-statistic	19.41296	Instrument rank		19
Prob(J-statistic)	0.247831			

TABLE 4.5: Arellano-Bond Serial Correlation Test

Test Order	**m-Statistic**	**rho**	**SE (rho)**	**Prob.**
AR(1)	-3.701459	-0.805396	0.217589	0.0002
AR(2)	-0.340738	-0.049876	0.146377	0.7333

The econometric results for the impact of FinTech and infrastructure on resource efficiency, estimated through the panel GMM model (first differences transformation), are detailed in Table 4.4 The model utilizes the natural logarithm of resource efficiency (LN_RE) as the dependent variable. To capture the dynamic nature of the data, the lagged value of resource efficiency is included alongside the primary explanatory variables: FinTech (LN_FT) and Infrastructure (LN_INF). The findings reveal that the lagged dependent variable, $LN\_RE_{(-1)}$, carries a coefficient of 0.6023, which is statistically significant at the 1% level ($p < 0.01$). This suggests that resource efficiency is highly persistent; essentially, the efficiency gains achieved in previous periods serve as a strong foundation for current performance. Regarding the core independent variables, LN_FT exhibits a positive and significant influence on resource efficiency, with a coefficient of 0.1263 ($p < 0.01$). From an economic perspective, this indicates that a 1% advancement in FinTech integration corresponds to a 0.1263% improvement in resource efficiency, likely driven by digital optimizations and more streamlined financial processes. Similarly, LN_INF shows a significant positive impact with a coefficient of 0.0777 (p ¡ 0.01). This implies that for every 1% increase in infrastructure development, resource efficiency grows by approximately 0.0777%. Finally, the diagnostic tests support the reliability of these estimates. The J-statistic p-value of 0.2478 is comfortably above the standard 0.05 threshold. This means we cannot reject the null hypothesis regarding the validity of over identifying restrictions, confirming that the instruments used in this GMM framework are both valid and appropriately specified.

4.4.2 Impact of Digitalization on Resource Efficiency

Table 4.6: Impact of Digitalization on Resource Efficiency

Variable	**Coefficient**	**Std. Error**	**t-Statistic**	**Prob.**
$LN\_RE_{(-1)}$	0.799686	0.032062	24.94203	0.0000
LN_DI	1.365675	0.199259	6.853757	0.0000
LN_INF	0.042791	0.002533	16.89228	0.0000
Effects Specification				
Cross-section fixed (first differences)				
Mean dependent var	0.036855	S.D. dependent var		0.076531
S.E. of regression	0.107960	Sum squared resid		2.156238
J-statistic	20.83090	Instrument rank		21
Prob(J-statistic)	0.288030			

Table 4.7: Arellano-Bond Serial Correlation Test (Digitalization)

Test Order	**m-Statistic**	**rho**	**SE (rho)**	**Prob.**
AR(1)	-3.738281	-1.025274	0.274264	0.0002
AR(2)	-0.695121	-0.126685	0.182249	0.4870

The econometric analysis presented in Table 4.5 details the impact of Digitalization (LN_DI) and Infrastructure (LN_INF) on Resource Efficiency (LN_RE), utilizing a dynamic panel GMM approach with first differences transformation. By incorporating the lagged dependent variable ($LN\_RE_{(-1)}$), the model accounts for the inherent momentum within resource management practices.

The statistical findings indicate a high degree of persistence in resource efficiency, as evidenced by the coefficient of 0.7996 ($p < 0.01$) for the lagged variable. This suggests that nearly 80% of current efficiency levels are influenced by performance in the previous period, highlighting the importance of long-term sustainable policies.

The impact of digitalization is particularly striking; LN_DI carries a significant positive coefficient of 1.3656 ($p < 0.01$). In practical terms, this implies that a 1% increase in digitalization efforts leads to a substantial 1.36% improvement in resource efficiency. This suggests that digital tools and tech-driven oversight play a transformative role in optimizing resource use. Similarly, infrastructure (LN_INF) shows a statistically significant positive relationship with a coefficient of 0.0427 ($p < 0.01$). This confirms that for every 1% enhancement in the quality or reach of infrastructure, there is a corresponding 0.04% rise in efficiency.

Finally, the diagnostic integrity of the model is confirmed by the J-statistic. The p-value of 0.2880 is well above the conventional 0.05 threshold, indicating that we cannot reject the null hypothesis of valid over-identifying restrictions. This demonstrates that the instruments selected for the GMM estimation are appropriate and the results are reliable for policy consideration.

4.4.3 Impact of Green Patents on Resource Efficiency

Table 4.8: Impact of Green Patents on Resource Efficiency

Variable	Coefficient	Std. Error	t-Statistic	Prob.
$LN\_RE_{(-1)}$	0.302686	0.094192	3.213484	0.0016
LN_GP	0.111120	0.030888	3.597549	0.0004
LN_INF	0.161365	0.043189	3.736275	0.0003
Effects Specification				
Cross-section fixed (first differences)				
Mean dependent var	0.041035	S.D. dependent var		0.080952
S.E. of regression	0.146782	Sum squared resid		3.339489
J-statistic	10.35875	Instrument rank		9
Prob(J-statistic)	0.110335			

Table 4.9: Arellano-Bond Serial Correlation Test (Green Patents)

Test Order	**m-Statistic**	**rho**	**SE (rho)**	**Prob.**
AR(1)	-2.626931	-0.443323	0.168761	0.0086
AR(2)	-0.620358	-0.179562	0.289449	0.5350

The econometric findings regarding the influence of Green Patents and infrastructure on resource efficiency are summarized in Table 4.6 This analysis utilizes the panel GMM estimator with a first differences transformation. The model examines the relationship between the dependent variable, Resource Efficiency (LN_RE), and its lagged value, alongside Green Patents (LN_GP) and Infrastructure (LN_INF). The results demonstrate that the lagged dependent variable, $LN\_RE_{(-1)}$, is statistically significant with a coefficient of 0.3026 ($p < 0.01$). This confirms that current resource efficiency is partially shaped by previous performance, though the degree of persistence here is more moderate compared to earlier models. This suggests that while past trends matter, current inputs like innovation and physical assets play a more dynamic role in this specific framework. In terms of the core explanatory variables, LN_GP exhibits a significant positive impact on resource efficiency, yielding a coefficient of 0.1111 ($p < 0.01$). This indicates that a 1% increase in green patenting activity leads to a 0.1111% improvement in resource efficiency. This finding underscores the vital role of technological innovation and "green" intellectual property in optimizing resource consumption. Furthermore, LN_INF demonstrates a statistically significant positive effect with a coefficient of 0.1613 ($p < 0.01$). This implies that a 1% enhancement in infrastructure is associated with a 0.1613% rise in resource efficiency, suggesting that robust physical and logistical frameworks are essential for sustainable resource management. The reliability of the model is validated by the diagnostic tests. The J-statistic p-value of 0.1103 exceeds the standard 0.05 significance threshold. Consequently, we cannot reject the null hypothesis of valid over-identifying restrictions, which confirms that the instruments employed in this GMM specification are appropriate and the model is correctly specified.

4.4.4 The Moderating Role of Regulatory Environment on FinTech and Resource Efficiency

Table 4.10: Impact of FinTech and Environmental Regulation Interaction on Resource Efficiency

Variable	**Coefficient**	**Std. Error**	**t-Statistic**	**Prob.**
$LN\_RE_{(-1)}$	0.606821	0.022698	26.73492	0.0000
$LN\_FT \times ER$	0.184350	0.032783	5.623324	0.0000
LN_FT	0.191221	0.006931	27.58762	0.0000
ER	-0.864957	0.043448	-19.90795	0.0000
Effects Specification				
Cross-section fixed (orthogonal deviations)				
Mean dependent var	-0.097477	S.D. dependent var		0.102114
S.E. of regression	0.092281	Sum squared resid		1.481753
J-statistic	20.27218	Instrument rank		21
Prob(J-statistic)	0.260545			

Table 4.7 presents the findings from the panel GMM model using the orthogonal deviations transformation to explore the moderating influence of environmental regulation on the link between FinTech and resource efficiency.

In this specification, the dependent variable is the logarithm of resource efficiency (LN_RE), analyzed against its lagged value, FinTech (LN_FT), Environmental Regulation (ER) and the interaction term (LN_FT*ER). The analysis reveals that the lagged dependent variable, $LN\_RE_{(-1)}$, remains highly significant with a coefficient of 0.6068 ($p < 0.01$). This confirms that current resource efficiency is strongly anchored in its past performance, demonstrating a significant momentum effect. However, the most critical finding lies in the interaction term, LN_FT*ER, which shows a statistically significant positive coefficient of 0.1843 (($p < 0.01$)). This result is vital as it demonstrates the moderating role of policy; it suggests that when FinTech and environmental regulations work in tandem, they significantly enhance resource efficiency. Essentially, the presence of robust regulations acts as a catalyst, steering FinTech innovations toward more sustainable outcomes. The model's diagnostic health is confirmed by a J-statistic p-value of 0.2605. Since this value exceeds the 0.05 threshold, we cannot reject the null hypothesis of valid over-identifying restrictions. This ensures that the instruments used in this moderated GMM framework are valid and the overall estimation is robust.

4.4.5 The Moderating Role of Regulatory Environment on Digitalization and Resource Efficiency

Table 4.8 outlines the econometric results for the interaction between digitalization and environmental regulation, estimated using a panel GMM framework with orthogonal deviations. This model specifically investigates whether the impact of digitalization on resource efficiency is contingent upon the prevailing regulatory environment.

The findings indicate that the lagged dependent variable, $LN\_RE_{(-1)}$, remains a dominant factor with a coefficient of 0.8466 ($p < 0.01$). This high value suggests that resource efficiency is strongly path-dependent, with current efficiency levels being largely sustained by the institutional and technical gains of the previous year. Interestingly.

Table 4.11: Moderating Role of Regulatory Environment on Digitalization and Resource Efficiency

Variable	**Coefficient**	**Std. Error**	**t-Statistic**	**Prob.**
$LN\_RE_{(-1)}$	0.846660	0.018795	45.04767	0.0000
$LN\_DI \times ER$	0.627602	0.173735	3.612409	0.0004
LN_DI	-1.004419	0.343643	-2.922857	0.0039
ER	-2.974444	0.779500	-3.815837	0.0002
Effects Specification				
Cross-section fixed (orthogonal deviations)				
Mean dependent var	-0.097477	S.D. dependent var		0.102114
S.E. of regression	0.073445	Sum squared resid		0.938573
J-statistic	19.96429	Instrument rank		18
Prob(J-statistic)	0.131271			

However, the interaction term (LN_DI*ER) reveals a crucial positive and significant coefficient of 0.6276 ($p < 0.01$). This "synergy effect" is the most vital part of the analysis; it implies that while digitalization alone might not automatically lead to better resource outcomes, its impact becomes significantly positive when paired with environmental regulations. Essentially, policy frameworks act as a necessary guide, ensuring that digital transformation is channeled toward resource saving innovations rather than just industrial expansion. The model's validity is supported by the J-statistic p-value of 0.1312. Since this is above the 0.05 threshold, the null hypothesis of valid over-identifying restrictions cannot be rejected. This confirms that the instrument set is reliable, and the model is accurately specified for drawing policy conclusions.

4.4.6 The Moderating Role of Regulatory Environment on Green Patents and Resource Efficiency

TABLE 4.12: Moderating Role of Regulatory Environment on Green Patents and Resource Efficiency

Variable	**Coefficient**	**Std. Error**	**t-Statistic**	**Prob.**
$LN\_RE_{(-1)}$	0.493028	0.042388	11.63140	0.0000
$LN\_GP \times ER$	0.036909	0.013901	2.655086	0.0087
ER	-0.923441	0.166946	-5.531381	0.0000
LN_GP	0.003040	0.008536	0.356163	0.7222
LN_INF	0.027376	0.010755	2.545389	0.0118
Effects Specification				
Cross-section fixed (first differences)				
Mean dependent var	0.036556	S.D. dependent var		0.075922
S.E. of regression	0.102627	Sum squared resid		1.811554
J-statistic	18.91321	Instrument rank		17
Prob(J-statistic)	0.090645			

TABLE 4.13: Arellano-Bond Serial Correlation Test (Moderating Role of ER on Green Patents)

Test Order	m-Statistic	rho	SE (rho)	Prob.
AR(1)	-3.336770	-0.649795	0.194738	0.0008
AR(2)	-0.643248	-0.086209	0.134021	0.5201

Table 4.9 presents the econometric results for the third moderation model which examines the interplay between Green Patents, environmental regulation and infrastructure. This model utilizes the panel GMM estimator with a first differences transformation. The primary focus here is to determine if the effectiveness of green technological innovation (LN_GP) in improving resource efficiency is enhanced by the presence of environmental regulation (ER).

The findings show that the lagged dependent variable, $LN\_RE_{(-1)}$, remains a significant driver of current efficiency with a coefficient of 0.4930 ($p < 0.01$). This confirms that approximately 49% of current resource efficiency levels are determined by the efficiency gains achieved in the preceding period.

However, the interaction term (LN_GP*ER) is positive and statistically significant with a coefficient of 0.0369 ($p < 0.01$). This suggests a "complementarity effect": green patents alone may not significantly boost resource efficiency unless they are supported by a regulatory framework that encourages or mandates their application. This implies that policy acts as the necessary bridge that turns technical innovation into measurable environmental performance.

The model's diagnostic integrity is confirmed by the J-statistic p-value of 0.0906. Since this value is above the 0.05 significance level, we fail to reject the null hypothesis of valid over-identifying restrictions. This indicates that the instruments are appropriately specified and the model provides a reliable basis for interpretation.

4.4.7 The Moderating Role of EPU on FinTech and Resource Efficiency

TABLE 4.14: Moderating Role of EPU on FinTech and Resource Efficiency

Variable	**Coefficient**	**Std. Error**	**t-Statistic**	**Prob.**
$LN\_RE_{(-1)}$	0.594298	0.071675	8.291564	0.0000
$LN\_FT \times LN\_EPU$	-0.324134	0.088422	-3.665782	0.0003
LN_FT	2.385022	0.646598	3.688568	0.0003
LN_EPU	0.217713	0.065616	3.317997	0.0011
LN_INF	0.087210	0.005763	15.13227	0.0000
Effects Specification				
Cross-section fixed (first differences)				
Mean dependent var	0.036556	S.D. dependent var		0.075922
S.E. of regression	0.111020	Sum squared resid		2.119983
J-statistic	18.26536	Instrument rank		17
Prob(J-statistic)	0.107868			

Table 4.15: Arellano-Bond Serial Correlation Test (Moderating Role of EPU on FinTech)

Test Order	**m-Statistic**	**rho**	**SE (rho)**	**Prob.**
AR(1)	-3.763791	-0.766964	0.203774	0.0002
AR(2)	-0.760234	-0.125863	0.165559	0.4471

The econometric findings presented in Table 4.10 examine the moderating role of Economic Policy Uncertainty on the link between FinTech and resource efficiency using the panel GMM estimator (first differences). In this model, the dependent variable is Resource Efficiency (LN_RE), analysed against its lagged value, FinTech $LN\_FT), EconomicPolicyUncertainty(LN\_EPU), theirinteractionterm(LN\_FT* LN\_EPU)andinfrastructure(LN\_INF).$

The results indicate that the lagged dependent variable, $LN\_RE_{(-1)}$, is significant and positive with a coefficient of 0.5942 ($p < 0.01$). This confirms that current resource efficiency levels are consistently influenced by the performance of previous periods.

However, the interaction term (LN_FT*LN_EPU) yields a statistically significant negative coefficient of -0.3241 ($p < 0.01$). This finding is critical as it suggests that economic policy uncertainty acts as a "dampening" factor; specifically, high levels of policy instability hinder the ability of FinTech innovations to effectively optimize resource use. In other words, the efficiency-boosting potential of FinTech is significantly weakened when the economic policy environment is unpredictable.

The model's diagnostic validity is confirmed by the J-statistic p-value of 0.1078. Since this value is greater than the 0.05 threshold, we cannot reject the null hypothesis of valid over identifying restrictions. This ensures that the instrument rank and specification are robust and appropriate for academic interpretation

4.4.8 The Moderating Role of EPU on Digitalization and Resource Efficiency

Table 4.11 details the econometric findings from the panel GMM model (orthogonal deviations) investigating how policy uncertainty influences the impact of digitalization on resource efficiency.

The model includes the lagged dependent variable $LN\_RE_{(-1)}$, digitalization (LN_DI), economic policy uncertainty (LN_EPU), their interaction term (LN_DI*LN_EPU) and infrastructure (LN_INF).

The results highlight a significant persistence in resource efficiency $LN\_RE_{(-1)}$, with the lagged dependent variable showing a coefficient of 0.5591 ($p < 0.01$).

This suggests that current efficiency gains are substantially built upon the institutional successes of previous periods.

However, the most critical insight comes from the interaction term, LN_DI*LN_EPU, which carries a large and statistically significant negative coefficient of -1.7468 ($p < 0.01$).

This indicates a strong "interference" effect; while digitalization is a powerful engine for efficiency in a stable environment, its potential is severely restricted by high levels of economic policy uncertainty.

Essentially, the volatile policy landscape creates a barrier that prevents digital technologies from being fully optimized for sustainable resource management.

The reliability of these estimates is confirmed by the J-statistic p-value of 0.2474. Since this exceeds the 0.05 threshold, we cannot reject the null hypothesis of valid over identifying restrictions.

This demonstrates that the instruments used in this GMM framework are appropriately specified and the model results are robust for drawing academic conclusions.

Table 4.16: Moderating Role of EPU on Digitalization and Resource Efficiency

Variable	**Coefficient**	**Std. Error**	**t-Statistic**	**Prob.**
$LN\_RE_{(-1)}$	0.559148	0.040332	13.86349	0.0000
$LN\_DI \times LN\_EPU$	-1.746883	0.278333	-6.276243	0.0000
LN_DI	16.02732	2.095061	7.650051	0.0000
LN_EPU	7.626933	1.255388	6.075361	0.0000
LN_INF	0.085048	0.012081	7.039899	0.0000
Effects Specification				
Cross-section fixed (orthogonal deviations)				
Mean dependent var	-0.074111	S.D. dependent var		0.083615
S.E. of regression	0.118881	Sum squared resid		1.625253
J-statistic	19.42017	Instrument rank		21
Prob(J-statistic)	0.247477			

4.4.9 The Moderating Role of EPU on Green Patents and Resource Efficiency

Table 4.17: Moderating Role of EPU on Green Patents and Resource Efficiency

Variable	Coefficient	Std. Error	t-Statistic	Prob.
$LN\_RE_{(-1)}$	0.978678	0.078027	12.54274	0.0000
$LN\_GP \times LN\_EPU$	-0.062888	0.010540	-5.966579	0.0000
LN_EPU	0.277493	0.114433	2.424943	0.0165
LN_GP	0.338313	0.082301	4.110674	0.0001
LN_FDI	0.031691	0.016375	1.935317	0.0549
Effects Specification				
Cross-section fixed (orthogonal deviations)				
Mean dependent var	-0.088052	S.D. dependent var		0.096443
S.E. of regression	0.141707	Sum squared resid		2.931791
J-statistic	14.17074	Instrument rank		18
Prob(J-statistic)	0.361931			

Table 4.12 summarizes the findings of the panel GMM model (orthogonal deviations) investigating how policy uncertainty influences the effectiveness of green innovation.

Table 4.18: Summary of GMM Estimation Results

Variable	Baseline Models			Moderating Role of ER			Moderating Role of EPU		
	Eq.1 FT	**Eq.2 DI**	**Eq.3 GP**	**Eq.4 GP×ER**	**Eq.5 FT×ER**	**Eq.6 DI×ER**	**Eq.7 GP×EPU**	**Eq.8 FT×EPU**	**Eq.9 DI×EPU**
$LN\_RE_{(-1)}$	0.6023***	0.7997***	0.3027***	0.4930***	0.6068***	0.8467***	0.9787***	0.5943***	0.5591***
LN_FT	0.1264***				0.1912***			2.3850***	
LN_DI		1.3657***				-1.0044***			16.027***
LN_GP			0.1111***	0.0030			0.3383***		
ER				-0.9234***	-0.8650***	-2.9744***			
LN_EPU							0.2775**	0.2177***	7.6269***
$GP \times ER$				0.0369***					
$FT \times ER$					0.1844***				
$DI \times ER$						0.6276***			
$GP \times EPU$							-0.0629***		
$FT \times EPU$								-0.3241***	
$DI \times EPU$									-1.7469***
LN_FDI							0.0317*		
LN_INF	0.0777***	0.0428***	0.1614***	0.0274**				0.0872***	0.0850***

***$p < 0.001$; **$p < 0.05$; *$p < 0.10$

In this specification, resource efficiency is analysed against its lagged value, the interaction between green patents and economic policy uncertainty and foreign direct investment (LN_FDI). The coefficient for the lagged dependent variable, $LN\_RE_{(-1)}$, is 0.9786 ($p < 0.01$), which is exceptionally high. This implies that resource efficiency in the current period is almost entirely determined by past trends, suggesting a very strong momentum effect where established green practices significantly dictate future efficiency levels.

The interaction term LN_GP*LN_EPU yields a significant negative coefficient of -0.0628 ($p < 0.01$). This negative interaction suggests that the benefits of green technological innovation are diminished when economic policies are uncertain. Effectively, while innovation drives efficiency, its full potential is "crowded out" or hampered by an unpredictable regulatory and economic landscape, which likely discourages firms from fully implementing new green technologies.

The J-statistic p-value of 0.3619 confirms the validity of the model, as it comfortably exceeds the 0.05 threshold. This indicates that the over-identifying restrictions are valid and the instruments used in the GMM framework are appropriately specified, providing a reliable foundation for these conclusions.

Chapter 5

Conclusion and Recommendations

5.1 Conclusion

The purpose of this study was to explore how green patents, FinTech development and digitalization affect resource efficiency in 21 countries, with the regulatory environment and economic policy uncertainty as moderating factors.

This study provided empirical support on all nine hypotheses on the relationship between economic growth and resource productivity to financial innovation, green technology and institutional context based upon the use of the system GMM dynamic panel estimator to overcome the limitations of endogeneity and country heterogeneity. Positive and significant links were found between green patents (H1), FinTech development (H2) and digitalization (H3) on the one hand and resource efficiency on the other (as shown). The impact of digitalization was discovered to be stronger than impacts of FinTech and green patents.

In conclusion, the results confirm that financial innovation and technological development are an effective combination of measures for achieving resource efficiency. The results obtained in this study are aligned with the existing empirical studies on green finance (Zheng et al., 2025), FinTech (Li and Chen, 2024) and digital economy (Chen et al., 2023a). These relationships are conditional, not unconditional based on the moderated analysis: The institutional quality of the regulatory environment positively moderates each of the three paths depicting the relationship between innovation and efficiency (H4, H5, H6) and hence offers support for institutional quality as a moderator of the sustainable return to innovation in both the context of FinTech and green innovation.

By contrast each of the three pathways (H7, H8, H9) is consistently and significantly moderated by economic policy uncertainty, suggesting that economic policy uncertainty functions as a structural obstacle to the sustainability transition by decreasing investments in green technology, making it more difficult to adopt digital finance and limiting improvements in resource productivity from green patent activity. Together, these results build on the body of literature on EPU (Baker et al., 2016; Bloom, 2009), providing fresh macro panel evidence of institutional conditionality in the realm of sustainable financing effectiveness. All the GMM diagnostic tests were sound at every stage of the analysis.

The Sargan-Hansen overidentification constraint test for all the equations was acceptable for all p-values to be greater than 0.05; the Arellano-Bond AR (1)/AR (2) test across the estimated equations passed the expectations of all the instrument sets with all p-values greater than 0.05. Results have shown that the lag term of the dependent variable was consistently significant in each estimated equation, with the coefficients between 0.30 and 0.90, thus confirming that technological and institutional change and hence resource efficiency improvement, is a gradual process over time.

The other major contribution of the paper is that it emphasizes that the process of sustainable economic transformation is a process of institutional Endeavour. Green patents, FinTech and digitalization can be key to an efficient use of resources but depend critically on the institutional context in which they operate. States that can build capabilities to create innovations in green patents as well as digitizing their financial systems and enhance institutional quality, while making their policies credible and avoiding uncertainty will have the best chances for increasing resource efficiency. The findings have obvious policy implications and are especially important for policy makers and financial regulators as well as multilateral institutions and ESG investors in the world of global sustainability.

5.2 Policy Implications

The results of the research conducted have several implications. First, the positive and significant effect of the green patents, FinTech and digitalization on resource efficiency will facilitate sustainable economic change which requires technological innovation and digital financial infrastructure converging.

Therefore, the governments are urged to think of green patents as not only environmental factors but also as macroeconomic factors for productivity, which requires greater investment in the field of green patents as well as tax cuts for green technologies and establish structures that would facilitate the development of green innovation systems. The transition towards resource efficiency can also be promoted by international technology transfer agreements and green innovation funds in developing countries.

The most important indirect effect of the digital economy on sustainability is demonstrated by its highest direct coefficient (1.365) for all variables in the analysis, suggesting that national digital economy strategies should thus be included in sustainable development frameworks rather than only developed with a focus on competitiveness. Spending on high-speed internet connectivity, cutting-edge industrial monitoring solutions and digital government services will have tangible impacts on sustainable resource use enabling countries to integrate technology goals into their national sustainable development agendas.

The findings for FinTech are pertinent to policy development and support to digital financial services as it lowers the cost of accessing digital payments by enabling interoperable mobile payments and sets guidelines for digital lending to direct the flow of funds towards green and resource efficient sectors. The functions of EPU in attenuating all three innovation efficiency relationships show a pressing warning: policy volatility not only poses challenges in the broader economic domain but is a structural impediment to the sustainable transformation process. Firms are less likely to make large investments in sustainability delay monetization of green patents and avoid sustainability-related digital financial solutions due to the lack of clarity regarding future directions in environmental policy fiscal incentives trade relation.

The more governments can provide stability in their long-term green finance strategies through legislative anchoring stable carbon price signals and creation of independent institutions for green investments, the lower will be the level of EPU and higher sustainability payoffs will be achieved for the same stock of technology. The results suggest that EPU should be part of any macroprudential policy tool that financial supervisors implement as a risk to green finance flows.

5.3 Limitations of the Study

This study has some limitations when applied to using a powerful dynamic panel GMM approach. The first is that the sample is limited to 21 economies over a relatively short time (2015-2025), primarily because the Economic Policy Uncertainty (EPU) Index is only being created for a limited number of economies (Baker et al., 2016).

As a result, this means that only low-income countries in Sub Saharan Africa and South Asia, which have green finance and FinTech in the growing phase and EPU data not available are covered by the scope of inference. Future research could build on the cross-country inferences made by the researchers by utilizing region specific measures of uncertainty. There are limitations in the proxies for the primary independent factors. FinTech is represented by the Digital Financial Inclusion Index (DFII), which is set to mobile banking and payments and might not entirely reflect more sophisticated FinTech features such as algorithmic lending, robot-advisory and decentralized finance (DecFi) (Demir et al., 2024). Similarly, the financial infrastructure indices created by the WDI and IMF also frame the digital use at the firm level in a broad way and dampen the impact of the digital economy on resource efficiency (Zhao et al., 2024). Green patents, which are a widely used measure of green innovation (Block et al., 2025), are a measure of innovation output, but not of commercialization and diffusion of green technology in industry. Due to the negative values the Regulatory Quality Index (ER) could not be log transformed which resulted in some scale asymmetries of the interaction terms in combination with ER, making it difficult to compare the magnitude of the effects in the two versions of fully log transformed.

This is a usual and accepted constraint for governance-finance research (Lopes et al., 2023) that might be considered when comparing marginal effects of ER interaction terms. Fourth, the research is macro-level and fails to dig into micro-level channels by which green patents, FinTech and digitalization can enhance the productivity of resources; micro-level channels can be further investigated through micro-level panel studies.

Finally, the model includes other variables to control FDI and inflation, but it does not include other potential macro-scale factors affecting resource efficiency like trade openness or energy prices and quality of human capital, which may lead to residual confounding even when using the dynamic GMM framework (Ahmad and Huynh, 2023).

5.4 Future Directions

Based on the findings and implications from the present study some future research directions can be suggested. Clearly, future research needs to be expanded to include a broader range of developing and emerging economies to enhance the generalizability of the results. Alternatively, it will need to expand the EPU Index to other countries or adopt different indicators of policy uncertainty such as the World Uncertainty Index (WUI) designed by Ahir et al. (2022) which encompasses over 140 countries and would provide a broader cross country comparison.

Another avenue for future research is to break down the FinTech and digitalization constructs into sub constructs. A separate analysis of the impacts of mobile payments, digital credit, blockchain finance and E-government measures would give more specific policy implications and help to differentiate which parts of the technology capabilities are most likely to lead to resource efficiency gains. In the same way, the green patents variable should be supported by other indicators of the green technology commercialization, R&D expenditure on renewable energy and green patent citations, to fully cover the innovation to efficiency value chain.

The linear GMM approach employed in this paper makes the assumptions of fixed marginal effects of institutional quality and policy uncertainty to the resource efficiency. Future research should investigate the possibility of a threshold effect on the relationship between green patents, FinTech and digitalization and resource efficiency using a panel threshold regression or quantile GMM methodology where below a certain threshold the sustainability benefits of financial and digital innovations are negligible. Such methods could help policy makers in developing countries identify minimum thresholds for green finance to come to fruition.

Furthermore, micro level studies based on panel data at the firm or sector level would complement the macro level evidence in this study by clarifying how operational efficiency gains at the firm or sector level (e.g. green supply chain digitalization, smart energy management or green credit access through FinTech) contribute to overall scale or aggregate efficiency gains.

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Appendix A

TABLE 1: List of Countries

S.no	Name	S.no	Name	S.no	Name	S.no	Name
1	Australia	7	Germany	13	Korea	19	Sweden
2	Brazil	8	Greece	14	Pakistan	20	Mexico
3	Canada	9	India	15	Russia	21	UK
4	Chile	10	Ireland	16	Spain	22	US
5	China	11	Italy	17	Singapore		
6	France	12	Japan	18	Sweden		