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Balancing Growth and Sustainability: Can Green Innovation Curb the Ecological Impact of Resource-Rich Economies?

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Abstract: The global economy faces a critical challenge: balancing economic survival through natural resource utilization with the imperative of long-term environmental sustainability. Green innovation presents a viable solution, yet its effectiveness hinges on establishing well-structured legislative frameworks. This study, covering the period 1996 to 2022, examines the moderating effect of green innovation on the relationship between natural resource rents and ecological footprint while also considering the roles of globalization, financial development, and energy transition in the ten most resource-abundant countries. Utilizing the augmented mean group (AMG) estimator, the findings indicate that natural resource rents significantly contribute to ecological footprint, reinforcing concerns about resource-driven environmental degradation. However, green innovation mitigates these adverse effects, promoting sustainable resource management in alignment with SDG 12 (Responsible Consumption and Production). Additionally, renewable energy and globalization positively influence environmental conditions, reinforcing the drive toward clean and affordable energy (SDG7), while economic growth, financial development, and non-renewable energy exacerbate environmental harm. Furthermore, foreign direct investment (FDI) increases ecological footprint, reinforcing the Pollution Haven Hypothesis for resource-rich economies. Rigorous robustness checks using CCEMG, FMOLS, and DOLS methodologies, along with country-specific analyses, affirm the empirical validity of these results. In light of these conclusions, the paper advocates for legislative reforms to enhance sustainability and optimize resource utilization, ensuring a balanced approach to economic development and environmental preservation.

Keywords: environmental footprint; natural resources; green innovation; energy transition; financial development; globalization; energy consumption

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1. Introduction

The global economy is currently experiencing a challenging period marked by issues ranging from escalating greenhouse gas (GHG) emissions to deteriorating human health conditions, shortened life expectancy, declining labor productivity, low economic growth, and pervasive food insecurity [1]. The increasing effects of climate change pose a considerable challenge across all areas, underscoring the urgent need for a sustainable way of living, particularly in addressing the depletion of natural resources. The need to be more cautious and ensure sustainable natural resource consumption hinges on the fundamental roles these resources play in the socioeconomic life of every nation. The criticality of natural resources to the survival of humanity and the ecosystem cannot be overstated for at least three reasons. First, the well-being of individuals is intricately linked to the availability of natural resources. For instance, the existence of every human depends significantly on the presence of clean air, nourishing vegetables, and safe drinking water. Moreover, natural resources play a vital role in providing human beings with shelter and warmth, enabling them to thrive and flourish [2]. Second, empirical evidence suggests that a country possessing abundant natural resources will experience a significantly faster pace of development compared to a nation with limited or no access to such resources [3]. This is premised on the ground that there exists a positive correlation between economic development and the availability of natural resources. Third, some governments of certain nations, especially developing economies, depend on the stream of income accruable from natural resources, often called rents [4,5].

Notwithstanding the apparent benefits derivable from natural resources, it is no gainsaying that every depletion comes with costs both forthe ecosystem and the peaceful coexistence of the human race. Alluding to this fact, the Stockholm Declaration of 1972, under the auspice of the United Nations, had its second principle focusing on the imperativeness of safeguarding the earth's precious natural resources as a precondition to securing the well-being of present and future generations [6]. It mentioned, in specific terms, the inevitability of preserving air, water, land, flora, wildlife, and exemplary natural ecosystems through meticulous planning and management whenever required. Recently, the United Nations Conference of the Parties' 26th, 27th, and 28th editions all stressed the importance of prioritizing natural resources management in the drive toward accomplishing the carbon neutrality targets [7,8]. Consequently, achieving the key objectives of sustainable development relies, to a large extent, on the sustainable depletion of natural resources. Efficient management of resources in sectors such as mining, forestry, fishing, quarrying, and agriculture is essential for minimizing environmental harm, safeguarding biodiversity, and addressing climate change. This can be achieved by ensuring the sustainability and conservation of natural resources. According to [9], the excessive exploitation of natural resources has led to their depletion and significant damage to the environment. The consequences of resource overuse, such as pollution, loss of biodiversity, and soil erosion, are evident in the overexploitation of water, minerals, and forests. In essence, there is a need to offset the negative externalities of natural resources from the overall ecological effects to keep their depletion safe and sustainable for the human race. As [10] points out, trade and labor dynamics influence the extent to which resource-rich economies manage these environmental challenges. Countries with greater integration into global markets may experience intensified resource extraction pressures, requiring stricter regulatory measures to prevent long-term ecological damage.

The primary objective of this study is to examine the ecological effects of natural resource rent on environmental pollution in a group of selected and well-organized top-ten natural resource-endowed economies. Due to the deteriorating effects of natural resources, empirical findings have suggested that the engagement of green innovation is significant for balancing the two conflicting goals of reducing ecological damages and increasing growth rates [2]. Specifically, green innovation has been noted to effectively mitigate carbon dioxide and other greenhouse gas emissions. For instance, green technology focuses on the development and utilization of sustainable energy sources, including solar, wind, and geothermal power, to mitigate the impact of climate change [11]. Green technologies reduce reliance on fossil fuels by generating cleaner energy. Additionally, they foster sustainable management of water and marine resources through conservation initiatives, wastewater treatment processes, and programs aimed at protecting marine life. Consequently, two effects of green innovations are examined, comprising the direct and indirect effects. While the direct effects consider the impacts of green innovation on ecological footprint without the interference of any other variables, the indirect effects measure how green innovation mitigates ecological footprint through the suppression of the deteriorating impacts of natural resource rents.

The empirical objectives of the current study extend to examining the criticality of three important indicators of environmental quality comprising institutions, globalization, financial development, and energy transition in the natural resources rent–ecological footprint model. For instance, institutional frameworks have a substantial influence on the relationship between natural resource use and environmental repercussions, notably the ecological footprint [12]. Robust institutions act as gatekeepers in resource-rich economies, minimizing the negative environmental effects often associated with extraction. Resource rents can be used sustainably if legislative frameworks, governance, and environmental standards are strictly enforced. This approach encourages investments in cleaner technologies, green infrastructure, and environmental restoration initiatives. For example, governments with high institutional quality are better able to enforce pollution controls, undertake and monitor environmental impact assessments, and allocate resource revenues to long-term sustainable development efforts [13]. Conversely, the abundance of natural resources often leads to environmental harm in contexts where institutional capacity is either weak or corrupt; this issue is widely referred to as the "resource curse" [14].

Globalization has emerged as a powerful influence on the dynamics of the modern world, with diverse environmental consequences. While it is often linked to advancements in technology and economic development, globalization also affects social interactions, production techniques, and consumption patterns, resulting in significant changes to environmental outcomes [15]. For example, it promotes the worldwide sharing of eco-friendly technologies and best practices, allowing nations to work together on sustainability initiatives and implement cleaner production processes [16]. However, these advantages are often eclipsed by globalization's propensity to accelerate industrial expansion, encourage resource-intensive lifestyles, and intensify consumption patterns, especially in developing nations seeking to engage with global markets.

Moreover, globalization enhances the size and intricacy of supply chains, which in turn impacts the ecological footprint of nations. The demand for processing, storage, and transportation associated with globally sourced products—especially food items—frequently results in heightened carbon emissions [17]. In contrast, localized economies typically incur lower environmental costs. Consequently, the environmental implications of globalization are indicative of deeper transformations in production systems, global economic priorities, and consumption behaviors rather than merely stemming from trade or mobility.

The ecological effects of financial development are two-fold. First, there are viewpoints alluding to the fact that financial development has the potential to promote environmental quality through the enhancements of investments in research and development (R&D) for environmental sustainability and renewable energy [2]. This is due to the fact that financial development can significantly draw foreign direct investment (FDI) and promote R&D investments, thereby resulting in to increase in economic growth rates while at the same time reducing environmental pollutants [18,19]. The other views on the financial development–ecological degradation relationship submit that financial development promotes ecological damages by escalating the consumption needs of the industrial and household units for fossil fuels energy [17,20].

The characteristics and trajectory of the energy transition significantly impact its effect on ecological sustainability. Energy policies that focus on the growth of fossil fuels, often viewed as a short-term fix for energy security challenges, tend to exacerbate environmental harm by increasing greenhouse gas emissions, disrupting land, and polluting the atmosphere [1]. Conversely, a transition to renewable energy sources such as solar, wind, and hydroelectric power offers a sustainable pathway that ensures long-term energy stability while substantially reducing ecological harm [21]. The capacity of renewable energy to decouple economic growth from environmental degradation is a key reason for its adoption. A successful transition requires a comprehensive overhaul of energy production, consumption, and infrastructure rather than merely replacing one energy source with another [22]. The global objective of achieving 100% renewable energy by 2050 underscores the urgency of phasing out fossil fuels to address climate change, enhance energy independence, and achieve net-zero emissions. This transformative shift demands not only an increase in investments in clean energy and storage solutions but also the integration of smart grid technologies to ensure efficiency, equity, and resilience in energy distribution.

One of the primary contributions of this study to the existing literature is its detailed breakdown of green innovation indicators, which is grounded in the previously outlined empirical objectives. The research specifically utilizes two comprehensive metrics for assessing green innovation: the proportion of research and development (R&D) expenditure relative to GDP and the number of patent applications related to environmentally friendly technologies. This dual approach, which encompasses both the input (R&D expenditure) and output (patents) aspects of innovation, significantly enriches the analytical framework of the study. Highlighting how countries transform their innovation investments into viable ecological results adds valuable insights to the ongoing discourse on environmental sustainability. Additionally, by integrating these two measures, the study provides a deeper understanding of how innovation can mitigate environmental harm and foster cleaner production methods.

The second major contribution of this study lies in its novel methodology for examining the impact of green innovation on the relationship between environmental degradation and natural resource rents. By incorporating interaction terms between natural resource rents (NRR) and two distinct indicators of green innovation—research and development expenditure (GINRD) and green innovation through patent applications (GINPA)—the study offers fresh empirical insights into the conditional effects of innovation within resource-intensive economies. This analytical approach highlights the moderating influence of innovation in evaluating the environmental sustainability of natural resource exploitation. The consistently negative and statistically significant coefficients of the interaction terms (NRR $\times$ GINPA and NRR $\times$ GINRD) indicate that countries with higher levels of environmental innovation can mitigate the adverse ecological impacts typically associated with dependence on natural resources. This strongly supports the notion that innovation—particularly in green technologies and research and development investments—serves not only as a driver of economic growth but also as an essential tool for minimizing environmental harm in resource-rich nations. Consequently, this study contributes to the existing literature by demonstrating how green innovation can effectively reconcile the utilization of natural resources with the goal of environmental sustainability.

The third contribution of this study lies in its application of the STIRPAT (Stochastic Impacts by Regression on Population, Affluence, and Technology) framework to explore the connection between natural resources and ecological footprints while also incorporating the aspect of institutional quality, specifically measured through corruption control. By highlighting the significance of corruption control, the study underscores the critical role that institutional robustness plays in shaping environmental outcomes and illustrates how ecological degradation linked to resource exploitation can be intensified by ineffective governance. Importantly, by integrating governance as a vital technological and regulatory factor influencing the environmental repercussions of human activities, this analysis enhances the explanatory capacity of the STIRPAT model. This refined version of the STIRPAT framework facilitates a more comprehensive and policy-relevant investigation of sustainability challenges in resource-rich economies.

The fourth contribution of this study is the incorporation of resource-type heterogeneity through a dummy variable analysis that distinguishes between countries rich in mineral resources and those rich in oil. The findings illustrate how the environmental consequences of resource extraction differ based on the predominant type of resource, as evidenced by the interaction of natural resource rents with these dummy variables. This methodological approach enhances the robustness of the analysis by moving beyond aggregated resource rent measures, allowing for a more nuanced understanding of ecological pressures. It reveals critical insights into how oil-dependent economies may incur greater environmental costs compared to those reliant on mineral extraction, thereby providing resource-rich nations with a strong empirical basis for developing targeted policy interventions.

The fifth contribution of this study lies in the application of three advanced panel estimation methods: augmented mean group (AMG), Common Correlated Effects Mean Group (CCEMG), and System Generalized Method of Moments (Sys-GMM), along with a commitment to methodological rigor. By employing AMG and CCEMG, the study enhances the reliability of long-term estimates by addressing unobserved cross-sectional dependence and slope heterogeneity, which are critical challenges in macro-panel datasets. The inclusion of Sys-GMM further strengthens the analysis by considering potential endogeneity and the dynamic interactions among the variables. This combination of methodologies not only reinforces the empirical validity of the findings but also contributes to the advancement of research methodologies in environmental economics, particularly in exploring the complex interconnections between ecological sustainability, institutional quality, and the utilization of natural resources.

The structure of the article is outlined as follows: Section 3 details the research methodology, while Section 2 reviews the pertinent academic literature. The findings are presented and analyzed in Section 4. Finally, Section 5 encompasses the conclusion, policy suggestions, and proposals for future research avenues.

2. Literature Review

The continuous rise in global greenhouse gas (GHG) emissions has prompted a surge of empirical studies focused on elucidating the complex issues related to unsustainable resource use. This section explores significant aspects of prior research relevant to the objectives of this study. To enhance coherence and clarity, the review is organized into three thematic categories: (i) the ecological effects of natural resource dependence, (ii) the ecological effects of green innovation, and (iii) the ecological effects of institutions.

2.1. The Ecological Effects of Natural Resource Dependence

Ref. [23] utilizes the moment quantile regression approach within the framework of the Environmental Kuznets Curve (EKC) to investigate the influence of natural resource rents and corruption control on environmental quality, specifically focusing on ecological footprints and carbon emissions. The research encompasses an analysis of 152 countries from 2002 to 2018, utilizing available data for a thorough evaluation. The results indicate that effective corruption control leads to improved environmental conditions, especially in areas with subpar environmental quality, by decreasing pollutant emissions and enhancing resource efficiency. Furthermore, the structure of energy consumption is identified as a significant factor; higher energy intensity negatively impacts the environment, whereas an increased reliance on renewable energy helps to alleviate these adverse effects. Nonetheless, the connection between urbanization and environmental quality is not clearly defined, with findings differing based on the indicators employed. Ref. [24] examines the correlation between ecological footprint and ecological deficit among 30 OECD countries from 1990 to 2019. Additionally, it investigates the impact of natural resource rent diversification, environmental technologies, trade openness, and income in conjunction with natural resource rents. The results indicate that the diversification of natural resource rents worsens ecological degradation, particularly in countries with less ecological deterioration. Conversely, nations with already poor ecological conditions experience severe ecological deterioration due to the exploitation of natural resources. It is worth noting that in OECD countries, environmental advancements and uncertainties contribute to ecological improvements, although their effects vary across different ecological levels. Ref. [25] investigates the relationship among ecological green policies, technological advancements, economic development, and revenues from natural resources while evaluating their effects on the ecological footprint in both high-growth and low-growth green economies from 1990 to 2021. Utilizing sophisticated econometric techniques, such as Westerlund's cointegration test and the method of momentsquantile regression, the research reveals that renewable energy sources, technological advancements, ecological policies, and taxation contribute to a reduction in the ecological footprint across both types of economies. Conversely, economies that are less environmentally friendly exhibit a negative correlation between ecological sustainability and natural resource utilization, indicating insufficient environmental policies, limited green innovation, and a lack of clean energy implementation.

Furthermore, ref. [26] investigates the impact of economic growth, technological innovation, natural resource rent, and renewable energy on the ecological footprint in the United States spanning from 1970 to 2019. The outcomes of a unique testing method known as Bootstrapping ARDL reveal that while fossil fuels harm environmental conditions, renewable energy alternatives have a positive effect. The results also confirm a strong link between ecological well-being and technological progress. These conclusions, representing crucial progress in sustainable development post-COVID-19 crisis, carry significant policy implications for lawmakers concerning natural resources and technological advancements aimed at enhancing ecological quality. Ref. [27] estimates the impact of energy consumption and natural resource usage on environmental sustainability for OECD countries. Data on CO_2 emissions, ecological footprint, and carbon footprint from 1980 to 2016 are utilized to represent declining environmental quality. The study employs the augmented mean group (AMG) estimator for long-term estimation, considering country-specific dependencies and slope parameter variability. Findings indicate that renewable energy helps slow environmental degradation, while non-renewable energy has a detrimental effect. Natural resource extraction increases CO_2 emissions but does not significantly impact ecological and carbon footprints. The study underscores the need for efficient natural resource utilization and greater use of renewable energy for sustainable development.

2.2. The Ecological Effects of Green Innovation

Ref. [16], which analyzes 17 emerging economies from 2003 to 2021, investigates the potential coexistence of green growth and the reduction of ecological footprints. The findings, derived from robust estimations using augmented mean group (AMG) and three-stage least squares (3SLS) methods, indicate that energy consumption in the transportation, residential, and industrial sectors contributes to an increase in ecological footprints while negatively affecting green growth by −1.639, −2.272, and −0.699, respectively. Conversely, greenfield investments (0.335) and innovations in green technology (0.738) both foster green growth and help reduce the ecological footprint. Additionally, when the share of renewable energy usage surpasses a certain threshold, the adverse impacts of energy consumption in these sectors on both ecological footprints and green growth are lessened. Ref. [28] analyzes data from Pakistan spanning 1999 to 2022 to assess the effects of green energy, green technology innovation, and foreign direct investment on the ecological footprint (EFP) while also accounting for the influences of trade openness and economic growth (EGR). To ensure the reliability of the data, we utilized various econometric methods. We employed canonical co-integrating regression and fully modified ordinary least squares to explore the long-term relationships among the variables under investigation. The results indicate that green energy and green technology innovation play a crucial role in mitigating environmental degradation. Conversely, economic growth and foreign direct investment have contributed to an increase in the ecological footprint, reinforcing the notion that Pakistan faces significant pollution challenges. Ref. [29] examines the relationship between resource sustainability in Sub-Saharan Africa (SSA) through comprehensive econometric methods, emphasizing green innovations, renewable energy, and financial development. Utilizing techniques such as the cross-sectional augmented autoregressive distributed lag (CS-ARDL), cross-sectional augmented distributed lag (CS-DL), and common correlated effect mean group (CCEMG), our findings revealed that (i) the relationship between natural resources and sustainability is nonlinear in SSA. (ii) In contrast to the environmental advantages of green technology and renewable energy in the region, natural resources negatively impact their environmental sustainability. (iii) The interplay between financial development and natural resources has detrimental effects on the ecosystems of these countries. (iv) The synergy between natural resources and both green innovations and renewable energy enhances the ecological quality in SSA. (v) Urbanization poses a threat to environmental sustainability by amplifying ecological footprints.

Furthermore, ref. [30] examines the interplay between exports of ICT goods, innovations in environmental technology, and mineral rents within OECD nations, highlighting the significance of technological progress in economies reliant on natural resources. The research finds that increased ICT exports contribute to higher mineral rents by enhancing the efficiency of resource extraction and boosting market competitiveness. Nevertheless, innovations in environmental technology alleviate certain adverse environmental impacts by promoting sustainable mining practices and cleaner production methods. The study employs panel data analysis to provide empirical support for the notion that technology-oriented economies can achieve a balance between resource utilization and environmental responsibility. Ref. [31] assesses the impact of environmental policies and green innovation on environmental sustainability and energy structure. Out of the 55 countries within the African Continental Free Trade Area (AfCFTA), 31 were selected for this study. The analysis employed dynamic ordinary least squares (DOLS) and fully modified ordinary least squares (FMOLS) models. The significant empirical results indicate that a 1% increase in green innovations leads to a reduction in ecological footprints by 0.7% (DOLS) and 1% (FMOLS). Furthermore, a rise in environmental legislation can decrease ecological footprints by 10.12% (DOLS) and 21.87% (FMOLS). Additionally, a 1% increase in renewable energy contributes to an enhancement in environmental sustainability by 3.26% (DOLS) and 1.82% (FMOLS). Conversely, a 1% increase in non-renewable energy results in a decline in environmental sustainability by 1.55% (FMOLS) and 4.59% (DOLS). Ref. [32] assesses the effectiveness of environmental regulations in mitigating ecological footprints while considering the roles of innovation and renewable energy. Our research employs a cross-sectional autoregressive distributed lags methodology, utilizing panel data from 29 OECD nations spanning the years 1990 to 2020. The findings indicate that environmental policies significantly reduce ecological footprints in OECD countries. However, the effectiveness of these policies is influenced by the degree of industrialization and the balance of biocapacity. Additionally, our analysis reveals that innovation enhances environmental quality in OECD nations, while renewable energy contributes to the reduction of ecological footprints. In contrast, industrialization exerts a more substantial environmental impact than population density. Importantly, all factors, with the exception of economic growth, exhibit a bidirectional causal relationship with the ecological footprint.

2.3. The Institutional Effects of Green Innovation

Ref. [33] investigates the evolving relationships that affect environmental quality from the first quarter of 1990 to the fourth quarter of 2020, focusing on the interplay between the rule of law, corruption, foreign direct investment (FDI), and renewable energy. We employed advanced analytical techniques, including Quantile-on-Quantile Granger Causality (QQGC) and Wavelet Quantile Regression (WQR). The findings from the WQR analysis indicate that renewable energy contributes to a reduction in the ecological footprint. While the detrimental effects of corruption are pronounced in the short term, they tend to lessen over time. The influence of FDI is inconsistent, with strong governance mitigating immediate adverse effects. Initially, the rule of law may impose additional stress on the environment; however, it ultimately fosters long-term sustainability. According to the QQGC analysis, all variables examined demonstrate a one-way directional Granger causality, indicating that each factor both affects and is affected by the others. Ref. [34] examines the impact of renewable energy utilization, institutional quality, and output growth on consumption-based carbon dioxide (CCO_2) emissions in the BRICS nations—Brazil, Russia, India, China, and South Africa from 1996 to 2020. To achieve this, the study employed the innovative panel method of moments quantile regression (MMQR) alongside advanced econometric techniques, including unit root testing and second-generation cointegration analysis. The analysis from MMQR indicates that GDP exerts a positive and statistically significant influence on CCO_2 emissions across all quantiles, implying that economic growth contributes to environmental degradation. Conversely, both institutional quality and the adoption of renewable energy sources demonstrate a negative and significant effect on CCO_2 emissions, indicating their role in mitigating environmental harm. Ref. [35] examines the influence of the previously mentioned factors on the economies of the Southern Common Market (MERCOSUR) from 1990 to 2021, utilizing the Environmental Kuznets Curve (EKC) framework. The study employed second-generation econometric panel techniques. Findings indicate that Information and Communication Technology (ICT) and Intellectual Quotient (IQ) play a significant role in mitigating the ecological impact on the environment. Additionally, IQ and ICT collaborate to diminish environmental pollution. Factors such as trade, energy consumption, and economic growth contribute to the increase in the ecological footprint (EF). The findings affirm the relevance of the EKC hypothesis within MERCOSUR nations. Moreover, the primary outcomes and the results from the robustness test conducted using the augmented mean group estimator align closely. The study concludes that to achieve the sustainable development goal of environmental sustainability, advancements in ICT innovation and the enhancement of the IQ framework are essential.

Additionally, ref. [36] investigates the assertion concerning the Next 11 (N-11) nations. It analyzes the impact of institutional quality and renewable energy on the ecological footprint of these countries from 1990 to 2022, employing the cross-sectionally augmented autoregressive distributed lags (CS-ARDL) methodology. The study reveals that while economic growth typically leads to environmental degradation, an increase in renewable energy usage can mitigate the ecological footprint, provided that institutional quality positively influences pro-environmental results. This approach underscores the vital importance of institutional quality in formulating policies aimed at promoting environmental sustainability. The results emphasize the necessity for governments to enhance institutional quality and provide a framework for policymakers in the N-11 nations to boost investments in renewable energy resources, thereby aiding in the achievement of environmental sustainability objectives. Ref. [37] investigates the influence of renewable energy and technological innovation in promoting a more sustainable global environment. It highlights the intricate interplay among ecological footprint, renewable energy usage, and technological advancements in G20 nations from 1990 to 2021, particularly when considering the moderating effect of institutional quality, which underscores the necessity for a more thorough analysis. The long-term analysis indicates that both technological progress and renewable energy exert a significant negative effect on the ecological footprint. In G20 countries, while institutional quality negatively moderates the relationship between ecological footprint, renewable energy, and technological innovation, factors such as economic growth, foreign direct investment, and urbanization have shown a positive and significant influence on the ecological footprint.

2.4. Empirical Gaps

The existing body of research has been assessed, and it has been determined that certain gaps must be filled. These omissions may explain why the literature lacks a conclusive outcome. Despite extensive research on environmental degradation and natural resource utilization, there remains a significant lack of comparative, cross-national studies focusing on the world's most resource-abundant economies. Most existing literature tends to concentrate on individual countries or specific regional groups, such as the OECD or MENA, often overlooking the unique yet comparable ecological challenges encountered by resource-rich nations. Additionally, the diverse characteristics of natural resources have not been adequately explored; for example, the environmental consequences of mineral extraction in Australia and Canada differ markedly from those associated with oil wealth in Saudi Arabia and Venezuela. This study addresses this gap by categorizing countries based on their primary type of natural resource (oil versus minerals) and assessing how this classification influences their ecological footprints.

Moreover, while renewable energy and green innovation have garnered attention as means to achieve ecological sustainability, there remains a significant gap in definitive empirical evidence regarding their effectiveness in resource-limited contexts. The threshold effects and conditional dynamics associated with green innovation—specifically, whether the environmental advantages of such innovations depend on the level of resource utilization or the quality of supporting institutions—are infrequently addressed in current studies. Additionally, the connection between the implementation of green technologies and the abundance of natural resources is not well understood. This research seeks to provide deeper insights into the interplay between innovation, resource availability, and environmental impact by investigating how green innovation and energy transition policies mitigate ecological damage in nations rich in resources.

Lastly, there is limited understanding of the impact of institutional quality on environmental outcomes, particularly in high-resource economies characterized by diverse governance structures. Despite the acknowledged importance of institutional factors such as the rule of law, corruption control, and regulatory quality, few studies have examined their interaction with environmental innovation and natural resource utilization. Additionally, comparative research between countries with strong institutional frameworks, like the United States and Canada, and those with weaker governance, such as Iran and Venezuela, remains scarce. This study addresses this gap by employing institutional interaction terms to investigate how governance affects the ecological footprint of green innovation and reliance on natural resources, ultimately offering a more thorough and policy-relevant framework for sustainable resource management.

3. Methodology

3.1. Data and Sources

This research analyzes the ten countries with the most abundant natural resources worldwide, namely Australia, Brazil, Canada, China, Iran, India, Russia, Saudi Arabia, Venezuela, and the United States. These nations were chosen for their substantial roles in global resource extraction, energy generation, and environmental interactions. The study spans from 1996 to 2022, with the initial year selected based on the availability of institutional quality data proxied by control of corruption (CC), while the most recent ecological footprint (EF) data were reported in 2022. The availability of explanatory variables also influenced the chosen time frame, as many indicators have limited reporting periods. It was crucial to ensure a consistent dataset across all variables to accurately establish the parameters of the study. This time frame facilitates a comprehensive examination of long-term trends in resource use, environmental sustainability, and economic aspects, providing significant insights into how natural resource wealth, technological progress, and policy decisions affect ecological results. The selected variables and their respective measurements are reported in Table 1.

Table 1. Data measurement.

Variable	Denotation	Measurements	Source
Ecological Footprint	EFP	Global hectares per capita	[38]
Green Innovation	GIN	number of patent applications	[39]
		Research and development expenditure (% of GDP)	[39]
Natural Resource Rents	NRR	Total Natural Resource Rents % of GDP	[39]
Control of Corruption	CC	Estimate	[39]
Non-RenewableEnergy	NRE	Fossil Fuels % of total final energy	[39]
Renewable Energy	RE	Renewable energy of total final energy	[39]
Financial Development	FDV	Index of financial depth, access, and efficiency	[40]
Globalization	GLO	KOF globalization index	[41]
Economic Growth	GDPPC	GDP per capita constant 2010 USD	[39]
Urbanization	URBN	Urban population % of total population	[39]

Source: Author compilation.

Furthermore, the selection of explanatory variables is grounded in established theoretical models and empirical studies, facilitating a comprehensive analysis of the interplay between natural resource utilization, environmental sustainability, and economic challenges. To enhance the reliability of the data, rigorous data cleaning methods were implemented, including linear interpolation to address missing values, outlier detection, and data harmonization across various sources. These measures guarantee the consistency of the dataset, thereby reinforcing the empirical analysis.

3.2. Variables: Economic Intuition Behind the Measurement of Variables and Justification Within the STIRPAT Framework

The selection of variables in this study is grounded in strong economic intuition, ensuring a comprehensive analysis of environmental sustainability, innovation, and economic development. Each variable aligns with the STIRPAT (Stochastic Impacts by Regression on Population, Affluence, and Technology) framework, an econometric adaptation of the IPAT model, which explains environmental impact (I) as a function of population (P), affluence (A), and technology (T). By integrating these variables, the current study can effectively assess the complex interactions between economic progress, resource management, and environmental outcomes.

Environmental Impact (I) is indicated by the ecological footprint (EFP). The ecological footprint, measured in global hectares per capita, assesses the quantity of biologically productive land and water required to sustain a particular population, effectively quantifying human consumption of natural resources [42]. This metric serves as a vital indicator of sustainability, reflecting the extent of environmental strain caused by economic activities. As the dependent variable in the STIRPAT model, the ecological footprint provides a comprehensive measure of environmental degradation resulting from population growth, economic progress, and technological innovation [43].

Urbanization (URBN) functions as a representative measure for population (P) within the STIRPAT framework. Defined by the proportion of individuals living in urban areas, urbanization is a vital demographic metric. The rapid growth of urbanization intensifies the demand for energy, transportation, and infrastructure, potentially worsening pollution and environmental challenges [44]. Furthermore, the ecological footprint often expands due to increased industrial activities, waste production, and changes in land use in urban settings. However, urbanization can also promote sustainability initiatives, such as enhancing energy efficiency and fostering the creation of green infrastructure, by enabling economies of scale.

GDP per capita (GDPPC), often associated with economic growth, serves as a proxy for wealth (A). Economic growth, as reflected by GDP per capita (adjusted to constant 2010 USD), is a significant driver of environmental change [39]. The complex interplay between economic factors and environmental outcomes is represented by the affluence (A) component of the STIRPAT model.

A crucial technological component of the STIRPAT framework, Green Innovation (GIN), serves as a proxy for technology (T) and is quantified through research and development (R&D) spending as a percentage of GDP and the number of patent applications. These indicators reflect the progress in developing environmentally sustainable technologies, with a higher number of green patents signifying increased efforts toward sustainable solutions. Additionally, R&D expenditure represents a nation's financial dedication to promoting innovation, which in turn propels the advancement of energy-efficient technologies, strategies for reducing emissions, and cleaner industrial practices [45]. By employing both metrics, a comprehensive viewpoint is attained; one assesses the endeavors in green innovation, while the other examines the tangible results. This integration ensures a more complete evaluation of the progress made in green technology.

Natural Resource Rents (NRR) serve as an indicator of resource dependence, quantified as the total natural resource rents expressed as a percentage of GDP. This metric reflects the extent to which an economy relies on its natural resources. Economies abundant in resources frequently engage in heightened extraction activities, which can result in deforestation, soil degradation, and increased carbon emissions [46]. The resource curse hypothesis posits that an overreliance on natural resources may impede sustainable development by diminishing the motivation for innovation and economic diversification [47].

Incorporating this variable into the STIRPAT framework aids in evaluating whether the management of resource wealth is sustainable or if it leads to environmental harm.

Governance and Institutional Influence are represented by the control of corruption (CC) metric. This measure significantly affects the enforcement of regulations, allocation of resources, and implementation of environmental policies, serving as an indicator of governance quality. Strong institutions are vital for enforcing environmental regulations and promoting responsible resource management, which in turn fosters sustainability [48]. Therefore, the quality of institutions is an essential element of the STIRPAT framework, as it significantly affects environmental outcomes.

In the STIRPAT model, both renewable energy (RE) and non-renewable energy (NRE) serve as critical indicators of the energy composition and emissions characteristics. NRE, which reflects the share of fossil fuels in overall energy consumption, contributes to greenhouse gas emissions and environmental harm; an increased share signifies greater ecological pressure [49]. Conversely, RE, represented by the share of renewable energy, illustrates the transition toward more sustainable energy sources and signifies progress in sustainability efforts [1]. These energy-related factors are vital for understanding the environmental impacts of energy consumption and are vital components of the STIRPAT model.

The Economic Mechanism for Sustainability is represented by financial development (FDV). Financial development, assessed through the indices of financial depth, access, and efficiency, plays a crucial role in fostering investments in clean technologies and green financing. A robust financial system enables both businesses and governments to fund environmental initiatives and renewable energy projects [50]. Conversely, inadequate financial institutions can limit access to sustainable investment opportunities. By analyzing how financial systems contribute to environmental sustainability, this variable enhances the STIRPAT model.

Globalization influences environmental sustainability via trade, foreign direct investment (FDI), and the dissemination of technology, as indicated by the KOF Globalization Index [41]. While globalization has the potential to facilitate the adoption of sustainable practices and green technologies, it may also exacerbate environmental issues by encouraging resource exploitation and the growth of highly polluting industries [51]. This research employs the STIRPAT framework to examine the contrasting effects of globalization.

3.3. Theoretical and Empirical Model

This study relies on the innovative STIRPAT (Stochastic Impacts by Regression on Population, Affluence, and Technology) framework introduced by [51]. This framework effectively highlights the significant impact of wealth and population growth on the environment. It systematically incorporates three key indicators—population (*P*), affluence (*A*), and technology (*T*)—to model these influences. Below is the model's formulation.

$$I = \beta P_i^{\sigma 1} \times A_i^{\sigma 2} \times T_i^{\sigma 3} \times \pi_i \quad (1)$$

where in Equation (1), I denotes the environmental factor represented by ecological footprint (EFP), β stands for the constant, $\sigma_1, \sigma_2, \sigma_3$ denote the exponential indicators for P represented by urbanization (URBN), A is proxied by economic growth (GDPPC), and T represents green innovation (GIN) proxy by two indicators comprising technology based on number of patent applications (GINPA) and research and development expenditure (GINRD). Similarly, π represents the error term, whereas the linear form could be specified as follows:

$$\text{lnEFP}_t = \beta_0 + \sigma_1(\text{lnURBN}_t) + \sigma_2(\text{lnGDPPC}_t) + \sigma_3(\text{lnGIN}_t) + \pi_t \quad (2)$$

Equation (2) is adapted to incorporate other variables of interest in line with the objectives of the current study as follows:

$$\begin{aligned} LEF_t &= \sigma_0 + \sigma_1 LURBN_t + \sigma_2 LGIN_t + \sigma_3 GDPPC_t + \sigma_4 LNRE_t + \sigma_5 LRE_t \\ &+ \sigma_6 LFDV_t + \sigma_7 LGLO_t + \sigma_8 LNRR_t + \sigma_9 LCC_t + \sigma_{10}(GIN * NRR)_t + \alpha_t \end{aligned} \quad (3)$$

Such that NRE denotes non-renewable energy, RE signifies renewable energy, FDV stands for financial development, GLO denotes globalization, NRR implies natural resource rents, and CC stands for control of corruption. Other variables stand as previously defined. To enhance easy tracking of the technological effects, two models are estimated to capture the direct and indirect impacts on ecological footprint in Equations (4) and (5) as follows:

$$\begin{aligned} LEF_{it} &= \sigma_0 + \sigma_1 LNRR_{it} + \sigma_2 LGINPA_{it} + \sigma_3 L(\mathrm{GINPA} \times \mathrm{NRR})_{it} + \sigma_4 CC_{it} + \sigma_5 LNRE_{it} \\ &+ \sigma_6 LRE_{it} + \sigma_7 LFDV_{it} + \sigma_8 LGLO_{it} + \sigma_9 LGDPPC_{it} + \sigma_{10} LURBN_{it} + \omega_{It} \end{aligned} \quad (4)$$

$$\begin{aligned} LEF_{it} &= \sigma_0 + \sigma_1 LNRR_{it} + \sigma_2 LGINRD_{it} + \sigma_3 L(\mathrm{GINRD} \times \mathrm{NRR})_{it} + \sigma_4 CC_{it} + \sigma_5 LNRE_{it} \\ &+ \sigma_6 LRE_{it} + \sigma_7 LFDV_{it} + \sigma_8 LGLO_{it} + \sigma_9 LGDPPC_{it} + \sigma_{10} LURBN_{it} + \omega_{It} \end{aligned} \quad (5)$$

To address the possible heterogeneity in the environmental effects of natural resources within the specified economies, we incorporate dummy variables that reflect the primary type of natural resource in each nation. The model states the following:

$$\begin{aligned} LEF_{it} &= \sigma_0 + \sigma_1 LNRR_{it} + \sigma_2 L(\mathrm{NRR}_{it} \times \mathrm{Oil\_dummy}) + \sigma_3 L(\mathrm{NRR}_{it} \times Mineral\_\mathrm{dummy}) \\ &+ \sigma_4 LGINPA_{it} + \sigma_5 \mathrm{LGINRD}_{it} + \sigma_6 CC_{it} + \sigma_7 LNRE_{it} + \sigma_8 LRE_{it} + \sigma_9 LFDV_{it} + \sigma_{10} LGLO_{it} \\ &+ \sigma_{11} LGDPPC_{it} + \sigma_{12} LURBN_{it} + \omega_{It} \end{aligned} \quad (6)$$

Oil_dummy is a binary dummy for oil-rich countries and Mineral_dummy is a binary dummy for mineral-rich countries.

3.4. Econometric Procedure

3.4.1. Slope Homogeneity (SH) and Cross-Sectional Dependence (CD)

Initial assessments are necessary to address panel data challenges and inform estimation techniques. SH and CD represent fundamental issues in panel data analysis that can lead to biased and inconsistent estimators [52]. To enhance the efficiency of SH evaluation, ref. [53] refined the test originally proposed by [54]. The statistical expressions for Swamy's test are provided in Equations (7) and (8).

$$\hat{\Delta}_{SCH} = (N)^{1/2}(2K)^{-\frac{1}{2}}\left(\frac{1}{N}S - K\right) \quad (7)$$

$$\hat{\Delta}_{SCHA} = (N)^{1/2}\left(\frac{2K(T-K-1)}{T+1}\right)^{-1/2}\left(\frac{1}{N}S - K\right) \quad (8)$$

The tilde delta and its adjusted counterpart are denoted by the symbols $\hat{\Delta}_{SCH}$ and $\hat{\Delta}_{SCHA}$, respectively. The number of countries, model specification, and period are represented by the parameters N, K, and T. The significance of CD and the dangers of ignoring it were underlined by [55]. Common shocks, unnoticed shared influences, spillover effects, and other externalities are some of the causes of CD [56]. The reliability of estimators is improved by CD detection.

3.4.2. Unit Root and Cointegration

Unit root testing is a logical next step after CD testing. When CD is identified, a second-generation unit root test is required because first-generation tests are insufficient to properly handle CD. Because it can take into account both SH and CD, the CADF unit root test is recommended. Furthermore, this test performs well in both T > N and T < N panel structures and maintains its dependability in the absence of data. Equation (9) provides the formula for the CADF test:

$$\Delta y_{it} = \alpha_i + \rho_i^* y_{i,t-1} + d_0 \overline{y}_{t-1} + d_1 \Delta \overline{y}_{t-1} + \varepsilon_{it} \quad (9)$$

In this context, $\overline{y}_t$ denotes the mean of the observed values. To address serial correlation within the panel, Equation (9) must be modified by incorporating the lagged first differences of y_{it} and $\overline{y}_t$, as illustrated in Equation (10):

$$\Delta y_{it} = \alpha_i + \rho_i^* y_{i,t-1} + d_0 \overline{y}_{t-1} + d_1 \Delta \overline{y}_{t-1} + \sum_{j=0}^{p} d_{j+1} \Delta \overline{y}_{t-j} + \sum_{k=1}^{p} c_k \Delta y_{i,t-k} + \epsilon_{it} \quad (10)$$

The proposed CADF model, as outlined in Equation (10), was developed to address significant issues related to panel data, including serial correlation, heteroskedasticity, structural breaks (SH), and cross-sectional dependence (CD) [57]. Cointegration is essential when the variables share the same order of integration, typically I(1). Additionally, the existence or lack of cointegration greatly influences the estimation of parameters. To evaluate the presence of cointegration within the dataset, the [58] test is employed. The validity of this test is determined by the results of two statistical measures: the panel means and the group-mean statistics. Moreover, its bootstrapping approach allows it to effectively address issues of SH and CD [59].

3.4.3. The Augment Mean Group (AMG) Estimator

The augmented mean group (AMG) estimator is a sophisticated panel data technique commonly employed to tackle challenges such as non-stationarity, cross-sectional dependence (CD), and slope heterogeneity (SH) within panel datasets. Developed by [60], the AMG estimator stands out from other second-generation methods by providing results that are tailored to individual countries. The implementation of this estimator is outlined in a two-step procedure, as detailed in Equations (11) and (12).

$$\text{AMG-Stage 1: } \Delta y_{it} = \gamma_i + \vartheta_i \Delta x_{it} + \rho_i \boldsymbol{f}_t + \textstyle\sum_{t=2}^{T} \sigma_i \Delta D_t + \varepsilon_{it} \quad (11)$$

$$\text{AMG-Stage 2:} \hat{\vartheta}_{AMG} = N^{-1} \textstyle\sum_{i=1}^{N} \hat{\vartheta}_i \quad (12)$$

In this study, the dependent variable, denoted as y_{it}, corresponds to EF, while the explanatory variables are represented by x_{it}. The cross-sectional parameter and the estimated AMG are indicated by ϑ_i and $\hat{\vartheta}_{AMG}$, respectively. Additionally, ΔD_t represents year dummies. The AMG approach can be applied to both panel structures where $T > N$ and $N > T$. To discern the various causal relationships, ref. [61] was employed, as it is important to note that impact does not equate to causation.

3.4.4. System Generalized Method of Moment

Methodological challenges, particularly endogeneity, emerge when assessing the connection between significant socioeconomic, governance, and energy-related factors and environmental quality as indicated by the ecological footprint. This relationship is bidirectional; for instance, policies promoting green innovation or renewable energy may be shaped by heightened ecological stress, which subsequently influences environmental outcomes. Additionally, ecological policies interact with governance aspects, such as the control of corruption, which impacts the effectiveness of regulations. Moreover, urbanization, globalization, financial development, and economic growth create feedback effects on environmental quality. As highlighted by [62] and Anderson and [63], incorporating a lagged dependent variable—ecological footprint—can lead to dynamic panel bias, making traditional estimation techniques like OLS and fixed effects inappropriate.

In accordance with the methodologies established by [64,65], we employ the System Generalized Method of Moments (System GMM) estimator to address the challenges at hand. This technique utilizes lagged values of endogenous variables as instruments, effectively mitigating endogeneity, eliminating omitted variable bias, and enhancing estimation efficiency. Given that System GMM accounts for the persistence of the ecological footprint while considering the endogeneity of factors such as green innovation, financial development, corruption control, renewable energy, natural resource rents, and economic growth, it is particularly suitable for our study. By integrating both level and differenced equations in Equation (13), this approach bolsters the reliability of our findings and ensures consistent parameter estimates.

$$\begin{aligned}
&EFP_{it} - EFP_{it-1} = \beta_1(\mathrm{EFP}_{it-1} - EFP_{it-1}) + \beta_2(\mathrm{NRR}_{it} - NRR_{it-1}) + \beta_3(\mathrm{GIN}_{it-1} - GIN_{it-1})\\
&+\beta_4(\mathrm{GIN} \times \mathrm{NRR}_{it-1} - GIN \times NRR_{it-1}) + \beta_4(\mathrm{CC}_{it-1} - CC_{it-1}) + \beta_4(\mathrm{NRE}_{it-1} - NRE_{it-1})\\
&+\beta_4(\mathrm{RE}_{it-1} - RE_{it-1}) + \beta_4(\mathrm{FDV}_{it-1} - FDV_{it-1}) + \beta_4(\mathrm{GLO}_{it-1} - GLO_{it-1})\\
&+\beta_4(\mathrm{GDPPC}_{it-1} - GDPPC_{it-1}) + \beta_4(\mathrm{URBN}_{it-1} - URBN_{it-1}) + (\varpi_{it} - \varpi_{it-1})
\end{aligned} \quad (13)$$

We employ the Arellano–Bond test to assess autocorrelation and the Hansen test to evaluate over-identification, thereby ensuring the robustness of our estimation approach and the dependability of our findings. The validity of the instruments is established through the Difference-in-Hansen Test (DHT), which supports the exogeneity of the instruments by not rejecting its null hypothesis [66]. Additionally, the model incorporates institutional quality, specifically measured by corruption control, aligning with the extended STIRPAT framework. Strong institutions, through the enforcement of laws, resource management, and the promotion of sustainability policies, significantly impact environmental outcomes. By integrating governance with economic factors, our research offers a comprehensive examination of human influences on the environment, thereby enhancing policy recommendations for sustainable development.

4. Result Presentation and Discussion

4.1. Descriptive Statistical Analysis of Key Economic and Environmental Indicators in Resource-Rich Countries

In countries abundant in resources, such as Australia, Brazil, Canada, China, Iran, India, Russia, Saudi Arabia, Venezuela, and the United States, descriptive statistics, as presented in Table 2, reveal insights into the distribution and variability of key indicators related to sustainability, economic growth, and resource management. An examination of the mean and standard deviation of the selected variables offers a deeper comprehension of their significance for these economies, particularly concerning their developmental trajectories and natural resource endowments.

The ecological footprint reveals varying levels of environmental impact, with a mean of 4.81 and a standard deviation of 2.76. Countries such as China, India, and the United States exhibit some of the largest ecological footprints due to their significant industrialization, high energy usage, and large populations. Concurrently, Canada, Australia, and Brazil, despite their rich natural resources, face considerable environmental strain from extensive mining, deforestation, and resource extraction activities. Specifically, Figures A1–A5 in Appendix A display the country specific divergence in ecological footprint trend. The significant differences in ecological footprints among these nations underscore the diverse levels of industrialization, resource management practices, and environmental policies they employ. The average natural resource rents for the sample amount to 10.23% of GDP, accompanied by a relatively high standard deviation of 13.02. This suggests significant variability in resource dependence, particularly as countries such as Saudi Arabia, Russia, Venezuela, and Iran rely heavily on fossil fuel exports, in contrast to the more diversified economies of China, India, and the United States. The considerable variation in resource rents also highlights differences in governance, industrial growth, and efforts toward economic diversification. Nations with high resource rents often face challenges associated with the resource curse, where an overreliance on extractive industries can hinder long-term sustainable development [67].

Table 2. Descriptive analysis.

	Mean	Std. Dev.	Skewness	Kurtosis	Jarque–Bera	Probability
EFP	4.81	2.76	0.43	2.01	19.18	0.00
GINPA	3.75	1.10	0.03	2.68	1.21	0.55
GINRD	1.22	0.80	0.59	2.60	17.57	0.00
NRR	10.23	13.02	0.94	4.70	72.18	0.00
CC	0.15	1.11	0.57	1.87	28.82	0.00
NRE	84.30	13.44	−0.57	2.62	16.18	0.00
RE	16.35	15.53	0.86	2.46	36.34	0.00
FDV	0.53	0.22	0.36	1.97	17.74	0.00
GLO	46.59	13.25	−0.01	2.21	7.05	0.03
GDPPC	3.98	0.58	−0.40	2.26	13.19	0.00
URBN	72.17	18.04	−1.43	3.67	97.12	0.00

Source: Authors computation.

The disparity in progress regarding sustainable technological advancements is underscored by the evaluation of green innovation through patent applications (mean = 3.75, Std. Dev. = 1.10) and research and development (R&D) spending (mean = 1.22, Std. Dev. = 0.80) as a proportion of GDP. Countries such as China, the United States, and India exhibit a higher number of patent applications due to their substantial investments in R&D, particularly in clean technology and renewable energy. Conversely, despite their rich natural resources, nations like Russia, Saudi Arabia, and Venezuela demonstrate lower levels of green innovation. This is largely attributed to their ongoing dependence on fossil fuels and the absence of robust policy incentives to facilitate sustainability transitions. While certain economies actively emphasize innovation, others remain behind in integrating environmental factors into their technological developments, as reflected by the moderate standard deviation in R&D expenditure.

The control of corruption index (mean = 0.15, Std. Dev. = 1.11) highlights notable disparities in governance quality among countries abundant in resources. Nations such as the United States, Canada, and Australia benefit from strong institutional structures that promote accountability and transparency. In contrast, countries like Venezuela, Iran, and Russia face significant governance challenges, which can hinder the effective management of their natural resources. In economies rich in resources, corruption often results in poor distribution of rents, inadequate regulatory enforcement, and environmental degradation, all of which obstruct progress toward sustainable development.

Energy consumption patterns reveal notable disparities among these countries. There is a marked difference in the dependence on fossil fuels, with non-renewable energy remaining predominant (mean = 84.30, Std. Dev. = 13.44). Countries such as Saudi Arabia, Russia, and Iran, due to their vast oil and gas reserves, are among the highest consumers of fossil fuels. In contrast, nations like China, the United States, and India are advancing in their energy transitions, even as they still rely heavily on coal and petroleum. Furthermore, there is considerable variation in renewable energy consumption (mean = 16.35, Std. Dev. = 15.53), indicating that while some countries, such as Canada and Brazil, effectively utilize hydro and bioenergy, others remain largely dependent on traditional fuels. The high standard deviation points to significant differences in energy policy frameworks, the adoption of technology, and incentives for investing in green energy.

The differences in development trajectories among these economies are further underscored by urbanization trends (mean = 72.17, Std. Dev. = 18.04). The swift pace of urbanization in countries such as China, Brazil, and India is driven by industrialization and population growth, which places increased pressure on the energy infrastructure and natural resources of these nations. Conversely, Russia and Canada exhibit lower urbanization rates, attributed to demographic factors and geographic distribution, despite their vast land areas. This significant variation in urbanization rates highlights the critical need for sustainable urban planning, particularly in rapidly developing economies where the challenges of resource consumption and environmental degradation are becoming more pronounced.

Lastly, the indicators for globalization (mean = 46.59, Std. Dev. = 13.25) and financial development (mean = 0.53, Std. Dev. = 0.22) reveal significant differences in the efficiency of capital markets and levels of economic openness. Developed countries such as the United States, Canada, and Australia benefit from their highly integrated financial markets, enabling them to allocate more resources to sustainable development initiatives. Conversely, geopolitical issues, restrictive regulations, and market inefficiencies often lead to financial limitations for resource-dependent nations like Russia, Venezuela, and Iran. While certain countries have established financial sectors that foster innovation and promote green growth, others still struggle with inefficiencies in capital distribution, as indicated by the moderate standard deviation in financial development.

The analysis of the distribution reveals the presence of extreme values, characterized by skewness and heavy tails in key variables such as urbanization, renewable energy consumption, and natural resource rents. A limited number of countries, including Saudi Arabia and Venezuela, seem to dominate these metrics, as evidenced by the positive skewness observed in R&D expenditure and resource rents. The negative skewness in urbanization, accompanied by a few low outliers, suggests that urbanization levels are generally high. For most variables, the Jarque–Bera test indicates non-normality ($p < 0.05$), which points to potential biases in ordinary least squares (OLS) estimation. To effectively address these issues, reliable econometric analysis may necessitate the use of alternative methods such as augmented mean group (AMG), common correlated mean group (CCEMG), and generalized method of moments (GMM).

4.2. Pre-Estimation Tests

The result of cross-sectional dependence for the three estimators in Table 3 provides empirical support to reach the conclusion that CD exists across the model. The CD results show a strong presence following the significance level at 1%. This is an indication that economic dynamism in one country among the selected sample has the potential to influence significantvariation in others. Similarly, slope heterogeneity was validated by the statistical significance of both the delta tilde and adjusted delta tilde across all models estimated. Consequently, it is concluded that slope heterogeneity (SH)and cross-sectional dependence (CD) are present in the stated model. In light of these results, second-generation tests will be employed in future analyses, including stationarity tests, cointegration tests, and parameter estimation.

Table 3. Cross-sectional dependence and slope heterogeneity.

Variables	Breusch–Pagan LM	Pesaran Scaled LM	Pesaran CD
EFP	11.043 [a]	15.423 [a]	14.033 [a]
GINPA	9.225 [a]	13.244 [a]	15.003 [a]
GINRD	8.112 [a]	7.211 [a]	19.133 [a]
NRR	13.511 [a]	19.003 [a]	14.013 [a]
CC	6.005 [a]	9.855 [a]	8.083 [a]
NRE	22.066 [a]	17.776 [a]	13.003 [a]
RE	15.332 [a]	14.116 [a]	15.553 [a]
FDV	17.399 [a]	13.322 [a]	12.044 [a]
GLO	11.043 [a]	10.003 [a]	14.229 [a]
GDPPC	22.117 [a]	25.100 [a]	21.033 [a]
URBN	10.032 [a]	9.988 [a]	13.013 [a]
Slope Heterogeneity			
Models	Delta tilde	$(\hat{\Delta}_{SCHA})$	
Model One	11.025 [a]	13.044 [a]	
Model Two	9.355 [a]	12.112 [a]	

Source: Authors computation. Note: [a] $p < 1\%$.

Unit root tests were conducted utilizing both the Cross-sectionally Augmented Dickey–Fuller (CADF) and the Cross-sectionally Augmented IPS (CIPS) methodologies to ensure the stationarity of the variables involved in the panel data analysis. To address potential non-stationarity and cross-sectional dependence within the dataset, these tests were applied at both the level and first-difference stages. The findings indicated that most variables exhibited non-stationarity at the level, suggesting the existence of unit roots, as detailed in Table 4. However, after applying the first differencing, the variables achieved stationarity, confirming that they are integrated of order one, or I(1).

Table 4. Stationarity tests.

Variables	CIPS		CADF	
	I(0)	I(1)	I(0)	I(1)
EFP	−0.226	−4.114 [a]	−2.033	−4.055 [a]
GINPA	−1.005	−3.662 [b]	−0.255	−4.066 [a]
GINRD	−1.215	−4.055 [a]	−1.087	−3.327 [b]
NRR	−1.313	−3.869 [b]	−2.053	−5.369 [a]
CC	−0.226	−4.628 [a]	−1.211	−3.526 [b]
NRE	−1.228	−4.712 [a]	−2.412	−4.782 [a]
RE	−0.199	−4.119 [a]	−1.267	−5.235 [a]
FDV	−1.558	−3.211 [b]	−1.322	−3.166 [b]
GLO	−0.882	−4.336 [a]	−2.060	−3.220 [b]
GDPPC	−2.188	−3.922 [b]	−1.103	−4.211 [a]
URBN	−2.022	−4.099 [a]	−1.325	−6.335 [a]

Source: Authors computation. Note: [a] $p < 1\%$, [b] $p < 5\%$.

To assess the presence of a long-term relationship among the variables, the [58] error-correction-based cointegration test was employed, as cointegration analysis is relevant only for variables that are I(1). This test is wellsuited for the panel dataset in question due to its robustness in the presence of cross-sectional dependence and heterogeneity. Despite short-term variations, the results from the Westerlund test indicate whether the variables exhibit a tendency to move together over the long term.

The results of the cointegration tests conducted on both models, utilizing the [58] methodology, are presented in Table 5. All four test statistics—the group-mean and panel-mean statistics (Gt, Ga, Pt, and Pa)—exhibit statistically significant values, providing strong evidence of cointegration. The consistent significance across all test metrics suggests that the variables in both models maintain a stable long-run equilibrium relationship despite potential short-term fluctuations. The existence of cointegration justifies the application of long-run estimation techniques in subsequent analyses, confirming that the theoretical or economic relationships among the variables are indeed valid. These results reinforce the robustness and reliability of the model frameworks employed in this research.

Table 5. Cointegrationresults.

	Value	z-Value	Probability
Model 1			
Gt	−3.154 [b]	−2.257	0.012
Ga	−5.711 [a]	3.065	0.002
Pt	−8.446 [a]	−4.911	0.000
Pa	−9.809 [a]	−2.587	0.005
Model 2			
Gt	−3.446 [a]	−3.144	0.001
Ga	−4.035 [a]	2.974	0.045
Pt	−12.188 [a]	−5.641	0.000
Pa	−15.792 [a]	−6.834	0.004

Note: [a] $p < 1\%$, [b] $p < 5\%$.

4.3. Long-Run Estimation Outcomes

Two sets of models comprising green innovation by parent application (Model One) and the second captured by research and development expenditure (GINRD) are presented in Table 6. The primary estimator is the AMG, whereas the CCEMG is employed for robustness purposes. Following the results, strong evidence is provided to support how green innovation significantly mitigates environmental degradation. Specifically, the findings from all models indicate a statistically significant and positive correlation between natural resource rent (NRR) and ecological footprint (EFP). This suggests that as income from natural resources—such as minerals, oil, or gas—increases, so does environmental degradation. Economies that rely heavily on these resources tend to experience heightened ecological stress, as evidenced by the consistently positive coefficients. This stress may arise from factors such as pollution, unsustainable extraction practices, or inadequate investment in green technologies. Although the relationship remains significant, it is somewhat less pronounced in CCEMG Model 2, underscoring the harmful effects of natural resource wealth on environmental health when not managed in a sustainable manner.

The coefficient for GINPA (Green Innovation through Patent Application) exhibits a notably negative value in both AMG and CCEMG Model 1 estimations, suggesting that technological progress reflected in green patents contributes to a decrease in ecological impact. Similarly, in both variants of Model 2, GINRD (Green Innovation through R&D expenditure) reveals a statistically significant negative effect, underscoring the important role that investments in green research play in promoting environmental sustainability. These results illustrate the effectiveness of innovation inputs and outputs in minimizing environmental damage, emphasizing the necessity of policies that foster green technology innovation for ecological progress. Copious empirical studies [11,28,51] have endorsed the moderating roles of green innovation on environmental pollutants, making it a significant driver of sustainability.

Table 6. Long-run empirical results.

Variables	Outcome Variable: Ecological Footprint (EFP)			
	AMG		CCEMG	
	Model 1	**Model 2**	**Model 1**	**Model 2**
NRR	1.243 [a] (0.335)	1.099 [a] (0.244)	0.988 [a] (0.116)	0.663 [b] (0.315)
GINPA	−0.923 [a] (0.215)		−0.522 [b] (0.235)	
GINRD		−1.083 [a] (0.331)		−0.863 [a] (0.422)
GIN × NRR	−0.218 [b] (0.035)	−0.705 [a] (0.117)	−0.158 [b] (0.065)	−0.332 [b] (0.145)
CC	−0.092 [b] (0.039)	−0.065 (0.037)	−0.119 [a] (0.034)	−0.077 [b] (0.029)
NRE	2.055 [a] (0.522)	1.021 [b] (0.422)	2.631 [a] (0.633)	0.788 [b] (0.369)
RE	−0.269 [a] (0.053)	−0.355 [a] (0.055)	−0.219 [a] (0.043)	−0.390 [a] (0.068)
FDV	0.558 [a] (0.155)	0.338 [b] (0.145)	0.224 (0.133)	0.412 [a] (0.116)
GLO	0.862 [a] (0.233)	0.612 [a] (0.103)	0.792 [a] (0.099)	0.695 [a] (0.225)
GDPPC	2.221 [a] (0.312)	2.822 [a] (0.448)	2.566 [a] (0.184)	1.447 [b] (0.511)
URBN	2.177 [a] (0.561)	3.980 [a] (1.011)	2.773 [a] (0.412)	3.727 [a] (1.208)

Source: Authors computation. Note: [a] $p < 1\%$, [b] $p < 5\%$.

The importance of sustainable development strategies for the environment is underscored by the connection between green innovation and natural resource rents (GIN × NRR). This interaction consistently yields significant negative coefficients across all models, with AMG Model 2 demonstrating the most pronounced effect (−0.705). This suggests that green innovation has the potential to mitigate the adverse environmental consequences associated with resource extraction. In conclusion, while resource rents can lead to environmental degradation, the adoption and investment in green technologies by nations can substantially reduce these negative effects. This interaction emphasizes the necessity of integrating green innovation into natural resource management frameworks.

The results indicate that the ecological footprint (EFP) is consistently reduced through effective corruption control (CC), highlighting the importance of robust governance for environmental sustainability. In three out of the four models analyzed, the impact is statistically significant, with the CCEMG estimates revealing the most substantial effect. Overall, the data suggest that curbing corruption is crucial for mitigating environmental degradation and advancing sustainable development objectives, although the positive impact is slightly lessened when considering green research and development. This empirical outcome is in line with existing findings that established the pertinent roles of institutions in environmental sustainability [34,36,37].

The reliance on non-renewable energy (NRE) remains a significant contributor to environmental degradation. The adverse effects of fossil fuel consumption on the environment are evident in the substantial and positive NRE coefficients observed across all models. Notably, the CCEMG Model 1 (2.631) demonstrates the most pronounced effects, suggesting that regions heavily dependent on non-renewable energy experience a marked increase in their ecological footprint. These results emphasize the urgent necessity to transition to more sustainable energy sources and highlight the environmental repercussions of persisting with fossil fuel dependence. An extensive body of literature has established the positive nexus between non-renewable energy and ecological footprint [68–70].

Conversely, the ecological impact is consistently mitigated through the use of renewable energy (RE). The advantages for the environment associated with the adoption of renewable energy are evidenced by the negative and statistically significant coefficients observed across all models. For instance, the AMG Model 2 indicates a notable reduction in ecological footprint corresponding to a rise in renewable energy utilization, with a coefficient of -0.355. These findings reinforce global sustainability objectives that advocate for transitions to clean energy and affirm the environmental advantages of advancing solar, wind, hydro, and other renewable energy technologies. The moderating roles of renewable energy have been firmly endorsed by previous findings [11,26,70].

Financial development (FDV) has a complex relationship with environmental outcomes. The AMG models indicate a positive and significant association between FDV and larger ecological footprints, implying that the expansion of the financial sector may result in heightened industrial activity and consumption, thereby exacerbating environmental issues. However, this correlation is not statistically significant in CCEMG Model 1, suggesting that the impact of financial development varies depending on whether investments are directed toward sustainable or non-sustainable initiatives. This highlights the necessity for financial systems to be oriented toward promoting green investments to truly enhance ecological health. The criticality of financial development to ecological quality has been documented in the existing studies [1,14,29].

In all models examined, globalization (GLO) has a positive and significant effect on the ecological footprint. This suggests that trade, capital movements, and technological exchanges enhance global economic integration, which often exacerbates environmental degradation. The results reveal that, as it currently stands, globalization is associated with practices that heighten ecological stress despite its potential benefits, such as technology transfer. Therefore, it is essential to reevaluate the trajectory of globalization to prioritize sustainability as a fundamental principle. The impacts of globalization on environmental pollutants are well documented in the literature [15,17,71].

In all models analyzed, a positive and statistically significant relationship exists between ecological footprint and GDP per capita (GDPPC), which serves as an indicator of economic growth. This indicates that as countries become more affluent, they tend to exert greater pressure on the environment. Although economic advancement is crucial, these results imply that without proper environmental protections, rising income can result in increased ecological harm. This observation aligns with the Environmental Kuznets Curve (EKC) hypothesis, which posits that environmental degradation escalates during the initial phases of economic development but may decrease with the implementation of sustainable policies at elevated income levels. Existing studies have affirmed the significant impacts of economic growth on the environment [2,9,57].

Ultimately, urbanization (URBN) demonstrates a robust positive impact on the ecological footprint, as evidenced by large and significant coefficients across all models. For instance, in CCEMG Model 2, urbanization has a coefficient of 3.727, indicating that a rise in urban populations leads to heightened environmental stress. This increase may stem from factors such as greater energy consumption, transportation demands, waste generation, and construction activities associated with expanding urban areas. These results underscore the critical need for sustainable urban planning and development strategies to mitigate the ecological consequences of urbanization. The critical roles that urbanization plays in influencing the variations in global ecological stability are well documented [44,72].

The economic and environmental conditions in several of the sampled countries, particularly China and the United States, align well with these empirical observations. To illustrate the adverse impacts of GINRD and RE on the ecological footprint, China has notably invested heavily in green research and development as well as renewable energy sources. The interaction term (GIN $\times$ NRR) suggests that China's initiatives in green innovation are helping to mitigate some environmental degradation, even though the country remains heavily dependent on non-renewable energy and continues to experience industrial expansion. Conversely, despite its advancements in technology, the United States has encountered environmental challenges due to its high GDP per capita, urbanization, and financial growth—factors that this study has identified as significantly contributing to an increased ecological footprint. Aligned with the insights on globalization (GLO), both countries exhibit a high degree of globalization, which may contribute to their larger ecological footprints despite advancements in technology. The unique attributes of these nations reinforce the broader observation that the outcomes of sustainability are shaped not only by the management and integration of economic and technological progress into environmental policy frameworks but also by these very factors themselves.

4.4. Short-Run Estimation Outcomes

A multifaceted interplay of institutional, technological, economic, and energy-related elements influences the short-term dynamics of the ecological footprint (EFP). To formulate effective and timely environmental policies, it is essential to comprehend these interconnections, particularly in countries striving for sustainability while also pursuing economic development. The results from the short-run System GMM estimation in Table 7 illustrate how different factors influence EFP within a brief timeframe, shedding light on which drivers exert an immediate environmental effect and which may require a longer duration to become apparent. Below, a detailed analysis of the short-term impact of each variable on EFP is provided, along with insights regarding the potential persistence or evolution of these effects over time.

The lagged ecological footprint (L.EFP) demonstrates a significant and positive impact in the short term, particularly evident in Model 2. This indicates that current ecological conditions continue to be affected by historical environmental degradation. Such persistence highlights the path-dependent nature of environmental impacts, where accumulated pollution and ecological strain do not dissipate immediately. While this effect is apparent in the short term, it has the potential to diminish over time if proactive environmental regulations, technological advancements, and sustainable practices are adopted to mitigate past damage.

In both models, the ecological footprint is notably and consistently influenced in a positive manner by natural resource rent (NRR). This suggests that the short-term degradation of the environment stems from the overexploitation of natural resources, primarily due to activities such as mining, deforestation, and fossil fuel extraction, which contribute to atmospheric pollution and disrupt ecosystems. However, if countries abundant in resources allocate their profits from resource rent toward clean technologies, renewable energy, and environmental restoration projects, this trend could potentially be reversed over time.

In the short run, green innovation exhibits a negative yet statistically insignificant effect when assessed through patent applications (GINPA). This finding suggests that simply submitting patents does not lead to immediate environmental advantages. The absence of a short-term impact may be attributed to the usual duration needed for the commercialization of patents and their widespread implementation. Nevertheless, once patented green technologies are integrated into production and energy frameworks, they could significantly reduce environmental strain in the long term. The ecological footprint is significantly and adversely affected by green innovation, particularly as indicated by expenditures on research and development (GINRD). This implies that prompt investments in green R&D are yielding cleaner practices and technologies that reduce environmental strain in the short term. Given that R&D fosters continuous innovation, its influence is likely to intensify over time as more sustainable solutions are developed and implemented across different sectors.

Table 7. Short-run empirical results.

	Outcome Variable: Ecological Footprint (EFP)	
Variables	**Model 1**	**Model 2**
L.EFP	0.319 [b] (0.152)	1.061 [a] (0.152)
NRR	0.112 [a] (0.051)	0.119 [a] (0.032)
GINPA	−0.958 (0.633)	
GINRD		−1.972 [a] (0.655)
GIN × NRR	−0.519 (0.295)	−1.255 [a] (0.317)
CC	−0.110 (0.095)	−0.088 (0.075)
NRE	0.588 [a] (0.153)	1.005 [b] (0.142)
RE	−0.129 [b] (0.062)	−0.105 [a] (0.033)
FDV	0.226 [a] (0.044)	0.318 [a] (0.048)
GLO	0.162 [b] (0.063)	0.212 [a] (0.053)
GDPPC	1.008 [a] (0.442)	1.652 [a] (0.338)
URBN	0.757 [a] (0.061)	0.922 [a] (0.211)
Constant	−14.557 [a] (2.361)	21.728 [a] (3.461)
AR(1)	0.005	0.011
AR(2)	0.137	0.256
Hansen	0.334	0.412
Fisher	26.321 [a]	23.323 [a]

Source: Authors computation. Note: [a] $p < 1\%$, [b] $p < 5\%$.

Investing in green research and development (R&D) can mitigate the environmental harm caused by resource exploitation, as demonstrated by the notably adverse relationship between green innovation (R&D) and natural resource rent (GINRD*NRR). This finding is particularly important for resource-dependent economies, as it indicates that innovation can help alleviate the negative ecological consequences associated with resource rents. As cleaner extraction methods and technologies gain traction, this relationship may become increasingly evident.

In the short term, there exists a negative correlation between ecological footprint and corruption control (CC), although it is statistically insignificant. This implies that reducing corruption may yield some environmental benefits, but these effects are likely to take time to materialize. For meaningful change, enforcement mechanisms must be strong and dependable, and institutional reforms typically require time to produce results. It is expected that effective corruption control will have a more substantial long-term influence on environmental governance and the enforcement of policies.

The environmental impact associated with the use of non-renewable energy (NRE) is markedly diminished, highlighting the ecological costs of persisting with fossil fuel dependence. The combustion of fossil fuels emits pollutants and greenhouse gases, making this correlation anticipated in the near term. This situation is expected to persist or potentially worsen over time unless there is a transition to cleaner energy alternatives, particularly if the demand for energy continues to increase. Conversely, in the short term, renewable energy (RE) greatly diminishes the ecological footprint. This indicates that initial shifts toward clean energy can immediately benefit the environment, likely due to the implementation of established technologies such as wind and solar power. As renewable energy becomes more cost-effective and widely adopted, it is expected to have an even more significant long-term effect and contribute more substantially to ecological sustainability.

Globalization (GLO) has a notable short-term positive effect on the ecological footprint, driven by heightened production, transportation, and consumption associated with international trade. Initially, globalization may promote pollution and activities that consume substantial resources. However, its long-term ecological consequences could be mitigated if it facilitates the dissemination of environmental technologies and the establishment of global environmental standards.

Economic growth, as indicated by GDP per capita (GDPPC), exhibits a notable positive correlation with ecological footprint, aligning with the initial phase of the Environmental Kuznets Curve (EKC), where environmental degradation escalates alongside rising income levels. As economies expand, there is generally an increase in energy consumption, industrial production, and overall consumption. However, if this growth is paired with structural changes, advancements in green technology, and effective policy reforms, the EKC hypothesis posits that the ecological footprint may eventually decrease in the later stages of economic development.

Urbanization (URBN) exerts a significant and positive influence on ecological footprint in the short term, highlighting the immediate environmental challenges posed by growing urban areas, such as heightened energy requirements, transportation-related emissions, and increased waste production. In the absence of sustainable urban planning, these challenges are likely to worsen. Conversely, over the long term, urban regions have the potential to evolve into hubs of sustainability through investments in intelligent infrastructure, eco-friendly public transportation, and green construction practices.

4.5. Accounting for Heterogeneity Effects in the Resource-Dependent Model

To address the variability in the environmental effects of natural resource rents (NRR), we implement dummy variables that reflect the predominant type of natural resource in each nation. In particular, we classify countries as either oil-rich or mineral-rich according to their main resource extraction activities, utilizing information from the World Bank and national resource reports.

i. Oil-rich countries include Saudi Arabia, Iran, Venezuela, and Russia, where crude oil and natural gas exports dominate total resource rents;
ii. Mineral-rich countries include Australia, Canada, and Brazil, where metal ores and minerals contribute the largest share of resource rents;
iii. Countries with a mixed or diversified resource base, such as China, India, and the United States, serve as the reference group in the regression.

Two binary (dummy) variables have been introduced to assess the influence of resource type on the ecological footprint: mineral_dummy representing countries primarily reliant on minerals and oil_dummy depicting oil-dependent countries. We create interaction terms between each dummy variable and natural resource rents (NRR), specifically NRR × oil_dummy and NRR × mineral_dummy, to differentiate the effects of these resource types. The AMG and CCEMG models utilize these interaction terms to analyze how the nature of natural resource extraction modifies the marginal effect of NRR on the ecological footprint. By distinguishing the specific costs associated with mineral and oil extraction, this approach enhances the policy implications of the findings and fosters a deeper understanding of their environmental consequences.

The extended findings of the ecological footprint model, which account for the varying environmental impacts of natural resource rents (NRR) across countries rich in oil, minerals, and mixed resources, are presented in Table 8. This classification enhances the policy relevance of the analysis by illustrating how the primary method of resource extraction influences ecological outcomes. In AMG and CCEMG analyses, NRR shows a significant and positive correlation with the ecological footprint (EFP). This indicates that, in general, a greater dependence on natural resource extraction is associated with environmental degradation. Nevertheless, as indicated by the interaction terms, this fundamental effect is notably influenced by the type of resource being extracted. For instance, oil-rich countries incur a considerably greater environmental cost per unit of resource rent compared to the reference group, which consists of nations with diverse resources. This conclusion is supported by the positive and highly significant interaction term NRR × Oil_dummy in both models (AMG: 1.722; CCEMG: 1.334). The findings suggest that the carbon-intensive characteristics of fossil fuel activities, the prevalence of flaring, and the more lenient environmental regulations in numerous oil-dependent economies contribute to the particularly detrimental impact of oil extraction and consumption on the environment.

In contrast, the interaction term between NRR and Mineral_dummy is also positive and statistically significant (AMG: 0.628; CCEMG: 0.592), although its effect is considerably less pronounced than that of oil rents. This indicates that while mineral extraction does contribute to environmental degradation, its marginal impact is not as severe as that associated with oil extraction. This discrepancy may be attributed to advancements in mining technology or the implementation of stricter environmental regulations in countries rich in mineral resources, such as Australia and Canada.

These differences underscore the significance of resource diversity—indicating that not all resource rents have the same negative impact—and highlight the necessity for environmental policies to reflect these variations. For instance, nations abundant in oil may need to adopt more stringent environmental regulations, implement cleaner extraction methods, and transition away from fossil fuels to mitigate their disproportionate ecological impact.

Table 8. Empirical outcomes of resource heterogeneity.

Variables	AMG	CCEMG
NRR	1.513 [b] – 0.585	1.503 [a] – 0.476
NRR × Oil_dummy	1.722 [a] – 0.442	1.334 [a] – 0.278
NRR × Mineral_dummy	0.628 [b] – 0.311	0.592 [b] – 0.268
GINPA	−0.335 [b] −0.125	−0.229 −0.135
GINRD	−0.836 [a] −0.241	−0.559 [a] −0.142

Table 8. *Cont.*

Variables	AMG	CCEMG
CC	−0.085 [b] −0.035	−0.089 [b] −0.044
NRE	1.265 [a] −0.322	1.771 [a] −0.453
RE	−1.088 [a] −0.473	−1.133 [a] −0.253
FDV	1.923 [a] −0.635	1.152 [b] −0.516
GLO	0.862 [a] −0.233	0.781 [b] −0.359
GDPPC	3.055 [a] −1.114	2.447 [a] −0.984
URBN	1.255 [b] −0.641	1.355 [a] −0.412
Constant	−11.366 [a] −3.066	14.268 [a] −2.731
Fisher Statistic	32.322 [a]	13.823 [a]

Source: Authors computation. Note: [a] $p < 1\%$, [b] $p < 5\%$.

5. Conclusions, Policy Recommendation, and Limitations

5.1. Conclusions

This study underscores the multifaceted and dynamic nature of environmental degradation, as measured by the ecological footprint (EFP), in the context of natural resource dependence, innovation, institutional quality, and economic development. The empirical results reveal that while natural resource rents (NRR) significantly contribute to environmental degradation, this adverse effect can be mitigated through the adoption of green innovations—both through patent applications and research and development expenditures. The negative interaction between green innovation and NRR (GIN $\times$ NRR) reinforces the strategic role of innovation in buffering the environmental costs of resource exploitation. Institutional factors such as corruption control (CC) and financial development (FDV) also show varying effects. While effective governance reduces ecological pressure, its short-term effects are limited, suggesting the need for sustained institutional reforms. Financial development, unless aligned with green financing mechanisms, tends to exacerbate environmental harm. Similarly, globalization and economic growth drive higher ecological footprints, affirming the importance of integrating sustainability into trade and economic policy frameworks.

The findings further highlight the contrasting environmental implications of energy types. Non-renewable energy (NRE) remains a primary driver of ecological stress, while renewable energy (RE) demonstrates significant potential in reducing environmental impact both in the short and long term. Urbanization also emerges as a key determinant of ecological degradation, necessitating sustainable urban planning. Lastly, the differentiated impact of natural resource types—oil versus minerals—on EFP is significant. Oil-dependent countries exhibit a markedly higher environmental toll, emphasizing the need for stricter environmental regulations and investment in cleaner extraction technologies in these economies. In sum, this study advocates for comprehensive, innovation-led, and institutionally anchored policy frameworks that decouple economic and resource growth from environmental harm. Such strategies are vital for countries aiming to transition toward sustainable development without compromising ecological stability.

5.2. Policy Recommendations

i. To sustain the enhancing roles of green innovation on environmental sustainability, the government should promote investment in clean technology through the provision of tax incentives, technology transfer agreements, and government-supported research and development initiatives. More so, policymakers should ensure that advancements in technology are aligned with sustainable production and consumption practices by incorporating green innovation within the principles of a circular economy. It is equally fundamental that the government should establish legislative frameworks that encourage businesses to adopt energy-efficient and low-carbon technologies, thereby improving the efficacy of green innovation in addressing environmental degradation;

ii. Specifically, China and India should increase government financing for renewable energy research and development, as well as adopt smart grid systems to improve energy efficiency. The United States and Australia must increase incentives for private-sector-driven green innovation, particularly in carbon capture and storage (CCS) and advanced renewable technologies. Concurrently, Saudi Arabia and Iran should form technology transfer agreements to speed up the adoption of clean energy and reduce their reliance on fossil fuels in their oil-dependent economies;

iii. The evidence indicates that renewable energy (RE) contributes to a reduction in ecological footprint (EF), while non-renewable energy (NRE) intensifies environmental harm. Therefore, policy measures should prioritize the rapid adoption of RE and implement stricter environmental regulations on fossil fuel companies. Governments ought to offer financial incentives for green energy initiatives, implement carbon pricing strategies, and promote upgrades to the energy grid to facilitate more efficient integration of RE. Additionally, a global transition to sustainable energy can be expedited by removing subsidies for fossil fuels and fostering research and development in clean technologies;

iv. Considering the dichotomy of energy mix across the sample countries, national policies should be customized to align with the unique energy mix of each country. Nations that are significantly dependent on fossil fuels, such as Saudi Arabia, Russia, Iran, and Venezuela, are encouraged to diversify their economic frameworks and gradually reduce their reliance on fossil fuels by utilizing green finance and introducing tax incentives for renewable energy initiatives. Countries with elevated emission levels, including China and India, ought to prioritize the establishment of more ambitious renewable energy goals, implement stricter coal regulations, and cultivate public–private partnerships to advance green technology development. Nations rich in renewable energy resources, such as Canada and Brazil, should focus on enhancing energy storage capabilities, ensuring sustainable management of hydropower, and increasing the adoption of renewable energy in the transportation and industrial sectors. Mixed-energy economies, like the United States and Australia, should work toward improving carbon taxation, increasing investments in next-generation renewable technologies such as hydrogen, and providing incentives for comprehensive decarbonization across various industries. These targeted strategies will promote environmental sustainability while effectively addressing the specific energy challenges encountered by each nation;

v. The escalating adverse ecological impacts of natural resource exploitation must be deliberately tackled to reduce environmental harm through sustainable management practices. To improve sustainable resource management, governance structures must be established to ensure that proceeds from natural resource extraction are reinvested in renewable energy projects and sustainability initiatives. Fiscal policies, such as resource taxation and the development of sovereign wealth funds, can help to reduce reliance on extractive sectors while also encouraging economic diversity. Furthermore, tougher environmental laws for mining, deforestation, and resource extraction are required to avoid long-term ecological damage;

vi. Strategies adapted to specific countries must adhere to these basic principles. Russia and Venezuela should concentrate on implementing resource taxation and creating sovereign wealth funds to reinvest extraction proceeds in clean energy projects. Canada and Brazil must strengthen their forest conservation rules and adopt sustainable mining techniques to reduce environmental damage. Simultaneously, Saudi Arabia and Iran should aim to reduce their dependency on oil by investing in economic diversification and green infrastructure projects, helping the transition to a more sustainable economy;

vii. Advancing green finance initiatives is essential for accelerating the transition to sustainability, as empirical studies have demonstrated the significant impact of financial development. To ensure that capital is directed toward clean technologies, renewable energy sources, and sustainable infrastructure, policies must promote green bonds, sustainability-linked loans, and requirements for ESG investments. Additionally, regulations should limit financing for fossil fuel projects and redirect resources toward environmentally friendly alternatives. By enhancing financial inclusion programs, businesses and communities, particularly in developing economies, will gain access to funding for sustainable initiatives;

viii. Strategies tailored to individual countries must align with these financial priorities. China and India should enhance their green bond markets to finance extensive renewable energy and infrastructure initiatives. The United States and Canada should implement more stringent sustainability-linked lending practices to limit funding for fossil fuel-dependent industries. Concurrently, Brazil and Australia should prioritize green microfinance efforts, aiding small clean energy enterprises and community-driven sustainability projects;

ix. To moderate the effects of FDI on green ecology, the government should implement policies that will enhance regulations on the compliance of multinational corporations (MNCs) with sustainability standards. Specifically, green foreign direct investment (GFDI) policies noted to be effective in drawing funding for climate adaptation, renewable energy, and green technology initiatives to promote environmental sustainability should be intentionally promoted. In particular, public–private partnerships (PPPs) in the sample economies can amplify the benefits of foreign direct investment (FDI) for sustainable development. Brazil and Canada should focus on sustainable agriculture and bioenergy projects that include rigorous environmental impact assessments, whereas Saudi Arabia and Russia ought to emphasize foreign direct investment (FDI) in solar, wind, and hydrogen sectors to reduce their dependence on oil. Meanwhile, China and India should enhance regulatory oversight of multinational corporations (MNCs) to prevent environmentally harmful investments and ensure corporate accountability;

x. The role of globalization unveils the inevitability of enhancing global environmental governance. It is essential to implement institutional reforms that foster transparency, strengthen anti-corruption initiatives, and bolster the enforcement of international laws. The adoption of digital governance solutions can facilitate the monitoring of emissions, deforestation, and pollution, thereby enhancing accountability. Nations ought to align their policies with international climate agreements, such as the Paris Agreement and activities associated with COP, to ensure effective compliance with sustainability standards. The United States and Australia should reinforce their climate commitments and introduce carbon tariffs on imports with high emissions, while China and India need to adjust their trade practices to conform to global sustainability standards. Concurrently, Russia and Iran should establish renewable energy trading partnerships to reduce reliance on fossil fuels and support a transition to cleaner global energy sources;

xi. The findings of the resource heterogeneity model indicate that a country's dependence on a specific resource significantly influences the environmental consequences of natural resource rents. Notably, the interaction terms reveal that the ecological footprint increases sharply in relation to oil rents, with the most severe environmental degradation observed in nations reliant on oil. This situation calls for targeted policy interventions in countries like Russia, Saudi Arabia, Iran, and Venezuela. These nations should prioritize reinvesting oil revenues into the development of clean energy, implementing stricter environmental regulations within the oil sector, and promoting carbon pricing mechanisms to account for the environmental costs associated with oil extraction and consumption as they transition away from oil dependency;

xii. Countries abundant in minerals, such as Canada, Brazil, and Australia, are experiencing a slight yet significant rise in their ecological footprint attributed to mineral rents. Policy responses in this sector should prioritize the rehabilitation of mined areas, improved environmental impact assessments, and the adoption of sustainable mining practices. Additionally, these nations could benefit from implementing resource certification programs and environmental taxes to encourage compliance with eco-friendly extraction standards. In summary, environmental policies tend to be more effective when tailored to the specific resource characteristics of each country, as this ensures that mitigation strategies directly tackle the unique challenges posed by different types of natural resource exploitation.

5.3. Limitations and Future Research Opportunities

This research examined ten countries using a dataset that covers the period from 1996 to 2022, which restricts the variety of estimation techniques and the applicability of the findings. Additionally, the study primarily employed ecological footprint (EF) as the key indicator of environmental sustainability rather than load capacity factor (LCF). This approach emphasizes the demand aspect of environmental degradation while neglecting the supply-side constraints on ecological sustainability. Consequently, the study does not sufficiently capture the equilibrium between environmental demand and the planet's capacity for regeneration, an essential factor for a comprehensive assessment of sustainability.

Future investigations should focus on examining LCF to enhance our understanding of environmental sustainability. Additionally, it is essential to integrate artificial intelligence (AI) modeling techniques, such as machine learning, deep learning, or hybrid AI methods, to enhance predictive accuracy and uncover intricate interdependencies among various factors. Moreover, to better comprehend the relationship between green innovation and natural resource rents in influencing ecological footprints, future studies should employ structural equation modeling (SEM) or mediation analysis frameworks. These innovative approaches will facilitate the exploration of the causal mechanisms that drive sustainability outcomes and offer a more detailed understanding of policy strategies for resource-abundant nations to mitigate environmental degradation. By addressing these limitations, future research can enrich the theoretical framework, enhance methodological rigor, and increase the policy relevance of sustainability studies. Lastly, to explore ecological sustainability within resource-dependent economies, this research concentrates on the ten most resource-abundant countries. While this approach provides valuable insights, it limits the relevance of the findings to countries with different levels of resource availability. Future research could enhance comparative validation by expanding the sample to encompass emerging or resource-limited economies.

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Appendix A

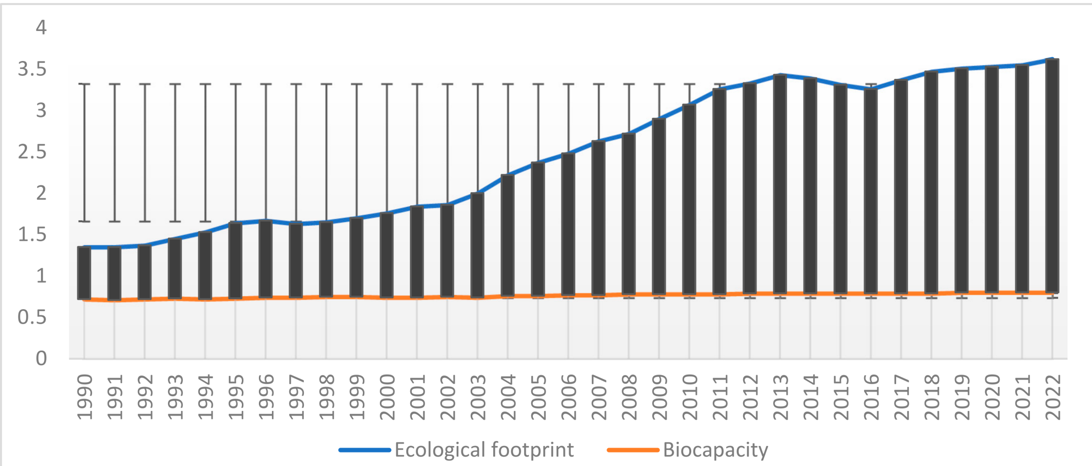

Figure A1. EF versus biocapacity in China. Source: Global Footprint Network (2024) [38]. The shaded area shows ecological deficit.

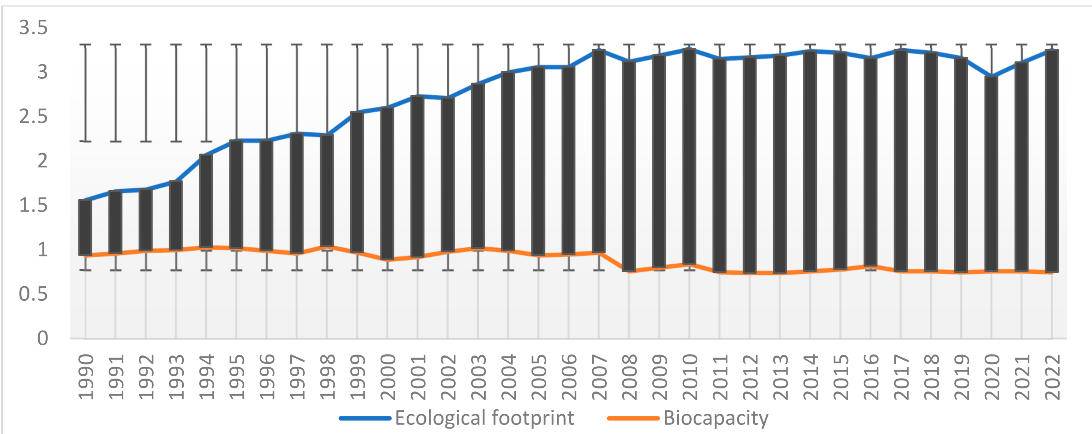

Figure A2. EF versus biocapacity in Iran. Source: Global Footprint Network (2024) [38]. The shaded area shows ecological deficit.

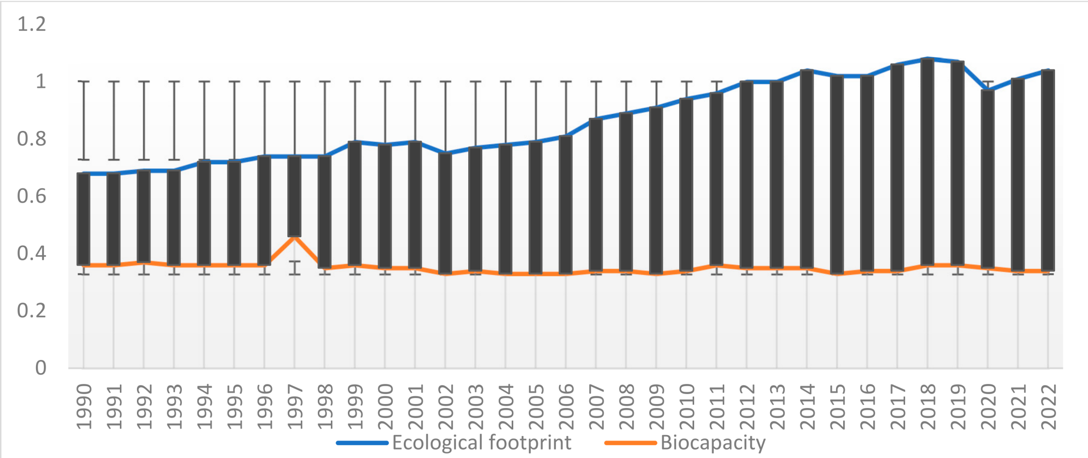

Figure A3. EF versus biocapacity in India. Source: Global Footprint Network (2024) [38]. The shaded area shows ecological deficit.

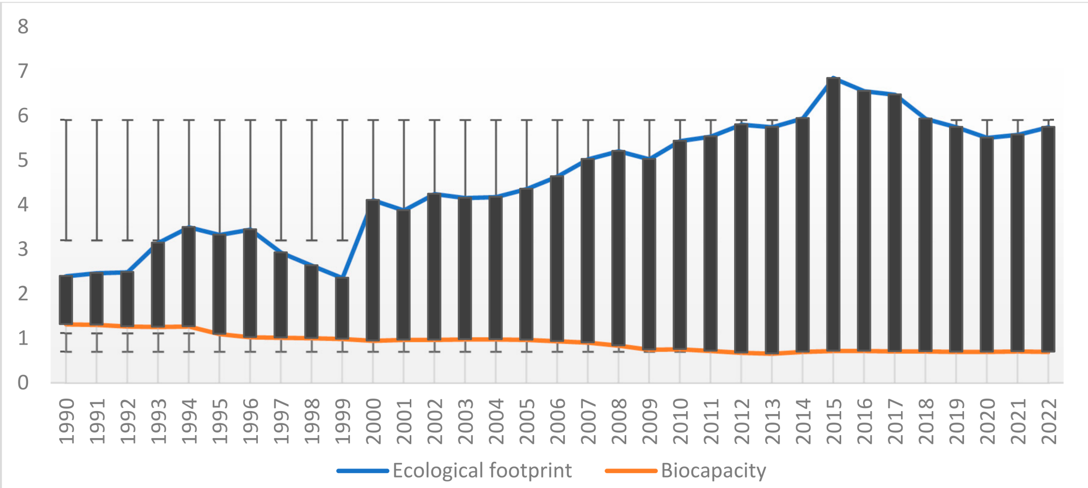

Figure A4. EF versus biocapacity in Saudi Arabia. Source: Global Footprint Network (2024) [38]. The shaded area shows ecological deficit.

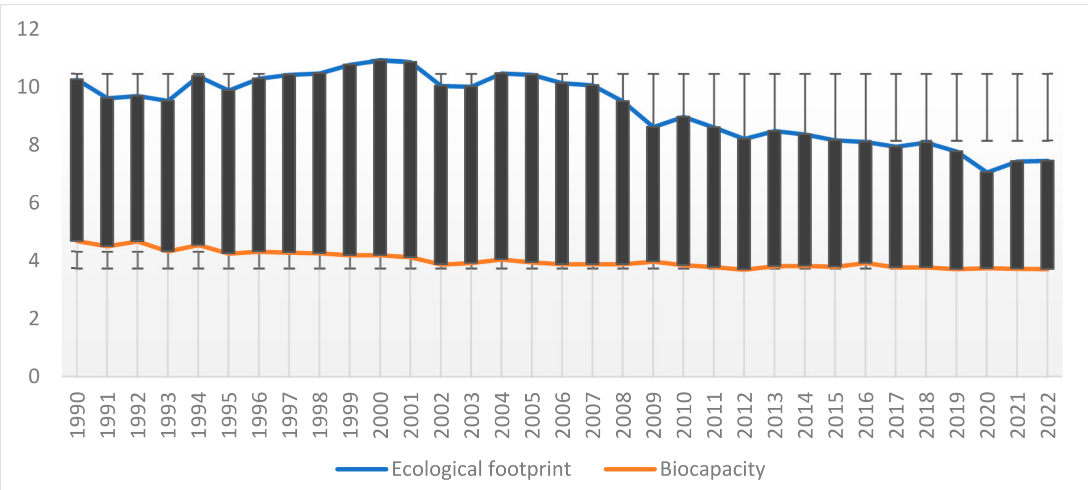

Figure A5. EF versus biocapacity in the United States of America. Source: Global Footprint Network (2024) [38]. The shaded area shows ecological deficit.

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