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THE IMPACT OF ENVIRONMENTAL POLICY, TECHNOLOGICAL INNOVATIONS, AND DIGITALISATION: DOES CONTEXT MATTER IN NATURAL RESOURCE MANAGEMENT IN SUB-SAHARAN AFRICA?

Forthcoming: The Extractive Industries and Society

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Abstract

The paper assesses the role of environmental policy, technological innovations, digitalisation, and natural resources management across 29 Sub-Sahara Africa (SSA) countries from 1999 to 2022. The findings are contingent on various econometric approaches that account for cross-sectional dependencies, notably: PVAR-GMM, Granger causality and Quantile Regressions. The findings show that stringent environmental policies in resource-rich countries positively influence natural resource management practices. However, in resource-poor countries, the impact of such policies is less significant. Moreover, the results show that technological innovations, particularly in digital infrastructure, can strengthen resource management practices across both resource-rich and resource-poor countries in SSA. In resource-rich nations, fostering the development of digitalisation, marked by increased fixed broadband subscriptions and digital infrastructure, correlates with more effective resource management. Conversely, the impact of digital advancement on resource management practices in resource-poor countries appears to be less pronounced, indicating potential challenges in leveraging digital technologies for resource management in these contexts. These findings underline the importance of sustainable resource management in promoting long-term economic growth, social equity, and environmental sustainability across SSA. Policy implications are discussed.

Keywords: Natural Resource Management; Environmental Policy; Technological Innovations; Digitalisation

1. Introduction

The motivation of this study stems from three primary factors. Firstly, the degradation of natural resources in Sub-Sahara Africa (SSA) poses significant challenges to sustainable development, affecting ecosystems, biodiversity, and local livelihoods (IRENA, 2022). By investigating the roles of environmental policy-technological innovations-digitalisation, this study aims to identify effective strategies for mitigating environmental degradation and advancing conservation efforts. Secondly, technological advancements such data-driven monitoring systems offer promising avenues for optimizing natural resource management (Niloofar et al., 2021). Understanding how these innovations intersect with environmental policies and digital trends can inform the development of innovative approaches to address resource management challenges effectively. Lastly, sustainable resource management is crucial for fostering long-term economic growth, social equity, and environmental sustainability (Ahmad et al., 2020; Ahmed et al., 2020; Jahanger et al., 2022). Through an examination of the interplay between environmental policy-technological innovations, and digitalisation, this study seeks to identify opportunities for integrating these factors into comprehensive resource management strategies aligned with the United Nations' sustainable development goals (SDGs). Accordingly, consistent with extant literature (Tsani et al., 2020; Nchofoung et al., 2021; Asongu et al., 2024), efficient resource management is essential for sustainable development, especially as it pertains to core targets such as SDG1 (i.e., extreme poverty reduction), SDG2 (ending hunger, achieving food security and improving nutrition and promoting sustainable agriculture) and SDG8 (i.e., ensuring decent work and economic growth).

In SSA, Basedau (2005) and Pérez & Claveria, (2020), examine the paradoxical nature of resource-rich countries, where the exploitation of abundant natural resources often leads to economic challenges and governance issues that adversely impact environmental well-being. Asongu et al. (2018) examine the intersection of environmental degradation and inclusive development in SSA, considering the role of information and communication technology in driving sustainable outcomes. Moreover, the role of governance quality in shaping environmental outcomes cannot be overstated. Studies by Oyewole et al. (2019), Sheba and Bello (2020) and Ukhurebor et al. (2021) highlight the importance of effective institutions and regulatory frameworks in mitigating environmental degradation and promoting climate change adaptation. These findings underscore the critical role of transparent and accountable governance structures in addressing environmental challenges. There is also a growing body of literature on the relevance of information technology and innovation in economic development and environmental sustainability (Ritter, 2019; Perrons, 2021; Storey, 2023; Corrigan & Ikonnikova, 2024).

In SSA, the connections among environmental policy-technological progress-digitalisation, and the management of natural resources are receiving increased attention. There is a widespread recognition that uncontrolled economic expansion, urban development, and industrialization often lead to extensive extraction of natural resources in the pursuit of economic advancement (Danish et al., 2019). Empirical studies by Kim & Kim, (2012), Kounetas and Tsekouras (2008) and Sadorsky, (2010) examine the impact of technological innovation on carbon emissions, highlighting the importance of considering economic development levels and supporting infrastructure. Moreover, environmental regulations play a crucial role in driving technological innovation and fostering a transition towards cleaner technologies, as advocated by (Porter and Linde, 1995).

While some studies have touched upon the environmental impacts of resource extraction in SSA, a comprehensive analysis of the multifaceted linkages between regulation-technology-digitalization, and their influence on management practices across the continent is lacking (Adedoyin et al., 2020; Erdogan et al., 2021). Many existing studies have primarily focused on measuring environmental harm through carbon emissions, neglecting the broader array of natural resources and their diverse environmental consequences in SSA (Erdogan et al., 2021). However, recent years have seen initial efforts to address this gap by exploring the environmental effects of economic development beyond carbon emissions, particularly in Europe and emerging economies (Hassan et al., 2019; Ibrahim and Ajide, 2021; Nathaniel and Adedoyin, 2022). Nevertheless, research in this domain remains limited for SSA, emphasizing the necessity for further examination and comprehension of the relationship between environmental policy-technology-digitalization, and natural resource management on the continent.

Existing literature lacks comprehensive studies exploring the interplay between environmental regulation-technology-digitalization, and resource management in Africa. However, understanding how regulation-technology, and digitalization mediate the relationship between resource extraction and management can provide valuable insights into responsible sustainable practices, an area largely unexplored previously (Abid, 2017; Danish et al., 2019; Duodu et al., 2021). This inquiry aligns with the growing recognition of the role of digital technologies in facilitating data-driven approaches to environmental conservation and resource governance (Muhar et al., 2018; Sala, 2019). Furthermore, it underscores the importance of considering the socio-economic and environmental contexts of SSA countries when developing policies and implementing technological solutions for sustainable resource management. Thus, there is a pressing need for more comprehensive and context-specific research to address the complex challenges of resource extraction and management in Africa.

The paper addresses a critical gap in the literature by exploring the interconnectedness of regulation-technology, and digitalization in resource-rich and resource-poor countries. It offers a novel perspective on the contextual factors shaping natural resource management strategies, contributing significantly to the existing body of knowledge. By emphasizing this gap, it underscores the need for further research in this area, expanding beyond the narrow focus of existing studies that primarily measure environmental harm through carbon emissions. The paper advocates for a broader examination of the environmental consequences of resource extraction, particularly in SSA, highlighting the socio-economic and environmental contexts of these countries. This contextualization adds depth to the discussion and underscores the relevance of regulation-technology, and digitalization in shaping resource management practices. Moreover, the paper emphasizes the practical implications of understanding this interplay, identifying potential insights into responsible management practices and the role of digital technologies in environmental conservation and resource governance. Last, methodologically, the paper presents a contribution by employing advanced analytical techniques, including Panel Vector Autoregression (PVAR), Variance Decomposition, Impulse Response Function, and PVAR Causality, to investigate the relationships between environmental policies-technological innovations-digital infrastructure, and natural resource management practices. The findings reveal the differential impact of these factors in resource-rich and resource-poor countries, emphasizing the need for tailored approaches to sustainable resource management across the region. Overall, the paper contributes to the existing literature by identifying a gap, broadening the scope of inquiry, contextualizing research within SSA contexts, and highlighting practical implications for policy and practice.

The paper consists of five main sections. Section 2 offers a literature review, while Section 3 covers data sources, methodology, and the model used. In Section 4, empirical results are presented, followed by a discussion. Finally, Section 5 concludes the study and discusses policy implications.

2. Literature Review

Sub-Sahara Africa (SSA) is endowed with abundant natural resources, including minerals, metals, oil and gas reserves, which present considerable prospects for economic development and expansion (Musah et al., 2023; Sachs and Warner, 2001; Tsani, 2013). However, the extraction of these resources often gives rise to environmental challenges, social disparities, and technological limitations (Kragelund, 2020). Despite these hurdles, environmental policies play a pivotal role in regulating resource extraction activities, with the aim of minimizing environmental degradation, safeguarding biodiversity, and promoting sustainable practices (UNEP, 2012; UNEP, 2021). Concurrently, technological innovations hold promise in revolutionizing the extraction process by offering solutions for efficient resource utilization, effective waste management, and environmental conservation (Udobia and Akpan, 2023). Furthermore, the emergence of digitalisation has introduced new dynamics, facilitating enhanced connectivity, data-driven decision-making, and innovative solutions for resource management and governance (Chene, 2017).

2.1 Environmental policy-resource management

The literature on natural resources and economic development often focuses on the "resource curse" hypothesis, which suggests that countries rich in natural resources might experience slower economic growth and governance challenges like corruption and rent-seeking behavior (Ross, 2015). However, researchers have also found that with effective governance and resource management, countries can avoid the negative consequences of resource abundance and leverage their natural resources for economic development.

The environmental policy-natural resource underscores the interaction between regulations governing environmental practices and the management of natural resources, aiming to ensure sustainable resource utilization while mitigating adverse environmental impacts (Ekins et al., 2014; Rao et al., 2023). These policies provide frameworks for guiding resource extraction, conservation efforts, and sustainable development initiatives, establishing standards and incentives to promote responsible resource management and preserve biodiversity (Gong et al., 2023; Jhariya et al., 2021). Measures such as environmental impact assessments, emission standards, and habitat conservation plans seek to strike a balance between economic development and environmental protection by addressing negative externalities associated with resource exploitation (Rao et al., 2023). Additionally, environmental regulations, as argued by Porter and Linde (1995), can drive technological innovation, compelling firms to adopt innovative solutions that enhance productivity and competitiveness. For instance, stricter enforcement of environmental regulations in China since 2000 has prompted the adoption of advanced technologies, leading to increased productivity and international competitiveness (Chenran et al., 2019; Wang and Dong, 2019; Wang et al., 2019). This demonstrates how a stringent regulatory framework can catalyze positive changes in pollution-intensive industries, fostering a win-win scenario for economic growth and environmental protection(Shen et al., 2023).

At the core of the environmental policy-natural resource lies the recognition of the finite nature of natural resources and the need to manage them judiciously to meet present and future societal needs (Ahmed et al., 2020; Jahanger et al., 2022; WCED, 1987). This necessitates the implementation of policies that foster sustainable resource extraction, promote renewable energy sources, and encourage recycling and waste management practices (Altinoz and Dogan, 2021; Beltrami et al., 2021; Vidal-Amaro and Sheinbaum-Pardo, 2017). Additionally, environmental policies often integrate principles of ecosystem management, aiming to maintain the resilience and functionality of ecosystems upon which human societies depend (Jacobides and Lianos, 2021; "Millennium Ecosystem Assessment," 2005; Pan et al., 2023). By incorporating considerations of ecosystem services, such as clean air, water purification, and climate regulation, environmental policies seek to safeguard the natural capital that underpins sustainable development (Costanza, 1997; Rockström et al., 2009).

Moreover, the environmental policy-natural resource is evolving in response to technological advancements and shifts in the global economy, particularly with the rise of digitalisation (Garrity et al., 2010). Technological innovations play a crucial role in enhancing the efficiency of resource extraction, processing, and utilization, thereby influencing the environmental impact of resource management activities (Wei et al., 2010). From advancements in renewable energy technologies to the development of precision agriculture and smart resource monitoring systems, technology offers opportunities to optimize resource utilization while minimizing environmental harm (Stern, 2008). Furthermore, digitalisation introduces new dynamics, such as data-driven decision-making, remote sensing technologies, and digital platforms for environmental monitoring and compliance, which can enhance the effectiveness of environmental policies and natural resource management strategies (UNEP, 2021).

Building the above, technological innovations have historically played a crucial role in maximizing the utilization of natural resources, from the Industrial Revolution's exploitation of fossil fuels to modern techniques for mining minerals and harnessing renewable energy (Gacula, 2024; He et al., 2024). These innovations, driven by the quest for efficiency and sustainability in resource management (Stern and Kander, 2012; Xie et al., 2024), continually reshape the landscape of resource utilization. Advancements in renewable energy technologies, such as solar and wind power, and improvements in resource extraction methods, like hydraulic fracturing and deep-sea mining, underscore the transformative impact of technology on resource utilization (Zaman et al., 2024).

However, the technology-natural resource presents challenges and trade-offs (Sang et al., 2024). While technological innovations can enhance resource efficiency and reduce environmental harm, they may also exacerbate resource depletion and environmental degradation. For example, certain technologies, such as intensive agriculture practices and extractive industries, can lead to habitat destruction, soil erosion, and biodiversity loss (Chen et al., 2022). Additionally, the increasing demand for high-tech consumer electronics and electric vehicles reliant on rare earth minerals raises concerns about resource scarcity and supply chain vulnerabilities (UNEP, 2021).

To navigate the technology-natural resource effectively, stakeholders must adopt a holistic approach (Acemoglu et al., 2014). This involves promoting technological innovation that enhances resource efficiency, reduces environmental impacts, and fosters sustainability. Investment in research and development, education, and infrastructure is crucial to support the transition to a more sustainable and resource-efficient economy (Gacula, 2024; Rockström et al., 2009). Furthermore, addressing issues of equity, governance, and ethical considerations is essential to ensure that technological advancements benefit all stakeholders and mitigate social and environmental risks (Acheampong, 2023; Barrera-Santana et al., 2022).

Technological advancements play a crucial role in mediating the relationship between economic development and environmental sustainability. Asongu et al. (2018) explore the intersection of environmental degradation and inclusive development in SSA, highlighting the potential of information and communication technology (ICT) in driving sustainable outcomes. (Yimen et al., 2020) investigate how financial development can moderate the environmental impact of natural resource exploitation, emphasizing the importance of sustainable financial practices.

In SSA, the technology-natural resource nexus is exemplified by innovative initiatives addressing environmental and developmental challenges. For instance, the adoption of mobile technology in agriculture provides smallholder farmers with access to vital information, enabling informed decisions and improved productivity (Parthiban et al., 2024). Similarly, the rapid adoption of off-grid solar solutions is addressing energy access challenges in remote areas, contributing to environmental sustainability (IRENA, 2022). Additionally, e-waste recycling initiatives promote circular economy principles, reduce resource depletion, and create economic opportunities (Frimpong et al., 2024). These examples underscore the transformative potential of technology in promoting sustainable resource management in SSA.

2.2 Digitalisation-resource management

The digitalization-natural resource represents the intersection between digital technologies and the management, utilization, and conservation of natural resources. This highlights the transformative impact of digitalisation on how societies extract, process, and interact with natural resources, while also influencing environmental outcomes (Guan et al., 2024). Digital technologies, including data analytics, artificial intelligence, Internet of Things (IoT), and remote sensing, have revolutionized various aspects of natural resource management, from monitoring and assessment to decision-making and conservation efforts (UNEP, 2021).

At its core, the digitalization-natural resource embodies the potential for leveraging technology to enhance resource efficiency, sustainability, and resilience (Chen et al., 2024). Digital tools enable real-time monitoring of environmental parameters, resource extraction activities, and ecosystem health, allowing for more informed and adaptive management practices (Guan et al., 2024). For example, satellite imagery and remote sensing technologies facilitate the monitoring of deforestation, land degradation, and water quality, enabling proactive interventions to mitigate environmental impacts (Haq et al., 2024).

Furthermore, digitalization facilitates the optimization of resource utilization through predictive modeling, simulation, and optimization algorithms (Ma et al., 2024). Smart grids, for instance, utilize digital technologies to optimize energy distribution, reduce transmission losses, and integrate renewable energy sources, contributing to more efficient and sustainable energy systems (Khan and Hou, 2021). Similarly, digitalization enhances resource recovery and recycling processes, minimizing waste generation and promoting circular economy principles (Liu et al., 2023).

In SSA, the digitalization-natural resource is reshaping sectors such as agriculture, water management, and energy (FAO, 2020; IRENA, 2022; UN-Water, 2018). For instance, digital technologies like remote sensing and data analytics are improving crop monitoring and weather forecasting, empowering smallholder farmers with real-time information to enhance productivity (Gacula, 2024). Similarly, in water management, digital solutions are optimizing water distribution networks and monitoring water quality, addressing challenges of scarcity and inefficiency (UN-Water, 2018). Furthermore, in the energy sector, digital technologies are facilitating the integration of renewable energy sources and improving energy access in rural areas through innovations like smart meters and solar-powered mini-grids (GOGLA, 2021; IRENA, 2022).

2.3 The hypotheses

The preceding discussion has brought forth three empirical inquiries concerning the relationship among environmental policy-technology-digitalisation and natural resource management. Firstly, will the implementation of more stringent environmental policies influence resource management practices and outcomes in SSA? Secondly, can technological advancements enhance the effectiveness of natural resource management strategies within the region? Lastly, does the development of digitalisation, particularly through increased fixed broadband subscriptions and digital infrastructure, contribute to promoting sustainable resource management practices in SSA? The responses to these inquiries hold significant implications for policymakers. Should the answer to the first question be affirmative: it suggests that stricter environmental policies need not necessarily impede economic progress; instead, they could spur technological innovation, thereby enhancing corporate competitiveness and fostering economic growth. Moreover, an affirmative response to the second question implies the imperative for policymakers to embrace technological innovation as a driver for achieving sustainable development. Finally, if the answer to the third question is affirmative, it underscores the unforeseen benefits of strong environmental regulations in stimulating eco-friendly technological innovation and enhancing sustainable resources management.

Based on these three related questions, we test the following hypotheses in the context of SSA:

H1: Implementation of stringent environmental policies positively influences resource management practices and outcomes in SSA.

H2: Technological advancements have a positive impact on the effectiveness of natural resource management strategies in the region.

H3: Development of digitalisation, characterized by increased fixed broadband subscriptions and digital infrastructure, fosters sustainable resource management practices in SSA.

To ensure comprehensiveness, we consider various factors that are recognized to impact environmental policy-technology-digitalization, and natural resource management in the region (Abdulqadir, 2024).

3. Data and Methodology

3.1 Model estimation

Based on the hypotheses in Section 2, we formulate Equation (1) that captures the relationship between environmental policy-technological innovations-digitalisation and natural resources management.

$$NR = f(EP, TI, D) \quad (1)$$

where NR denotes total natural resource rent, EP denote environmental policy (business regulatory environment (BRE), policy and institutions for environmental sustainability (PIES) and policies for social inclusion (PSI)), Technological innovations denote (ICT goods exports (% of total goods exports) (ICTGE) and ICT goods imports (% total goods imports) (ICTGI)) and digitalisation denotes (fixed broadband subscriptions (per 100 people) (FBS1) and fixed broadband subscription (FBS)).

Intuitively, we incorporate the natural logarithm of the variables in the econometric equation for natural resources management in Equation (2):

$$ln(NR) = \alpha + \beta_1 ln(EP) + \beta_2 ln(TI) + \beta_3 \ln(D) + \beta_4 \ln(CONTROL) + \varepsilon \quad (2)$$

ln(*NR*) represents the natural logarithm of total natural resource rent, capturing the log-linear relationship between natural resource management and the explanatory variables. ln(*EP*), ln(*TI*), and ln(*D*) denote the natural logarithms of environmental policy, technological innovations, and digitalisation, respectively. These variables are log-transformed to address potential nonlinear relationships and facilitate interpretation. ln(*CONTROL*) represents the natural logarithm of control variables included in the model. α is the intercept term, indicating the baseline level of natural resource rent when all explanatory variables are zero. $\beta1$, $\beta2$, $\beta3$, $\beta4$ are the coefficients associated with the respective explanatory variables, representing the marginal effects of environmental policy, technological innovations, digitalisation, and control variables on natural resource rent. ε denotes the error term, capturing unobserved factors that influence natural resource management but are not accounted for in the model.

Table 1 presents the analysis of the relationships between environmental policy-technological innovations-digitalisation, and natural resource across 29 SSA countries[1] from 1999-2022. The data was sourced from the World Bank Development Indicators, [WDI], (2024). The countries were divided into 12 resource-rich and 17 resource-poor countries in SSA. According to the IMF (2013), a country is deemed 'resource-rich' when exports of non-

[1] List of countries: **Resources-rich countries** are Cameroon, Central African Republic, Ghana, Guinea, Kenya, Mali, Mozambique, Niger, Nigeria, Tanzania, Zambia and Zimbabwe**. Resources-poor countries**: Benin, Burkina Faso, Burundi, Cabo Verde, Comoros, Cote D'Ivoire, Ethiopia, Gambia The, Lesotho, Madagascar, Malawi, Mauritania, Rwanda, Sao Tome and Principe, Senegal, Togo and Uganda.

renewable natural resources such as oil, minerals, and metals constitute more than 25% of the value of the country's total exports. These resource-rich countries are the primary drivers of the SSA economy, contributing to over 80% of the total GDP of SSA. Notably, the export of non-renewable natural resources from SSA surged from US$56 billion in 2002 to US$288 billion in 2012, as reported by the (IMF, 2013).

Natural resource is measured by the total natural resource rents as a percentage of GDP, indicating the income derived from natural resource extraction. When using the World Development Indicators (WDI) (World Bank, 2024), the stringency of environmental policies is often measured through proxies that reflect governance quality and institutional effectiveness. For instance, the CPIA Policy and Institutions for Environmental Sustainability Rating (PIES) evaluates the strength of policies supporting environmental sustainability, while the CPIA Business Regulatory Environment Rating (BRE) assesses the conduciveness of regulatory frameworks to sustainability integration. Additionally, the CPIA Policies for Social Inclusion/Equity Cluster Average (PSI) and Voice and Accountability (V&A) measure inclusiveness and citizen participation, which are critical for the enforcement and societal acceptance of environmental policies (Manu et al., 2024). These indicators, sourced from the WDI and complementary datasets such as the Worldwide Governance Indicators (WGI), provide researchers with tools to quantify environmental policy stringency, compare governance effectiveness across regions, and analyze the interaction between regulatory quality and environmental sustainability. Technological innovations are captured by two indicators: the ICT Goods Exports (% of Total Goods Exports) (ICTGE), reflecting a country's technological competitiveness in ICT goods, and the ICT Goods Imports (% of Total Goods Imports) (ICTGI), indicating dependence on imported ICT products *inter alia* (Manu et al., 2024). Digitalisation represented by fixed broadband subscriptions (per 100 people) (FBS1), measuring broadband penetration, and fixed broadband subscription (FBS), quantifying the absolute number of broadband subscriptions, reflecting broadband infrastructure availability. The analysis employs Panel Vector Autoregression (PVAR) to account for cross-sectional dependencies and temporal dynamics in the relationships between these variables over the study period.

We controlled for several key economic indicators to better understand their influence on the relationship between environmental policy-technological innovations-digitalisation, and natural resource in SSA. Specifically, we included measures of economic growth, industrialization, and manufacturing activity. Economic growth was represented by GDP per capita (constant 2015 US$), which provides a standardized measure of economic output per person across different countries and time periods. Industrialization was captured by the percentage of industry (including construction) value added as a share of GDP, reflecting the contribution of industrial activities to overall economic output. Similarly, manufacturing activity was assessed using the percentage of manufacturing value added as a share of GDP, indicating the importance of manufacturing sector activities in driving economic growth and development. By controlling for these economic variables, we aimed to isolate the effects of environmental policies on sustainable development outcomes while accounting for the broader economic context in which these policies are implemented.

Table 1. Variables description

Variables	Measurements	Sources
Natural resource management	Total natural resources rents (% of GDP)	WDI
Environmental policy	CPIA business regulatory environment rating (1=low to 6=high) (BRE)	WDI
	CPIA policy and institutions for environmental sustainability rating (1=low to 6=high) (PIES)	WDI
	CPIA policies for social inclusion/equity cluster average (1=low to 6=high) (PSI)	WDI
	Voice and accountability (V & A)	
Technological innovations	ICT goods exports (% of total goods exports) (ICTGE)	WDI
	ICT goods imports (% total goods imports) (ICTGI)	WDI
Digitalisation	Fixed broadband subscriptions (per 100 people) (FBS1)	WDI
	Fixed broadband subscription (FBS)	WDI
Economic growth	GDP per capita (constant 2015 US$)	WDI
Manufacturing	Manufacturing, value added (% of GDP)	WDI
Industrialisation	Industry (including construction), value added (constant LCU)	WDI

Note: WDI World Bank Development Indicators, [WDI], (2024).

3.2 Econometric Approach

3.2.1 Panel Vector Autoregression (PVAR)

We incorporate the panel vector autoregression (PVAR) into Equation (1), we extend the model to capture the dynamic interactions among the variables over time. The PVAR framework allows us to analyze the simultaneous relationships between multiple variables in a panel dataset. The PVAR specification for Equation (1) as follows in Equation (3):

$$\boldsymbol{NR_{it}} = \boldsymbol{\alpha_i} + \boldsymbol{\beta_{1i}EP_{it}} + \boldsymbol{\beta_{2i}TI_{it}} + \boldsymbol{\beta_{3i}D_{it}} + \boldsymbol{\varepsilon_{it}} \tag{3}$$

$\boldsymbol{NR_{it}}$ represents the natural resource management variable for country *i* at time *t*. $\boldsymbol{EP_{it}}$, $\boldsymbol{TI_{it}}$, and $\boldsymbol{D_{it}}$ denote the environmental policy, technological innovations, and digitalisation for country *i* at time *t*, respectively. *ai* is the country-specific intercept, capturing the baseline level of natural resource management for each country. $\boldsymbol{\beta_{1i}}$, $\boldsymbol{\beta_{2i}}$, and $\boldsymbol{\beta_{3i}}$ are the country-specific coefficients associated with the respective explanatory variables, representing the marginal effects of environmental policy, technological innovations, and digitalisation on natural resource management. $\boldsymbol{\varepsilon_{it}}$ is the error term, capturing unobserved factors affecting natural resource management for country *i* at time *t*.

We extend the framework for estimating the dynamic responses of natural resource management to shocks in environmental policy-technological innovations, and digitalisation using a panel vector autoregression (PVAR) model and analyzing the impulse response functions in Equation (4).

$$Y_t = \alpha + \sum_{i=1}^{p} A_i Y_{t-i} + \sum_{j=1}^{m} B_j X_{t-j} + \varepsilon_t \quad (4)$$

Y_t is the vector of endogenous variables (including natural resource management). *Xt* is the vector of exogenous variables (including environmental policy, technological innovations, and digitalisation). A_i and B_j are coefficient matrices. *p* and *m* denote the number of lags for endogenous and exogenous variables, respectively. ε_t is the error term.

3.2.2 Impulse Response Function (IRF)

The impulse response function (IRF) is provided in Equation (5) as follows:

$$\Delta Y_t = \sum_{j=0}^{h} C_j \Delta X_{t-j} + \eta_t \quad (5)$$

Where ΔY_t is the change in the vector of endogenous variables (natural resource management). ΔX_{t-j} is the change in the vector of exogenous variables (environmental policy, technological innovations, and the digitalisation). C_j is the impulse response coefficient matrix capturing the dynamic response of Y_t to shocks in X_t. *h* is the number of periods over which the response is traced. η_t is the error term.

3.2.3 Variance Decomposition

The variance decomposition analysis allows us to understand the relative importance of different shocks in explaining the variability of natural resource management, within the context of a panel vector autoregression (PVAR) model. Equation (6) entailing variance decomposition can be represented as follows:

$$\Sigma = \sum_{i=1}^{p} A_i \Sigma \acute{A}_\iota + \sum_{j=1}^{m} B_j \, \Omega B_{j'} + \Psi \quad (6)$$

where Σ is the covariance matrix of the residuals (εt). Ω is the covariance matrix of the shocks to the exogenous variables. Ψ is the covariance matrix of the initial errors. The variance decomposition analysis calculates the proportion of the variance of natural resource management explained by each shock, including shocks to the endogenous variables (autoregressive shocks) and shocks to the exogenous variables (innovation or structural shocks).

By decomposing the variance, we can assess the relative importance of different factors, such as environmental policy, technological innovations, and digitalisation, in explaining the fluctuations in natural resource management over time. This analysis provides valuable insights into the drivers of variability in natural resource management and helps policymakers prioritize interventions to address the most influential factors.

3.2.4 Granger Causality

In a panel vector autoregression (PVAR) model, Granger causality can be tested between variables to determine if one variable can predict another (Granger, 1988). The general equation for testing Granger causality between two variables, say, variable *X* and variable *Y*, in a PVAR model is provided as follows in Equation (7):

$$NR_{it} = \alpha_i + \sum_{j=1}^{p} \beta_j EP_{i,t-j} + \varepsilon_{it} \tag{7}$$

NR_{it} represents natural resources management at time *t* for unit *i*. α_i is the unit-specific intercept or constant term. $\sum_{j=1}^{p} \beta_j EP_{i,t-j}$ is the sum of lagged values of environmental policy (EP) as predictors of natural resources management, where p represents the number of lagged terms included in the model, and βj are the coefficients associated with each lag. ε_{it} is the error term or residual, representing the difference between the observed value of natural resources management and the value predicted by the model. This equation tests whether past values of environmental policy (EP) can predict current values of natural resources management (NR). If the coefficients β_j are statistically significant, it suggests that past values of EP Granger cause NR, indicating a predictive relationship between environmental policy and natural resources management.

4. Empirical Results and Discussion

4.1. Environmental Policy-Resources Management nexus

Table 2 presents the results of the PVAR analysis, examining the relationship between environmental policy and resource management in both resource-rich and resource-poor countries in SSA. The findings highlight the critical role of policies and governance structures in shaping natural resources management practices.

In resource-rich countries, the results indicate that total natural resources rents (TNR) have a negative but statistically insignificant impact on resource management practices (Model 1). This suggests that fluctuations in natural resource rents, as a percentage of GDP, do not significantly influence management practices, aligning with the literature that emphasizes the resource curse and the challenges in managing abundant resources (Sachs and Warner, 2001; Tsani, 2013). In contrast, the business regulatory environment (BRE) in Model 2 shows a highly significant positive impact on resource management. With a coefficient of 1.851, a one-unit increase in BRE leads to a 185.1% improvement in natural resources management practices, underlining the importance of a favorable regulatory environment in fostering effective resource management and technological innovation, as discussed by Porter and Linde (1995).

Further, policy and institutions for environmental sustainability (PIES) in Model 3 exhibit a significant positive relationship with natural resources management. A one-unit increase in PIES corresponds to a 556.8% enhancement in management practices, highlighting the vital role of strong policies and institutions in promoting environmental sustainability (Musah et al., 2023; Sachs & Warner, 2001). Similarly, policies for social inclusion (PSI) in Model 4 show a significant positive effect, with a 275.7% improvement in natural resource management practices. This reinforces the importance of inclusive policies in mitigating environmental degradation and advancing sustainable resource management, as supported by (Oyewole et al., 2019 and Sheba and Bello 2020).

Voice and accountability (VA) in Model 5 also demonstrate a positive yet modest impact, with a 2.7% improvement in resource management practices. This suggests that enhancing governance and citizen engagement mechanisms can contribute to more effective resource management, as highlighted by (Kragelund 2020). Models 6 and 7 reveal that economic growth (GDP) and manufacturing activity both have significant positive impacts on natural resources management, with coefficients of 1.991 and 0.445, respectively. These results suggest that economic development and industrial activity can drive improvements in resource management practices, supporting the view that economic growth stimulates innovation and investment in cleaner technologies (UNEP, 2012; UNEP, 2021). However, it is essential to recognize the complexities associated with industrialization, as it can also lead to increased resource exploitation and environmental degradation if not carefully managed (IRENA, 2022).

Model 8 presents an interesting finding: industry has a negative impact on natural resources management, with a coefficient of -0.123. This suggests that industrial activities, if not adequately regulated, may exacerbate environmental degradation, as indicated by the negative environmental externalities often associated with industrialization (Stern, 2008).

In resource-poor countries, the results are more pronounced. TNR in Model 9 shows a significant negative impact on resource management, with a coefficient of -0.804. This highlights the challenges faced by resource-poor countries, where fluctuations in resource availability significantly affect management practices. However, the BRE again demonstrates a significant positive effect, with a coefficient of 0.587, suggesting that regulatory frameworks play an essential role in improving management practices in resource-poor countries. Interestingly, PIES has a negligible impact, with a coefficient of 0.038, indicating that policies for environmental sustainability may be less influential in resource-poor settings, perhaps due to the absence of sufficient resources for implementation.

Voice and accountability (VA) in resource-poor countries, on the other hand, show a significant positive impact (0.117), emphasizing the importance of governance structures and citizen engagement in improving resource management practices. Similarly, GDP has a significant positive effect, with a coefficient of 0.793, suggesting that higher economic development leads to better management practices, reinforcing the literature on the link between economic growth and environmental governance (Ahmed et al., 2020).

Finally, the positive coefficients for manufacturing and industry (0.043 and 0.259, respectively) indicate that industrial activities contribute to improved resource management in resource-poor countries. This suggests that economic activities, even in resource-scarce settings, can still play a role in enhancing resource management, though the environmental impacts of industrial growth must be carefully monitored.

In summary, these results support the empirical literature emphasizing the importance of governance, regulatory frameworks, and economic development in shaping effective resource management practices. While resource-rich countries benefit from abundant resources and strong policies, resource-poor countries face significant challenges related to resource scarcity. Nevertheless, both groups can improve their resource management practices through tailored policies that address their unique circumstances (Ahmad et al., 2020; Jahanger et al., 2022).

Table 2. PVAR GMM-Style results

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)
TNR	-0.106 (0.089)	1.851*** (0.246)	5.568*** (0.445)	2.757*** (0.402)	0.027*** (0.055)	1.991*** (0.569)	0.445*** (0.097)	-0.123** (0.243)	-0.804*** (0.051)	0.587** (0.248)	0.038 (0.201)	-0.271 (0.322)	0.117** (0.049)	0.793** (0.242)	0.043 (0.062)	0.259** (0.089)
BRE	0.010* (0.005)	0.878*** (0.026)	-0.058** (0.022)	0.196*** (0.023)	-0.008** (0.003)	0.046 (0.038)	-0.001 (0.007)	-0.016 (0.016)	-0.005 (0.008)	0.839*** (0.049)	0.098** (0.031)	0.045 (0.036)	0.005 (0.008)	0.084** (0.039)	0.011 (0.012)	-0.042** (0.016)
PIES	0.010 (0.007)	-0.090*** (0.022)	0.593*** (0.038)	0.383*** (0.040)	0.001 (0.004)	0.172** (0.052)	0.062*** (0.008)	-0.038** (0.023)	-0.017 (0.011)	0.172*** (0.041)	0.835*** (0.044)	0.190*** (0.063)	0.006 (0.010)	0.083 (0.051)	-0.013 (0.012)	-0.021 (0.020)
PSI	-0.007** (0.003)	0.013 (0.012)	-0.028 (0.013)	1.000*** (0.019)	0.006** (0.002)	0.017 (0.023)	0.009** (0.003)	0.000 (0.010)	-0.004 (0.004)	0.082** (0.024)	-0.064** (0.019)	1.067*** (0.027)	0.004 (0.005)	-0.019 (0.025)	-0.016** (0.006)	0.010 (0.010)
VA	1.466*** (0.208)	-7.903*** (0.572)	-9.853*** (0.694)	14.033*** (0.918)	-0.372** (0.139)	15.817*** (1.406)	0.191 (0.197)	-5.367*** (0.580)	-0.150* (0.066)	-0.261 (0.261)	0.773* (0.305)	-1.347* (0.586)	1.154*** (0.085)	-2.257*** (0.461)	-0.066 (0.082)	0.711*** (0.161)
GDP	0.145*** (0.012)	-0.398*** (0.027)	0.222*** (0.035)	0.219*** (0.042)	-0.046*** (0.006)	1.003*** (0.062)	-0.002 (0.012)	-0.027 (0.028)	-0.020* (0.009)	0.039 (0.031)	-0.055* (0.024)	0.171*** (0.039)	0.029*** (0.008)	0.805*** (0.039)	-0.004 (0.010)	0.051** (0.015)
MANUF	0.001 (0.022)	1.316*** (0.070)	0.566*** (0.074)	-0.879*** (0.089)	0.069*** (0.014)	-0.990*** (0.115)	0.952*** (0.029)	0.387*** (0.051)	-0.008 (0.034)	-0.620*** (0.168)	0.203 (0.127)	0.120 (0.191)	0.017 (0.034)	0.030 (0.193)	1.073*** (0.047)	-0.046 (0.078)
INDUSTRY	0.059*** (0.013)	-0.218*** (0.026)	0.473*** (0.035)	-0.151*** (0.043)	-0.014 (0.006)	-0.061 (0.064)	-0.099*** (0.014)	0.942*** (0.027)	-0.071*** (0.018)	-0.133 (0.085)	-0.028 (0.075)	0.251** (0.109)	0.077** (0.023)	-0.532*** (0.129)	-0.046* (0.025)	1.145*** (0.046)

Note: ***, **, * indicate statistical significance at the 1%, 5% and 10% levels, respectively. Standard errors in parentheses. To conserve space, the interpretation is based on the first row in Model (1)-(8) for **resources-rich countries** and Model (9)-(16) for **resources-poor countries** where total natural resources is the dependent in the PVAR model.

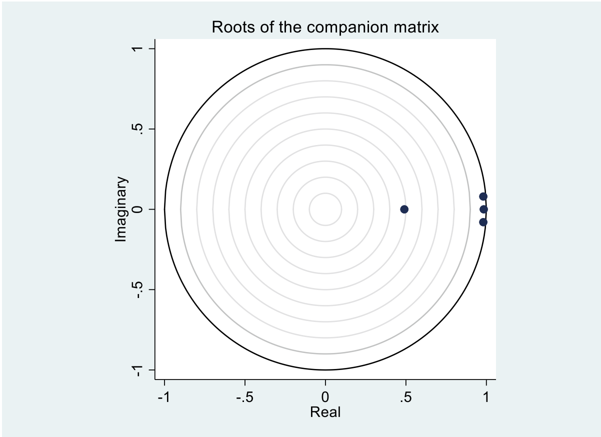

Figure 1. Stability Graph (Resources-rich)

The stability graph satisfies resources-rich countries within the context of environmental policy-resources management. A stable relationship between environmental policy-resources management is distinguished by coefficients that maintain relative consistency, signifying a reliable and foreseeable impact of environmental policy-resources management or vice versa. Conversely, notable fluctuations in these coefficients indicate instability, likely stemming from shifting dynamics or external influences. Such stability typically fosters enhanced resource efficiency, diminished pollution, and the preservation of ecosystems, all contributing positively to environmental quality and sustainability (Chen et al., 2023). Furthermore, stable relationships facilitate the strategic planning and execution of measures to tackle environmental challenges like climate change, deforestation, and habitat destruction (Manu et al., 2022).

4.2 Technology-Resources Management Nexus

Table 3 presents the results of the PVAR analysis, investigating the relationship between technology and resource management in both resource-rich and resource-poor countries in SSA. The findings emphasize the significant role that natural resource revenues, technology, and economic growth play in shaping resource management practices, with notable differences between resource-rich and resource-poor countries.

In resource-rich countries, the positive coefficient of 0.575 for total natural resource rents (TNR) in Model 1 highlights the substantial influence of revenues derived from natural resources on resource management practices. This suggests that countries with higher natural resource income are more likely to invest in sustainable resource management strategies, leading to a 57.5% improvement in such practices. This supports the notion that financial resources from natural wealth can be leveraged for conservation efforts, environmental protection, and responsible resource utilization (Gacula, 2024; He et al., 2024). This finding aligns with the resource curse hypothesis, which suggests that while natural wealth can spur economic growth, it also necessitates effective management to avoid negative outcomes like environmental degradation and inefficiency (Sachs & Warner, 2001).

Moreover, in Models 2 and 3, the coefficients for information and communication technology (ICT) goods exports (% of total goods exports) and ICT goods imports (% of total goods imports) further emphasize the role of technology in resource management. The positive coefficients of 0.064 and 0.036, respectively, indicate that countries with higher proportions of ICT goods in their trade exhibit improved resource management practices. These results suggest that access to advanced ICT solutions through international trade contributes to a 6.4% and 3.6% improvement in resource management, respectively. This underscores the importance of technological advancements in facilitating efficient monitoring, planning, and conservation efforts, in line with the findings of (Stern and Kander 2012 and Xie et al.,2024).

The significant positive impact of GDP on resource management practices, with a coefficient of 1.930, indicates that economic growth plays a crucial role in promoting environmental protection and sustainable development initiatives. A one-unit increase in GDP results in a 193% improvement in resource management, suggesting that economic growth can drive investments in conservation and sustainable resource use across SSA. This finding aligns with the literature suggesting that economic growth is a key driver of environmental protection efforts (Ahmed et al., 2020). However, the negative coefficient for industrial activity (-0.725) highlights the adverse impact of industrialization on resource management. This suggests that higher levels of industrialization are associated with a 72.5% decrease in effective management practices, as industries contribute to environmental degradation through pollution, resource depletion, and habitat destruction (Abdulqadir, 2024; Manu et al., 2024). These results point to the need for balancing industrial development with sustainable practices to minimize environmental harm.

In resource-poor countries, TNR again shows a positive and statistically significant impact on resource management, with a contribution of approximately 89.7% to the variability in management practices. This reinforces the idea that natural resource revenues can play a pivotal role in improving resource management, even in countries with fewer resources (Barrera-Santana et al., 2022). However, the impact of ICT goods exports (ICTGE) is negligible in this context, contributing only 0.9%, suggesting limited influence on resource management practices in resource-poor countries. Conversely, ICT goods imports (ICTGI) demonstrate a significant positive effect, contributing approximately 11.2%, highlighting the importance of importing ICT technologies to enhance resource management in resource-poor settings. This finding is consistent with the literature suggesting that technology imports can be an important driver of improved resource management practices, particularly in developing countries (Chen et al., 2022).

GDP, while exhibiting a negative impact on resource management practices in resource-poor countries, is not statistically significant. The coefficient of -0.615 suggests that higher GDP levels may not necessarily lead to better resource management in these countries, a finding that contrasts with the positive relationship observed in resource-rich countries. This may be due to the fact that economic growth in resource-poor countries does not always result in investments in environmental protection or resource management (Uz Zaman et al., 2024). Additionally, manufacturing and industrial activity show negative impacts, although not statistically significant, suggesting that industrialization in resource-poor countries may exacerbate environmental challenges without proper management.

In conclusion, the results highlight the varying impacts of natural resources, technology, and economic indicators on resource management practices across resource-rich and resource-poor countries. Resource-rich countries benefit significantly from their natural resource revenues, which can be directed towards improving management practices, while technology and economic growth also play important roles. In contrast, resource-poor countries face greater challenges in resource management, but the import of ICT goods and improvements in governance can still enhance management practices. These findings align with the empirical literature, which underscores the need for tailored policies that account for the unique challenges faced by countries based on their resource endowments and economic conditions (Acheampong, 2023; Barrera-Santana et al., 2022).

Table 3. PVAR GMM-Style results

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
TNR	0.575***	0.064**	0.036**	1.930***	0.099	-0.725***	-0.897***	0.009	0.112**	-0.615	-0.089	0.285
	(0.103)	(0.019)	(0.021)	(0.701)	(0.113)	(0.301)	(0.053)	(0.010)	(0.043)	(0.453)	(0.093)	(0.182)
ICTGE	1.352**	0.044	-0.139	21.442***	-0.529	-8.395***	0.213	0.733***	-0.043	2.459	-0.555	-1.054
	(0.578)	(0.105)	(0.143)	(3.956)	(0.614)	(1.630)	(0.202)	(0.057)	(0.190)	(2.196)	(0.396)	(0.874)
ICTGI	0.396***	-0.021	0.405***	2.140***	-0.348**	-0.893***	0.048	0.028*	0.427***	0.912	0.324*	-0.621*
	(0.114)	(0.019)	(0.071)	(0.739)	(0.152)	(0.301)	(0.074)	(0.014)	(0.082)	(0.787)	(0.137)	(0.286)
GDP	0.027*	0.011***	-0.004	0.508***	-0.037**	0.186***	0.011	0.004**	0.007	0.883***	-0.009	0.047*
	(0.014)	(0.003)	(0.004)	(0.106)	(0.020)	(0.043)	(0.007)	(0.001)	(0.006)	(0.061)	(0.011)	(0.024)
MANUF	0.061**	0.014**	-0.037***	0.142	0.930***	-0.043	-0.037	-0.002	-0.037**	-0.300	1.009***	0.123
	(0.022)	(0.005)	(0.010)	(0.167)	(0.033)	(0.071)	(0.026)	(0.005)	(0.021)	(0.268)	(0.042)	(0.097)
INDUSTRY	0.005	0.008**	-0.005	-0.190**	-0.108***	1.036***	0.032*	0.008***	-0.014	0.124	-0.001	0.956***
	(0.018)	(0.004)	(0.004)	(0.097)	(0.023)	(0.041)	(0.013)	(0.002)	(0.011)	(0.111)	(0.021)	(0.045)

Note: ***, **, * indicate statistical significance at the 1%, 5% and 10% levels, respectively. Standard errors in parentheses. To conserve space, the interpretation is based on the first row in Model (1)-(6) for resources-rich countries and Model (7)-(12) for resources-poor countries where total natural resources is the dependent in the PVAR model.

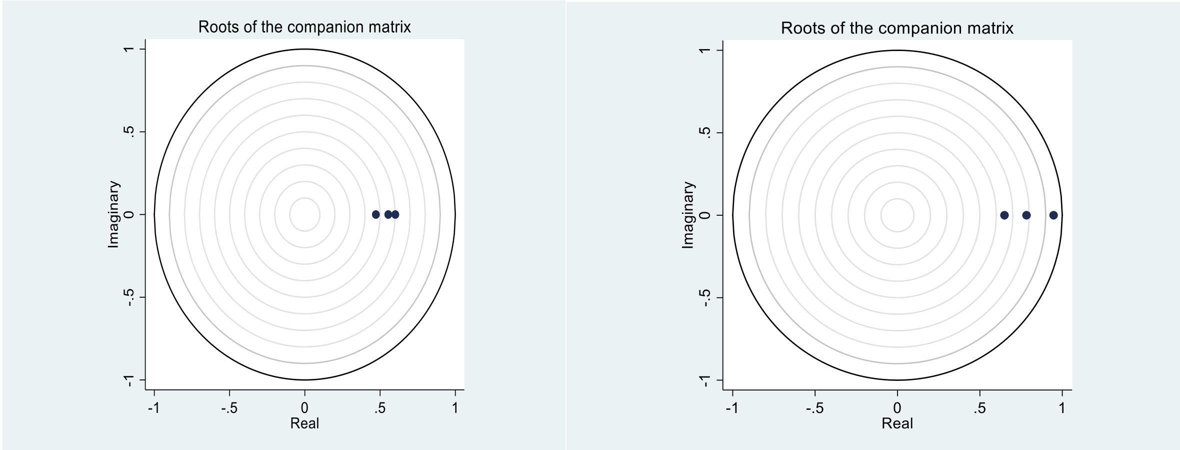

Figure 2. Stability Graph (Resources-rich and Resources-poor countries)

The stability graph displays the estimated coefficients of each variable in the PVAR model over time, facilitating the assessment of the relationships between technology-resources management over time or exhibit significant fluctuations. The stable relationships in technology-resources management can lead to more predictable and sustainable resource utilization practices. This stability fosters better long-term planning and management strategies, which can help mitigate environmental degradation, preserve biodiversity, and promote the efficient use of natural resources. Conversely, significant fluctuations in these relationships may lead to erratic resource management practices, contributing to environmental degradation, habitat loss, and biodiversity decline (Ntarmah et al., 2021). Therefore, maintaining stable relationships in technology-resources management is crucial for achieving environmental sustainability and ensuring the long-term health of ecosystems in SSA (Xuezhou et al., 2021).

4.3 Digitalisation-Resources Management Nexus

Table 4 presents the results of the PVAR analysis, which examines the relationship between digitalization and resource management in both resource-rich and resource-poor countries in SSA. The findings highlight the significant role of natural resource abundance, digital infrastructure, and economic growth in shaping effective resource management strategies, with marked differences between resource-rich and resource-poor countries.

In resource-rich countries, the coefficient of 0.022 for total natural resources (TNR) indicates that an increase in natural resource abundance positively influences resource management practices. Specifically, a one-unit increase in TNR results in a 2.2% improvement in management practices, reinforcing the notion that resource wealth can provide the financial capacity to invest in sustainable management and conservation efforts (Guan et al., 2024). This finding is consistent with the literature on the "resource curse," which suggests that while abundant natural resources present opportunities for development, effective management practices are essential to ensure that these resources are utilized sustainably (Sachs & Warner, 2001).

Furthermore, fixed broadband subscriptions per 100 people (FBS1) and total fixed broadband subscriptions (FBS) demonstrate a strong positive association with resource management, with coefficients of 1.946 and 1.949, respectively, both significant at the 1% level. These results highlight the transformative role of broadband infrastructure in improving resource management practices. Specifically, a one-unit increase in FBS1 results in a 194.6% improvement in management practices, emphasizing the importance of digital connectivity in facilitating efficient resource monitoring, data sharing, and decision-making processes (Chen et al., 2024). This aligns with the growing body of literature that underscores the role of digital infrastructure in enhancing governance and environmental sustainability (UNEP, 2021).

In addition to digital infrastructure, economic growth plays a significant role in resource management. With a coefficient of 1.780, GDP shows a strong positive effect on resource management practices, suggesting that higher levels of economic output contribute to more effective management strategies. This is consistent with findings in the literature that economic growth can provide the resources needed for investment in sustainable development and environmental protection (Stern, 2017). Similarly, manufacturing and industry both exhibit positive coefficients of 0.747 and 1.791, respectively, suggesting that increased industrial and manufacturing activities can drive improvements in resource management practices. A 74.7% increase in manufacturing activity and a 179.1% rise in industrial activity are associated with enhanced resource management. This is in line with the notion that industrialization can lead to the development of better resource management technologies and practices (Torras, 2017).

In resource-poor countries, the availability of natural resources (TNR) remains a key factor in shaping resource management, with TNR contributing 98.6% to the overall variability in management practices. This highlights the critical role that resource availability plays in guiding management decisions in resource-poor contexts. However, the negative but negligible impact of broadband subscriptions (FBS1 and FBS), contributing -3.2% and -3.3%, suggests that digital infrastructure may not be as influential in resource-poor countries. This finding aligns with studies indicating that digital infrastructure often has limited effects in countries where basic resource needs and governance challenges take precedence over technological advancements (FAO, 2020; UN-Water, 2018).

Economic indicators such as GDP, manufacturing, and industry also show negative impacts, albeit to a lesser extent, suggesting that industrial and economic growth may not have the same positive influence on resource management practices in resource-poor countries as seen in their resource-rich counterparts. This is consistent with literature that suggests economic development in resource-poor countries does not always translate into improvements in environmental governance or resource management due to limited capacity, governance issues, or competing development priorities (IRENA, 2022; UN-Water, 2018).

Overall, the results suggest that in resource-rich countries, prioritizing digital infrastructure development, improving broadband access, and strengthening governance frameworks can enhance resource management practices. This is supported by the empirical literature, which highlights the positive impact of technology on improving monitoring systems, regulatory frameworks, and decision-making processes for sustainable resource use (UNEP, 2021). In contrast, in resource-poor countries, the findings emphasize the importance of natural resource availability and capacity-building initiatives to address the unique challenges these countries face in managing their resources. This includes fostering renewable energy initiatives, promoting conservation practices, and supporting community-based resource management approaches, all of which are key strategies recommended in the literature to reduce environmental harm and ensure sustainable resource use (GOGLA, 2021; IRENA, 2022).

In conclusion, these findings support the broader empirical literature by demonstrating that the interplay between digitalization, natural resource management, and economic development varies across resource-rich and resource-poor contexts. While resource abundance and digital infrastructure are critical drivers of sustainable resource management in wealthier nations, resource-poor countries face unique challenges that require tailored policies focused on sustainable use and capacity building.

Table 4. PVAR GMM-Style Results

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
TNR	0.022**	1.946***	1.949***	1.780***	0.747***	1.791***	0.986***	-0.029	-0.033	1.115	-0.067	-0.130
	(0.146)	(0.509)	(0.487)	(0.690)	(0.186)	(0.412)	(0.070)	(0.018)	(0.022)	(0.711)	(0.116)	(0.254)
FBS1	0.119	4.780***	-3.476***	-1.511**	0.299**	0.862**	0.770***	0.942***	-0.083	7.117***	0.221	-1.974**
	(0.121)	(0.505)	(0.481)	(0.860)	(0.115)	(0.444)	(0.183)	(0.071)	(0.080)	(1.716)	(0.274)	(0.619)
FBS	0.218	2.092***	-0.975**	-1.291	0.399***	1.160**	0.915***	0.088	0.742***	8.477***	0.223	-2.239**
	(0.134)	(0.449)	(0.429)	(0.858)	(0.126)	(0.449)	(0.221)	(0.062)	(0.078)	(2.089)	(0.321)	(0.720)
GDP	0.086***	-0.115***	0.122***	0.750**	-0.049***	0.001	0.040***	0.006**	-0.011***	1.128***	0.005	-0.014
	(0.018)	(0.065)	(0.063)	(0.081)	(0.014)	(0.051)	(0.009)	(0.002)	(0.002)	(0.075)	(0.012)	(0.025)
MANUF	0.112***	-0.371***	0.350***	-0.185	1.024***	0.070	-0.048*	-0.006	0.014	-0.718**	0.957***	0.230**
	(0.026)	(0.101)	(0.097)	(0.144)	(0.027)	(0.089)	(0.024)	(0.010)	(0.011)	(0.230)	(0.046)	(0.087)
INDUS	0.053*	-0.177*	0.189*	0.072	-0.100***	0.781***	0.075***	0.023***	-0.031***	0.527***	0.007	0.869***
	(0.028)	(0.088)	(0.085)	(0.103)	(0.020)	(0.069)	(0.017)	(0.004)	(0.005)	(0.135)	(0.025)	(0.050)

Note: ***, **, * indicate statistical significance at the 1%, 5% and 10% levels, respectively. Standard errors in parentheses. To conserve space, the interpretation is based on the first row in Model (1)-(6) for resources-rich countries and Model (7)-(12) for resources-poor countries where total natural resources is the dependent in the PVAR model.

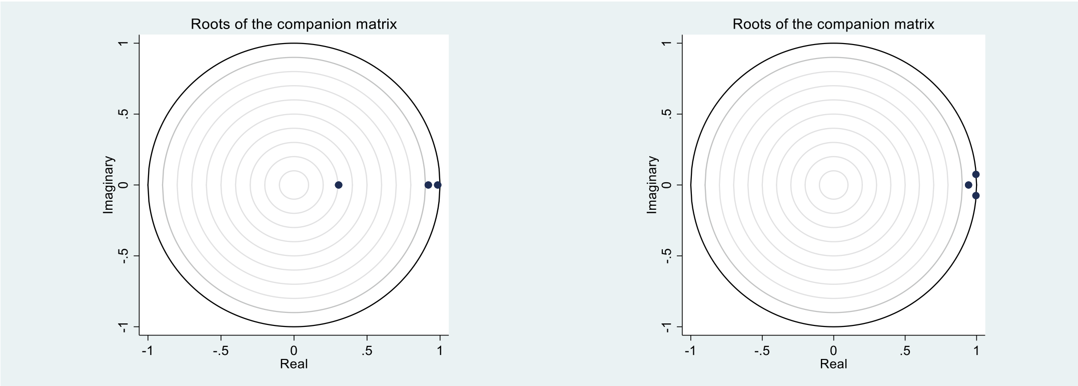

Figure 3. Stability Graph (Resources-rich and Resources-poor countries)

The stability graph for digitalisation-resources management tracks the consistency of estimated coefficients representing these factors over time or across different groups. Stability indicates a predictable impact of digitalisation on resources management, or vice versa, while fluctuations suggest instability. Stable relationships foster efficient resource use and environmental sustainability, facilitated by digital technologies (Manu et al., 2020). They enable better monitoring, analysis, and decision-making, resulting in reduced pollution, enhanced biodiversity conservation, and improved responses to environmental challenges like climate change and habitat loss.

4.4 IRF

Figures 4 and 5 present the Impulse Response Functions (IRFs), which illustrate how environmental policy, technological innovations, and digitalisation respond over time to a one-unit shock in natural resources. Initially, all variables show stability, with no immediate response at the forecast horizon of 0. However, as the shock propagates, distinct response patterns emerge for each variable. The business regulatory environment (BRE) and policies for environmental sustainability (PIES) display a positive response at the first forecast horizon, indicating an initial increase following the shock. This positive response persists in subsequent forecast horizons, although it gradually diminishes, remaining significant. These findings align with the empirical literature, which suggests that robust regulatory frameworks and sustainability policies are crucial for managing natural resource shocks, with effects that endure over time (Ma et al., 2024). Similarly, policies for social inclusion (PSI) show an initial positive response at forecast horizon 1, followed by a gradual decrease in subsequent horizons. Despite this decline, the response remains significant, underscoring the long-term impact of inclusive policies on resource management (Liu et al., 2023).

Voice and accountability, in contrast, exhibit no immediate response at the forecast horizon of 0 but show a significant positive response at forecast horizon 1, highlighting an immediate increase following the shock. This result, which diminishes over time but remains significant, supports the view that improvements in governance and citizen engagement can be crucial in adapting to shocks in resource availability, with sustained effects over time (Gacula, 2024). These findings underscore the lasting influence of institutional and policy factors in shaping responses to resource shocks, reinforcing existing research on the dynamic relationships between governance, policy, and resource management.

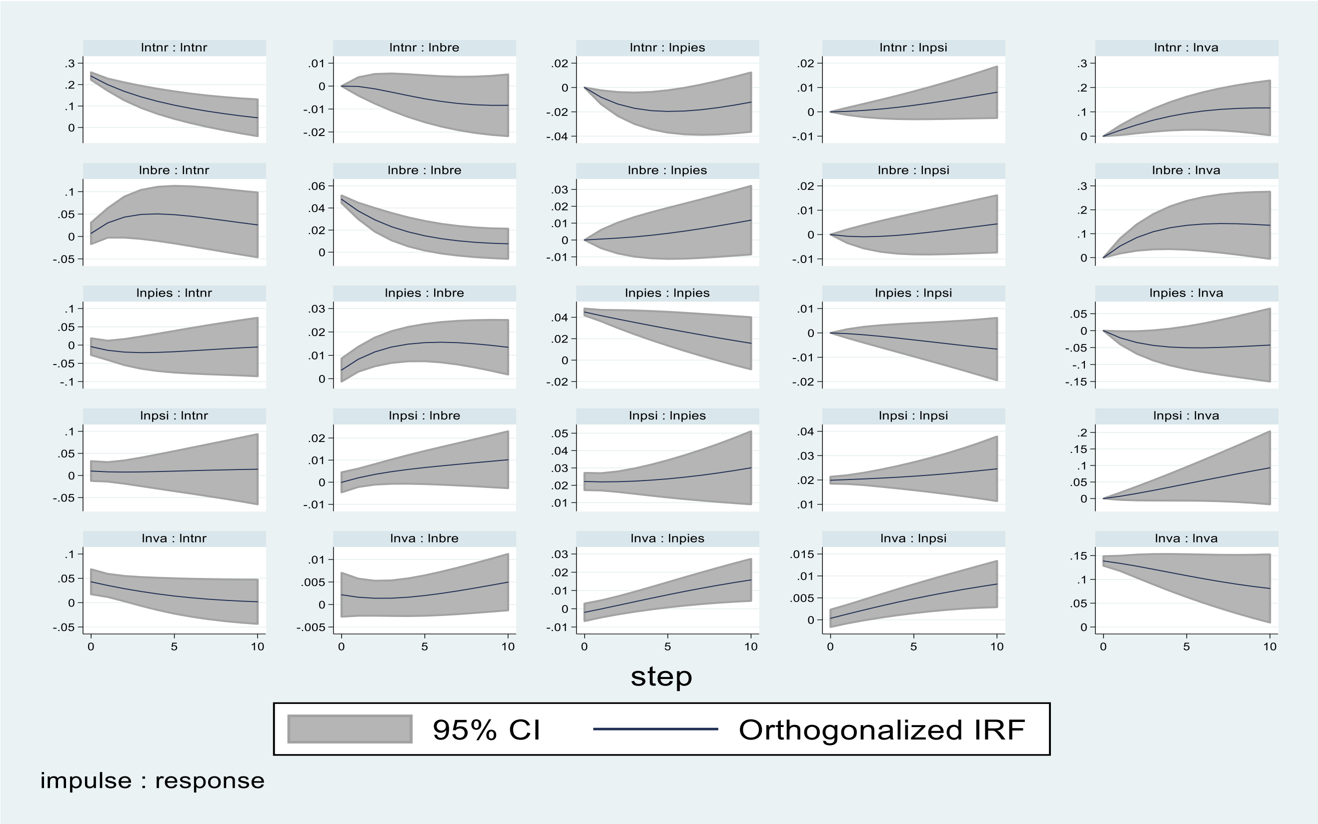

Figure 4. IRF Graph (Natural Resources-Environmental Policy)

In Figure 5, ICT goods exports (ICTGE) exhibit a positive response at the first forecast horizon, indicating an immediate increase following the shock in total natural resource rents (TNR). This positive response persists over subsequent horizons, gradually diminishing but remaining significant, suggesting a sustained impact of TNR on ICTGE. This finding aligns with empirical literature, which highlights the long-term relationship between natural resource availability and technological innovation, particularly in the digital economy (Parthiban et al., 2024). Similarly, ICT goods imports (ICTGI) show an immediate positive response at forecast horizon 1, followed by a gradual decrease over time while remaining significant, indicating a sustained yet diminishing impact on ICTGI from the shock in TNR. This supports the idea that shocks to resource availability can stimulate international trade in ICT goods, with diminishing effects as markets stabilize (Parthiban et al., 2024).

Additionally, fixed broadband subscriptions (FBS1 and FBS) display an initial positive response at forecast horizon 1, indicating an immediate increase following the shock. This positive response persists over subsequent horizons, gradually diminishing but remaining significant. These results highlight a sustained impact of TNR on FBS1 and FBS, reinforcing the importance of technological infrastructure in responding to resource shocks, as better connectivity can enhance resource management and economic growth (Frimpong et al., 2024). Together, these findings emphasize the enduring influence of technological and digital factors on resource management practices in the face of resource shocks, supporting the view that technological advancements can help mitigate the challenges posed by resource fluctuations.

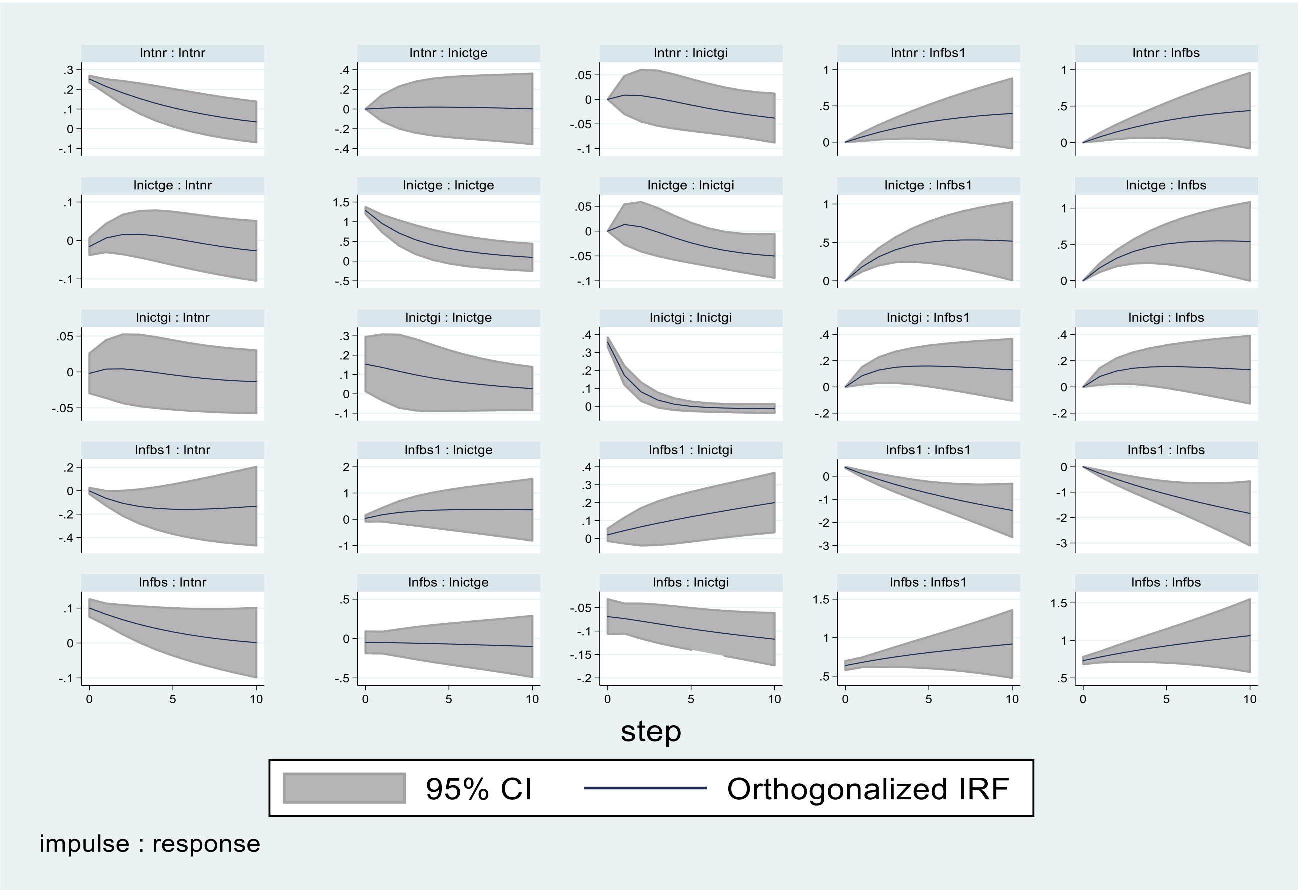

Figure 5. IRF Graph (Natural Resources-Technology-Digitalisation)

4.5 Variance decomposition

Table 5 presents the variance decomposition results, providing an insightful analysis of the relative contributions of environmental policy, technological innovations, and digitalisation to variations in natural resources management practices in both resource-rich and resource-poor countries within SSA.

In resource-rich countries, fixed broadband subscriptions (FBS1 and FBS) are the most influential factors in explaining the overall variance in resource management practices, contributing 29.0% and 36.5%, respectively. This suggests that advancements in broadband infrastructure play a crucial role in enhancing resource management by facilitating more efficient monitoring, data sharing, and decision-making processes. These findings align with existing literature that emphasizes the transformative impact of digital technologies on governance and resource management (Asongu et al., 2018). The substantial contribution of broadband infrastructure supports the argument that access to advanced ICT solutions can drive improvements in environmental monitoring and resource governance, particularly in resource-rich nations where the wealth from natural resources can be leveraged to invest in digital infrastructure.

Additionally, GDP emerges as a significant contributor, accounting for 6.0% of the overall variance. This reinforces the well-established notion that economic growth is closely linked to improved resource management, as higher GDP levels provide the financial capacity to invest in sustainable development initiatives and environmental protection measures (Stern & Kander, 2012). The contribution of manufacturing (0.5%) and industry (0.4%) also highlights the interconnectedness between industrial activities and resource management strategies, further supporting the idea that industrialization can either contribute to or hinder effective resource management, depending on the governance and technological frameworks in place (Stern & Kander, 2012).

The regulatory environment and political stability, represented by business regulatory environment (BRE), policy for social inclusion (PSI), and voice and accountability (VA), collectively contribute 9.8% to the overall variance. While these variables individually have modest impacts, their combined influence underscores the importance of institutional arrangements and political frameworks in shaping resource management practices. This is consistent with the literature that highlights the role of effective governance in facilitating sustainable resource management and mitigating the adverse effects of resource extraction (Xie et al., 2024; Barrera-Santana et al., 2022).

In contrast, in resource-poor countries, the primary driver of variability in resource management practices is total natural resources (TNR), which accounts for a striking 93.7% of the overall variance. This emphasizes that fluctuations in the availability of natural resources are the most significant determinant of resource management practices in these countries. As such, the findings align with the literature, which suggests that in resource-poor settings, natural resource availability directly influences the strategies adopted for resource management (Haq et al., 2024). The overwhelming influence of TNR highlights the dependence of resource-poor countries on the availability and management of natural resources as the primary source of income and development.

The contribution of the business regulatory environment (BRE) and policy for social inclusion (PSI) is more modest in resource-poor countries, with BRE contributing 1.5% and PSI contributing 1.4%. These findings are consistent with previous studies suggesting that while regulatory frameworks and social inclusion policies are important, their impact in resource-poor countries is often constrained by limited institutional capacity and governance challenges (Danish et al., 2019). Similarly, the contributions of voice and accountability (VA) and ICT goods exports (ICTGE) are relatively small, accounting for 0.4% and 0.8%, respectively. While governance structures and ICT goods exports may play a role in resource management, their effects in resource-poor countries appear to be limited compared to the overwhelming influence of natural resource availability (Erdogan et al., 2021).

Fixed broadband subscriptions (FBS1 and FBS) and GDP also make minimal contributions to the overall variance in resource-poor countries, each accounting for less than 0.1%. These results align with findings from the literature that digital infrastructure and economic growth, while important, have a more limited impact in contexts where natural resource abundance is scarce and where basic governance challenges dominate (FAO, 2020; IRENA, 2022).

Overall, the results from the variance decomposition analysis support the empirical literature by demonstrating that, in resource-rich countries, technological innovations, such as broadband infrastructure, along with economic indicators and institutional frameworks, play a significant role in shaping resource management practices. In contrast, in resource-poor countries, the availability of natural resources remains the dominant factor, with technological and economic variables contributing less significantly. These findings underscore the need for tailored strategies to address the unique challenges faced by countries with differing resource endowments. In resource-rich countries, leveraging digital infrastructure and strengthening governance frameworks can drive more sustainable resource management, while in resource-poor countries, enhancing natural resource management requires addressing governance challenges, promoting resource conservation, and implementing policies that prioritize sustainable use (Abid, 2017; Danish et al., 2019; Duodu et al., 2021).

Table 5. Variance Decomposition Results

Period	TNR	BRE	PIES	PSI	VA	ICTGE	ICTGI	FBS1	FBS	GDP	MANUF	INDUSTRY
						Resources-rich countries						
1	1.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
2	0.267	0.112	0.037	0.001	0.018	0.039	0.048	0.157	0.308	0.001	0.002	0.011
3	0.079	0.074	0.055	0.018	0.023	0.016	0.040	0.320	0.362	0.007	0.003	0.002
4	0.013	0.051	0.065	0.027	0.026	0.010	0.036	0.399	0.361	0.010	0.001	0.000
5	0.072	0.026	0.066	0.034	0.026	0.004	0.026	0.429	0.303	0.012	0.000	0.002
6	0.253	0.007	0.057	0.037	0.021	0.001	0.014	0.388	0.203	0.012	0.000	0.008
7	0.571	0.010	0.033	0.029	0.011	0.004	0.003	0.239	0.069	0.009	0.003	0.018
8	0.741	0.062	0.007	0.009	0.003	0.017	0.014	0.049	0.064	0.002	0.008	0.025
9	0.396	0.098	0.023	0.004	0.012	0.023	0.037	0.125	0.260	0.002	0.008	0.014
10	0.103	0.083	0.048	0.015	0.022	0.017	0.043	0.290	0.365	0.006	0.005	0.004
						Resources-poor countries						
1	1.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
2	0.969	0.009	0.000	0.006	0.002	0.005	0.001	4.3E-05	0.000	0.006	0.000	0.002
3	0.948	0.014	0.000	0.011	0.003	0.007	0.002	4.0E-05	0.000	0.011	0.000	0.004
4	0.941	0.015	0.000	0.013	0.004	0.008	0.002	3.1E-05	0.000	0.013	0.000	0.004
5	0.938	0.015	0.000	0.014	0.004	0.008	0.002	2.7E-05	0.000	0.013	0.001	0.005
6	0.938	0.015	0.000	0.014	0.004	0.008	0.002	2.6E-05	0.000	0.013	0.001	0.005
7	0.937	0.015	0.000	0.014	0.004	0.008	0.002	2.6E-05	0.000	0.013	0.001	0.005
8	0.937	0.015	0.000	0.014	0.004	0.008	0.002	2.6E-05	0.000	0.013	0.001	0.005
9	0.937	0.015	0.000	0.014	0.004	0.008	0.002	2.6E-05	0.000	0.013	0.001	0.005
10	0.937	0.015	0.000	0.014	0.004	0.008	0.002	2.6E-05	0.000	0.013	0.001	0.005

Note: To conserve space, we report the results of the variance decomposition based on the tenth period. The full sample results, encompassing all periods of analysis, will be made available upon request.

4.6 PVAR Granger Causality Test

The Granger Causality tests shed light on the dynamic interactions between environmental policies, technological innovations, digitalization, and natural resource management in SSA. The findings highlight that environmental policies such as policies for environmental sustainability (PIES) and policies for social inclusion (PSI) significantly Granger cause natural resource rents (TNR), suggesting that effective governance and institutional frameworks drive improvements in resource management. This is consistent with the literature that underscores the role of strong institutions and inclusive policies in enhancing sustainable resource management (Hassan et al., 2019; Ibrahim and Ajide, 2021). However, reverse causality, where TNR influences PIES or PSI, was not supported, indicating that natural resource wealth does not necessarily improve policy frameworks in SSA, thus echoing the resource curse hypothesis where resource abundance does not guarantee better governance (Nathaniel and Adedoyin, 2022).

Interestingly, no significant causality was found between fixed broadband subscriptions (FBS) and TNR, as well as between ICT goods imports (ICTGI) and TNR, suggesting that while digital infrastructure and technology play a role in resource management, their relationship with resource rents may be more complex and context-dependent. The lack of causality between GDP and TNR further emphasizes the refined nature of economic growth and resource management in SSA. These findings align with the empirical literature suggesting that institutional factors are often more influential than resource wealth alone in shaping resource management outcomes (Hassan et al., 2019).

Table 6. Granger Causality Results

The Causality Path	Obs	F-Statistic	Prob.	Decision
BRE→TNR	374	0.377	0.685	The H_0 is valid
TNR→BRE		374	0.428	
PIES→TNR	374	0.634***	0.000	The H_0 is rejected
TNR→PIES		374**	0.007	
PSI→TNR	374	0.672*	0.011	The H_0 is rejected
TNR→PSI		374**	0.009	
FBS→TNR	374	0.584	0.558	The H_0 is valid
TNR→FBS		374**	0.000	
FBS1→TNR	374	1.071	0.343	The H_0 is valid
TNR→FBS1		374**	0.008	
ICTGI→TNR	374	0.007	0.992	The H_0 is valid
TNR→ICTGI		374**	0.003	
INDUSTRY→TNR	374	0.280**	0.004	The H_0 is rejected
TNR→INDUSTRY		374**	0.005	
GDP→TNR	374	0.930*	0.032	The H_0 is rejected
TNR→GDP		374**	0.005	
ICTGE→TNR	374	1.245**	0.009	The H_0 is rejected
TNR→ICTGE		374**	0.001	
MANUF→TNR	374	1.063**	0.006	The H_0 is rejected
TNR→MANUF		374**	0.009	
VA→TNR	374	2.252**	0.006	The H_0 is rejected
TNR→VA		374**	0.005	
PIES→BRE	374	+9.064**	0.000	The H_0 is rejected
BRE→PIES		374	0.321	
PSI→BRE	374	6.050**	0.002	The H_0 is rejected
BRE→PSI		374	0.298	

FBS→BRE	374	0.636**	0.009	The H_0 is rejected
BRE→FBS		374**	0.005	
FBS1→BRE	374	0.319**	0.006	The H_0 is rejected
BRE→FBS1		374**	0.000	
ICTGI→BRE	374	3.248**	0.039	The H_0 is rejected
BRE→ICTGI		374**	0.006	
INDUSTRY→BRE	374	0.060**	0.001	The H_0 is rejected
BRE→INDUSTRY		374**	0.038	
GDP→BRE	374	0.303	0.738	The H_0 is valid
BRE→GDP		374**	0.004	
ICTGE→BRE	374	0.843	0.431	The H_0 is valid
BRE→ICTGE		374	0.637	

Note: *, ** and ***, respectively represent significance levels at 10%, 5% and 1%. To conserve space, we did not report for all the sample. The full sample results, encompassing all periods of analysis, will be made available upon request.

4.7 Panel Quantile Regression (Robustness Test)

Table 7 presents the results of the impact of environmental policy, technology, and digitalization on resource management across different percentiles (25%, 50%, 75%, and 95%) in both resource-rich and resource-poor countries within SSA. The findings highlight the varying significance of these factors across different contexts, supporting and reinforcing several key trends identified in the study.

In resource-rich countries, environmental policies such as policy for social inclusion (PSI) and voice and accountability demonstrate consistently positive impacts across all percentiles, which aligns with the literature emphasizing the importance of governance and accountability in improving resource management outcomes. Improved social inclusion policies and stronger governance frameworks contribute to more sustainable management practices, particularly in resource-rich countries, where resource wealth can create opportunities for institutional improvements (Stern & Kander, 2012). These results also echo findings from Asongu et al. (2018), who argue that effective governance is essential in managing the environmental challenges associated with resource wealth, such as pollution and biodiversity loss.

Furthermore, the results reveal a significant and positive link between ICT goods exports (ICTGE) and resource management practices across all percentiles. This finding reinforces the literature on the role of technological advancements in enhancing resource management outcomes. The positive impact of ICTGE supports previous studies (Kim & Kim, 2012; Sadorsky, 2010) that have highlighted how the export and integration of ICT technologies into national economies can improve resource management, both through better data analytics and enhanced decision-making processes. The widespread availability and application of ICT technologies can help resource-rich countries optimize the use of their natural resources and improve governance frameworks, as technology facilitates transparency and more informed policymaking.

Additionally, fixed broadband subscriptions (FBS1 and FBS) have substantial positive impacts on resource management practices, with results significant at the 1% level across most percentiles. This finding aligns with the work of Kounetas and Tsekouras (2008), who found that increased broadband access fosters better governance and improves access to information, both of which are crucial for effective resource management. As broadband connectivity improves, so does the ability of institutions to monitor and manage natural resources effectively, a crucial factor in countries with abundant natural resources.

In contrast, in resource-poor countries, while the overall trend shows positive impacts of voice and accountability and ICTGE on resource management, the degree of impact varies across the percentiles. Better governance and technology are indeed linked to improvements in resource management, reflecting findings from Danish et al. (2019), who emphasized that these factors play a vital role in overcoming challenges associated with resource scarcity. These findings suggest that even in resource-poor settings, where the resource base is limited, technological advancements and stronger governance mechanisms can still contribute to more efficient and sustainable management practices. However, the variability in the impact of industrial development (manufacturing and industry) across percentiles suggests a less consistent relationship between industrialization and resource management outcomes in resource-poor countries. This is in line with the empirical literature that highlights how industrial development can have mixed effects on resource management, depending on factors such as governance quality and technological capabilities (Danish et al., 2019).

Overall, the findings from Table 7 support the empirical literature by demonstrating that technological advancements, improvements in governance, and inclusive policies are crucial for enhancing resource management outcomes in both resource-rich and resource-poor countries in SSA. However, these relationships are context-specific, with technology and governance playing more prominent roles in resource-rich countries, while in resource-poor countries, the availability of natural resources remains the dominant factor. The results underscore the need for context-specific policies and interventions that address the unique challenges faced by countries in managing their resources effectively (Ahmad et al., 2020; Ahmed et al., 2020; Jahanger et al., 2022).

Table 7. MM-QR Results

	Resources-rich countries				Resources-poor countries			
	25%	50%	75%	95%	25%	50%	75%	95%
BRE	0.131 (0.425)	0.321 (0.330)	0.491 (0.428)	0.769 (0.770)	0.268 (0.310)	0.216 (0.250)	0.147 (0.371)	0.059 (0.662)
PIES	0.342 (0.393)	-0.189 (0.306)	-0.052 (0.396)	0.172 (0.711)	0.080 (0.280)	0.082 (0.225)	0.084 (0.335)	0.088 (0.598)
PSI	0.894** (0.474)	1.204** (0.367)	1.483** (0.475)	1.938** (0.862)	-0.291 (0.416)	-0.251 (0.334)	-0.197 (0.497)	-0.128 (0.887)
VA	0.533*** (0.112)	0.398*** (0.085)	0.276** (0.109)	0.078** (0.208)	0.762*** (0.099)	0.716*** (0.080)	0.655*** (0.118)	0.575** (0.211)
ICTGE	0.032** (0.023)	0.039** (0.018)	0.045** (0.023)	0.056** (0.042)	0.037** (0.015)	0.032** (0.012)	0.026** (0.018)	0.018** (0.032)
ICTGI	0.010 (0.048)	-0.017 (0.037)	-0.023 (0.048)	-0.034 0.086	0.039 (0.062)	0.021 (0.050)	-0.003 (0.074)	-0.034 (0.133)
FBS1	0.097** (0.048)	0.061** (0.037)	0.028** (0.048)	0.025** (0.088)	0.040** (0.019)	0.028** (0.015)	0.013 (0.023)	-0.008 (0.040)
FBS	0.082** (0.051)	0.067** (0.040)	0.054 (0.051)	0.032 (0.092)	0.049** (0.024)	0.035** (0.020)	-0.017 (0.029)	0.007 (0.052)
GDP	1.475** (0.461)	1.667*** (0.359)	1.840*** (0.465)	2.122** (0.835)	0.770** (0.332)	0.779** (0.267)	0.790** (0.396)	0.805 (0.708)
MANUF	0.005 (0.177)	0.081 (0.138)	0.159 (0.178)	0.285 (0.321)	0.008 (0.078)	-0.034 (0.063)	-0.088 (0.094)	-0.159 (0.167)
INDUSTRY	0.519** (0.244)	0.696*** (0.188)	0.856*** (0.244)	1.117** (0.444)	-0.078 (0.179)	-0.038 (0.144)	0.015 (0.214)	0.083 (0.383)

Note: ***, **, * indicate statistical significance at the 1%, 5%, and 10% levels, respectively. Standard errors in parentheses.

5. Conclusion and Policy Recommendations

In this paper we address the knowledge gap on the relationships between environmental policy-technological innovations-digitalisation, and natural resources management in SSA. Unlike previous studies that often focus solely on carbon emissions, this research advocates for a more comprehensive investigation of the environmental impacts of resource extraction. By centering on the socio-economic and environmental contexts of SSA countries, the study underscores the necessity of considering these factors when crafting policies and implementing technological solutions for sustainable resource management. This contextual approach enriches the discourse and underscores the significance of regulation-technology-digitalization in shaping resource management practices. Additionally, the research highlights that strict environmental regulations in countries abundant in resources have a positive effect on the management of natural resources. However, in countries with limited resources, the impact of such regulations is less significant. Furthermore, advancements in technology, especially in digital infrastructure, have the potential to enhance resource management practices in both resource-rich and resource-poor countries within SSA. While promoting digitalisation in nations rich in resources is associated with improved resource management, there are obstacles to effectively utilizing digital technologies for resource management in resource-limited settings. In summary, these findings emphasize the crucial role of sustainable resource management in fostering long-term economic growth, social equity, and environmental preservation across SSA.

5.1 Theoretical implications

In resource-rich countries, the findings support the resource curse theory, which suggests that despite the abundance of natural resources, poor governance, and weak regulatory frameworks often hinder effective resource management. The study underscores the importance of strong business regulatory environments, inclusive policies, and institutional sustainability for fostering better management practices. In contrast, in resource-poor countries, the study emphasizes the significance of governance structures, economic growth, and institutional quality in managing scarce resources. It suggests that in such contexts, policies focusing on strengthening regulatory frameworks and improving governance mechanisms are crucial for enhancing resource management outcomes. Both sets of findings suggest that context-specific strategies are essential for addressing the unique challenges and opportunities in managing natural resources across SSA, particularly through institutional and economic development lenses.

5.2 Practical implications

By clarifying the differential impact of environmental policies-technological innovations in resource-rich and resource-poor countries, the study informs the design and implementation of strategies that address the unique challenges and opportunities within each context. For resource-rich countries, the findings underscore the importance of leveraging stringent environmental policies and investing in digital infrastructure to enhance resource management practices, thereby promoting economic growth, environmental conservation, and social welfare. Conversely, for resource-poor countries, the study highlights the need for capacity-building initiatives focused on sustainable resource use and governance frameworks that prioritize equitable access to resources while minimizing environmental harm. Furthermore, the study emphasizes the potential of digital technologies to facilitate resource management efforts, suggesting opportunities for collaboration and knowledge-sharing among stakeholders to harness digital solutions effectively.

5.3 Limitations and future applied research directions

The paper was constrained by data and the analysis relies on aggregated data at the country level, which may obscure intra-country variations in resource management dynamics. Future research could explore sub-national variations to capture localized impacts and tailor interventions accordingly. Additionally, the study primarily focuses on the relationship between environmental policies-technological innovations, and resource management outcomes, neglecting other potential influencing factors such as cultural, institutional, and geopolitical contexts. Future research could adopt a more comprehensive approach by integrating these factors into the analysis to provide a more holistic understanding of resource management processes in SSA. Moreover, while the study examines the impact of digital infrastructure on resource management, it does not delve into specific digital technologies or implementation challenges. Future research could explore the effectiveness of specific digital solutions, such as remote sensing technologies or blockchain-based systems and investigate the barriers to their adoption in resource management contexts. By addressing these limitations and delving deeper into these research directions, future studies can further enrich our understanding of sustainable resource management practices in SSA and contribute to more effective policy interventions and practical solutions.

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Appendices

Appendix Table 1. Descriptive statistics

	TNR	BRE	PIES	PSI	VA	ICTGE	ICTGI	FBS1	FBS	GDP	MANUF	INDUST
Mean	1.831	1.186	1.186	1.214	2.355	-2.031	1.162	-3.147	7.829	6.723	2.277	26.133
Median	1.772	1.253	1.253	1.253	2.398	-1.881	1.202	-2.733	7.922	6.722	2.283	26.837
Maximum	3.896	1.504	1.504	1.459	2.944	3.042	2.461	1.750	13.247	8.207	3.910	31.222
Minimum	0.209	0.916	0.693	0.833	1.386	-11.047	-1.806	-9.976	1.386	5.527	-0.306	19.574
Std. Dev.	0.798	0.133	0.158	0.132	0.355	2.032	0.593	2.450	2.564	0.590	0.605	2.751
Skewness	0.290	0.000	-1.039	-0.776	-0.535	-0.661	-0.868	-0.517	-0.272	0.149	-0.388	-0.521
Kurtosis	2.380	2.848	4.272	3.733	2.500	3.952	5.078	2.792	2.554	2.661	5.035	2.530
Jarque-Bera	12.263	0.394	100.989	50.025	23.695	45.116	124.678	18.877	8.401	3.465	80.631	22.205
Prob.	0.002	0.821	0.000	0.000	0.000	0.000	0.000	0.000	0.015	0.177	0.000	0.000
Sum	747.193	483.686	484.026	495.476	961.032	-828.653	474.074	-1283.88	3194.117	2743.172	928.864	10662.43
Sum Sq. Dev.	259.161	7.233	10.100	7.057	51.206	1680.301	143.226	2443.782	2676.043	141.586	149.092	3079.156

Appendix Table 2. Correlation matrix and multicollinearity results

Variables									VIF	TOL
BRE	1.000								3.010	0.332
PIES	0.143	1.000							2.660	0.375
PSI	0.187	0.707	1.000						2.410	0.416
VA	0.439	0.641	0.722	1.000					2.260	0.443
ICTGE	0.236	0.253	0.331	0.246	1.000				2.200	0.454
ICTGI	-0.032	0.150	0.174	0.193	0.133	1.000			1.380	0.723
FBS1	0.159	0.211	0.042	0.159	-0.065	0.306	1.000		1.320	0.757
FBS	-0.045	0.141	0.187	0.200	0.251	0.057	-0.262	1.000	1.230	0.811

GDP	0.128	0.333	0.396	0.327	0.641	0.041	-0.120	0.740	1.000				1.140	0.876
MANUF	-0.261	0.054	-0.055	-0.076	-0.123	-0.096	-0.215	0.562	0.240	1.000			1.130	0.883
INDUS	-0.078	0.008	0.026	-0.023	0.195	0.131	-0.033	-0.222	-0.044	-0.200	1.000		1.050	0.954
BRE	0.139	0.324	0.310	0.172	0.535	0.091	0.171	-0.079	0.475	-0.211	0.453	1.000		

Appendix Table 3. Cointegration test

Kao	Statistic	p-value
Modified Dickey–Fuller t	-6.142***	0.000
Dickey–Fuller t	-11.910***	0.000
Augmented Dickey–Fuller t	-7.202***	0.000
Unadjusted modified Dickey–Fuller t	-20.531***	0.000
Unadjusted Dickey–Fuller t	-16.992***	0.000

Appendix Table 4. Unit root test and cross-sectional dependency test

	CS Test (Test Statistic)				CIPS	
Var	Breusch-Pagan LM	Pesaran scaled LM	Bias-corrected scaled LM	Pesaran CD	(First difference)	Stationary?
TNA	728.822***	35.945***	35.576***	16.452***	10.232***	Yes
BRE	791.923***	39.771***	39.402***	-0.721	-4.211***	Yes
PIES	731.234***	34.321***	37.734***	4.453***	-4.190***	Yes
PSI	1569.893***	86.943***	86.573***	12.770***	6.889***	Yes
VA	2846.796***	164.366***	163.997***	53.310***	-5.769***	Yes
ICTGE	419.767***	17.206***	16.836***	3.797***	-9.285***	Yes
ICTGI	384.589***	15.073***	14.703***	10.675***	-8.978***	Yes
FBS1	2281.116***	130.067***	129.697***	44.569***	-5.345***	Yes
FBS	2673.995***	153.889***	153.519***	51.598***	-4.956***	Yes
GDP	2673.995***	153.889***	153.519***	51.598***	-5.073***	Yes
MANUF	931.228***	48.218***	47.848***	6.784***	-9.615***	Yes
INDUSTRY	1985.398***	112.136***	111.767***	42.258***	-6.289***	Yes