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Financial inclusion and knowledge diffusion for green growth in Sub-Saharan African countries

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ABSTRACT

This article examines the associated and interactive effects of financial inclusion measured through financial inclusion index and knowledge diffusion, measured through research and development (R&D), internet usage, and education, on green growth measured by CO2 emissions intensity due to production, in Sub-Saharan Africa. Based on a sample of 36 countries and data spanning the period from 2004 to 2018, the analysis employs POLS, Newey & West, and Driscoll & Kraay estimation methods. The findings reveal that financial inclusion, R&D, and internet usage exacerbate CO2 emissions intensity from production, thereby hindering green growth. Conversely, education plays a positive role by reducing production-related CO2 emissions and promoting sustainable practices. Education improves green growth, yet knowledge production through R&D deteriorates green growth when interacting with financial inclusion. Similarly, internet usage, when it interacts with financial inclusion, harms green growth. These results indicate that financial inclusion, R&D, and internet usage negatively impact green growth by increasing CO2 intensity related to production. The study recommends better alignment to green financial inclusion, sustainable R&D, and digital policies with environmental sustainability objectives while advocating for the promotion of environmental education to support green growth. To maximize sustainable development benefits, Sub-Saharan African countries need to adjust their development strategies by incorporating greener practices into financial inclusion, R&D, and digital technologies.

Contribution/Originality: This research addresses gaps in understanding the relationship between financial inclusion, knowledge dissemination, and green growth. It provides insights into the relationship between financial inclusion and green growth, highlighting the role of knowledge with dimensions unexplored in previous studies, such as knowledge diffusion and CO2 emissions intensity due to production.

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1. INTRODUCTION

Sub-Saharan Africa, known for its vast natural resources and ecological diversity, faces numerous challenges in achieving sustainable development. In this context, green growth offers a promising pathway to tackle these challenges, fostering inclusive and sustainable economic growth within the region. According to Pearce, Markandya, and Barbier (1989) green growth refers to an economic model that seeks to maximize human well-being while reducing environmental risks and safeguarding natural resources for future generations. This approach requires a transition towards sustainable production and consumption patterns that not only lower greenhouse gas emissions but also reduce dependence on fossil fuels, thereby promoting the efficient use of renewable resources (Kolade et al., 2022; Raihan, 2023).

Moreover, in Sub-Saharan Africa (where deforestation, land degradation, and pollution of air and water are pressing issues) the adoption of sustainable economic practices has become essential (Dietz, Bowen, Dixon, & Gradwell, 2009; N. Stern, 2017). Initiatives such as the United Nations' 2030 Agenda for Sustainable Development emphasize the role of green growth in advancing Sustainable Development Goals (SDGs) across Sub-Saharan Africa. Specifically, SDGs like SDG 7 (affordable and clean energy) and SDG 13 (climate action) highlight the urgency of investing in renewable energy, sustainable resource management, and climate adaptation strategies within the region.

Despite its potential, green growth in Sub-Saharan Africa faces significant obstacles. Rahman (2024) indicates that common barriers include limited green infrastructure, inadequate policy frameworks, and a lack of funding for environmental initiatives. Furthermore, persistent socio-economic challenges and weak institutional capacity continue to hinder progress toward a greener economy. However, even with these challenges, promising examples of progress are beginning to emerge. For instance, the African Renewable Energy Initiative seeks to mobilize investments for large-scale renewable energy projects across the region (Asongu & Le Roux, 2019). Similarly, grassroots efforts such as community-led reforestation and waste management projects contribute to building a more resilient and inclusive green economy.

At this juncture, financial inclusion plays an essential role in addressing these challenges. Providing access to finance, promoting green entrepreneurship, and mobilizing savings for sustainable investments, financial inclusion offers mechanisms to support green growth by stimulating clean technology investments and enhancing community resilience (Beck, Demirgüç-Kunt, & Martinez Peria, 2007; Rahman, 2024). As such, financial inclusion emerges as a crucial element in advancing sustainable economic progress across Sub-Saharan Africa.

Financial inclusion has become an increasingly vital topic with profound implications for the economic and social development of Sub-Saharan Africa. However, despite notable progress in recent years, challenges persist, particularly in extending financial access to marginalized populations. Beck et al. (2007) define financial inclusion as equitable access to and effective use of financial services (such as bank accounts, credit, insurance, and payment services) by all segments of society. Within Sub-Saharan Africa, achieving financial inclusion remains both a complex and crucial factor for advancing green growth.

Indeed, much of the region's population is either unbanked or underbanked, with limited access to formal financial services. The World Bank reports that nearly 66% of adults in Sub-Saharan Africa still lack a formal bank account (European Investment Bank, 2017). Contributing factors include insufficient financial infrastructure, high service costs, limited identification documentation, and distrust of formal financial institutions. Nevertheless, mobile technology has recently expanded financial service access, positioning Sub-Saharan Africa as a global leader in mobile financial services. Mobile-based solutions like money transfers, bill payments, and microloans have become accessible via mobile phones, fostering the region's green economy potential (Asongu & Le Roux, 2019).

Furthermore, financial inclusion supports green growth by facilitating access to funds needed to finance green projects (Venkataramani, Maupin, Ngenoh, Thirumurthy, & Kariuki, 2017). It encourages innovation and growth in green sectors by providing financial incentives to entrepreneurs and businesses dedicated to clean technologies and sustainable practices (Beck et al., 2007; Murshed et al., 2023). By enhancing access to savings and insurance, financial inclusion strengthens individuals' and communities' resilience against environmental shocks, such as natural disasters or fluctuations in agricultural prices (Asongu & Le Roux, 2019). Additionally, it mobilizes savings toward sustainable investments, such as socially responsible investment funds (Afonso & Blanco-Arana, 2024; Saqib, Ozturk, & Usman, 2023) thereby supporting the green economy.

In providing capital to eco-friendly entrepreneurs and businesses, financial inclusion facilitates the establishment of green enterprises, creating green jobs and promoting economic inclusion (Zheng & Li, 2022). Although the benefits of financial inclusion for green growth are extensive (Chen, Ramzan, Hafeez, & Ullah, 2023; Song, Gong, & Song, 2024) it is also essential to consider and manage potential downsides. Risks such as unsustainable financing practices, increased economic inequality, dependency on financial technology, resource strain, and unaddressed negative externalities must be carefully navigated to ensure a genuinely sustainable transition to a green economy (Markandya, Galarraga, & González-Eguino, 2017; Moser & Urban, 2017).

In Sub-Saharan Africa, knowledge diffusion plays a critical role in fostering socio-economic development and addressing pressing local challenges. However, the region still confronts numerous barriers that impede this process, such as limited access to educational resources, underdeveloped communication infrastructure, linguistic and cultural differences, low investment in research and development, and limited collaboration and networking opportunities (Asongu & Le Roux, 2019). Defined by Rogers (2003) as a dynamic and multidimensional process, knowledge diffusion encompasses the creation, sharing, transfer, and utilization of knowledge, information, and ideas across various channels and among diverse stakeholders. Within this context, it also has the potential to amplify the impact of environmental policies and contribute significantly to the green economy.

Indeed, knowledge diffusion encourages the sharing of information on effective green practices and technologies, facilitating the adoption of sustainable methods (Amankwah-Amoah, Debrah, & Acquaah, 2023; Widera, 2021). This spread of best practices and scientific insights can drive the implementation of more efficient environmental practices across industries and key sectors (Ijoma et al., 2022). Moreover, knowledge diffusion enhances the capabilities of stakeholders involved in the green economy (including entrepreneurs, policymakers, and civil society organizations) by providing them with relevant information on the economic opportunities and potential benefits associated with green initiatives, thus encouraging private investment in green projects (Moser & Urban, 2017). By raising awareness of environmental challenges and sharing adaptation strategies, knowledge diffusion also fosters community and business resilience to environmental changes (Markandya et al., 2017).

Yet, this analysis highlights an ongoing debate surrounding the benefits and limitations of financial inclusion for green growth. While some argue for its positive impacts, others note unresolved issues contributing to the divide. Notably, financial investments in green growth may sometimes prioritize short-term or unsustainable projects, potentially jeopardizing the long-term viability of these initiatives (Asongu & Le Roux, 2019; Genovese & Zoure, 2023). Additionally, greenwashing practices within financial institutions may misrepresent certain products or investments as environmentally friendly despite their adverse impacts (Markandya et al., 2017). Furthermore, financial inclusion efforts may not always reach the most vulnerable populations, who might face socio-economic barriers to benefiting from green growth opportunities (Bender et al., 2021). Importantly, knowledge diffusion approaches can sometimes overlook traditional and indigenous knowledge on sustainable resource management, limiting the effectiveness and scope of interventions aimed at supporting green growth (Valente, 2010). Nevertheless, for these knowledge to be disseminated, several dimensions including human capital (e.g., through education and training), technological innovations with the internet serving as both an innovation and a means of knowledge dissemination, and research and development constitute tools whose popularization for the green growth is important. The motivation behind this research lies in the desire to fill knowledge gaps, critically evaluate established concepts, and promote an integrated approach to foster a more sustainable and inclusive green economy.

This study holds particular significance for African countries for several reasons. Firstly, the African region is alarmingly facing the adverse effects of climate change on its geography and the vulnerability of its biodiversity. Secondly, Africa, compared to other developing regions of the world, has a relatively low level of financial inclusion, at 43% compared to 63% (International Monetary Fund (IMF), 2023) but with high potential due to greater penetration of digital financial inclusion (European Investment Bank, 2017) which could boost private initiatives in the green economy. The continent's economy heavily relies on polluting activities, leaving countries with limited means to adapt to climate change. In Africa alone, adaptation costs could reach $50 billion annually by 2050 in a scenario of 2°C temperature rise (Global Center on Adaptation (GCA), 2021); as for the mitigation costs associated with the energy transition in Africa, they are estimated at around $190 billion annually until 2030 (report published in 2022 by the International Energy Agency (IEA)). However, according to the International Monetary Fund (IMF) (2023) the current volume of climate finance received by the region falls far short of these needs. Advanced countries, on their part, are far from meeting the commitment made in 2009 to mobilize $100 billion annually for climate actions in developing countries. However, its heavy dependence on traditional energies continues to undermine the achievement of development goals, especially the Sustainable Development Goals (SDGs). Thirdly, while African countries have made impressive strides in knowledge dissemination over the past decades, the process of knowledge diffusion in Africa still faces numerous challenges. These include high levels of poverty, limited access to educational resources, healthcare, and basic infrastructure, as well as underdeveloped communication networks, linguistic and cultural barriers, low investment in research and development, and insufficient collaboration and networking. Achieving sustainable development by promoting a green economy, advancing social progress, and ensuring environmental protection remains a critical objective for African nations (World Bank (WB), 2017). Thus, investigating the relationships between financial inclusion, knowledge diffusion, and green growth[1] provides valuable insights into the sustainability of current economic practices and helps identify strategies to encourage cleaner and more sustainable activities. Additionally, this research can assist policymakers by highlighting potential trade-offs and synergies among financial access, economic growth, and environmental sustainability, offering guidance in formulating policies that promote sustainable and inclusive development in Africa.

This study offers several important contributions. Firstly, it addresses existing research gaps by pinpointing uncertainties surrounding the dissemination of knowledge on green growth in sub-Saharan Africa, as well as limitations in financial inclusion that may impede environmental sustainability. By illuminating these gaps, it establishes a foundation for further analysis and interventions aimed at enhancing sustainable development strategies in the region (Djoumessi, 2022). Secondly, this research enriches the theoretical framework by proposing an integrated approach to knowledge dissemination and financial inclusion within the context of green growth in sub-Saharan Africa. By examining the interactions between these dimensions, the study provides new insights into how these factors can influence the region's transition to a more sustainable economy (Moser & Urban, 2017). Thirdly, this study holds substantial socio-economic significance for sub-Saharan Africa by offering practical recommendations that can strengthen green growth efforts in the region. By identifying specific challenges and opportunities, it aids in directing policies and investments toward sustainable and inclusive initiatives that are likely to support long-term economic and social development (Markandya et al., 2017). Finally, this study contributes multidisciplinary insights by integrating perspectives from economics, environmental studies, sociology, and political science. Through a holistic approach, it captures the complexities of transitioning to green growth in sub-Saharan Africa and proposes innovative, practical solutions to these challenges (Amankwah-Amoah et al., 2023).

The following sections of this study include a review of literature on the relationships between financial inclusion, knowledge dissemination, and the green economy, a detailed explanation of the methodology, and a presentation of the results. This study concludes with a synthesis of the findings and deductions.

[1] Green growth is measured using a more recent and precise indicator—CO2 emissions intensity from production—provided by the Organisation for Economic Co-operation and Development (OECD), instead of the commonly used CO2 emissions metric.

2. LITERATURE REVIEW

2.1. Effects of Financial Inclusion on the Green Growth

The literature on the effects of financial inclusion on green growth presents varied perspectives. On one hand, researchers such as Allen, Demirguc-Kunt, Klapper, and Peria (2014) and Hatakka, Lindeman, and Suorsa (2016) underscore the potential benefits of financial inclusion. They argue that financial inclusion can stimulate investments in environmentally sustainable projects, promote the adoption of clean technologies, and strengthen community resilience against environmental shocks. Conversely, other researchers, including Lehmann, Ruhrort, and Schulte (2018) and Banerjee and Cáceres (2019) highlight the associated risks. Their findings point to concerns such as the unsustainable financing of green projects, the prevalence of financial greenwashing, and the potential exclusion of marginalized populations from financial services. These contrasting perspectives stress the importance of a balanced approach that maximizes the benefits of financial inclusion while mitigating its risks, ensuring that it truly contributes to environmental and social sustainability.

Building on these discussions, contemporary economic literature examines various facets of the interaction between green innovation, green finance, and financial inclusion within emerging economies. For example, R. Chen et al. (2023) demonstrate the positive impact of green innovation and financial globalization on green growth in these economies, noting the critical role of research in advancing ecological innovations. Meanwhile, Udeagha and Ngepah (2023) analyze Green Finance (GFN) and fintech's potential to achieve carbon neutrality among BRICS nations (Brazil, Russia, India, China, and South Africa) and advocate for developing specialized green financial products. Focusing specifically on China, Zheng and Li (2022) illustrate how digital financial inclusion could lower CO_2 emissions and raise per capita GDP in moderately developed regions. Furthermore, Murshed et al. (2023) highlight a positive correlation between financial inclusion, energy efficiency, and reduced CO_2 emissions in multiple emerging economies.

Similarly, Song et al. (2024) assess digital finance's role in supporting sustainable development in China, while Nham and Ha (2023) explore the link between financial development and the sustainability of the blue economy in Europe. Saqib et al. (2023) examine the ecological footprint of emerging economies, emphasizing technology and renewable energy integration as drivers of sustainable growth. In addition, Afonso and Blanco-Arana (2024) underline financial inclusion's vital contribution to economic growth in developing countries, while Niankara and Islam (2023) show how digital social assistance and electronic payroll can enhance global formal financial inclusion. Together, these studies deepen our understanding of financial inclusion's multifaceted role in green growth, highlighting both its potential benefits and areas requiring careful oversight.

2.2. Effects of Knowledge Diffusion on the Green Growth

The literature on the effects of knowledge diffusion on the green growth presents contrasting perspectives. Some researchers, such as Valente (2010) and Moser and Urban (2017) emphasize that knowledge diffusion can stimulate technological innovation in the field of the green economy, promote the strengthening of institutional capacities necessary for transitioning to a more sustainable economy, and thus contribute to more effective policies tailored to local contexts. Conversely, researchers like Sarewitz (2016) and Stern (2017) caution about potential risks associated with knowledge diffusion, notably the reliance on imported technologies and the spread of misinformation. They emphasize the importance of careful management to harness the benefits of knowledge diffusion while mitigating these risks, ultimately ensuring its positive impact on environmental and economic sustainability.

Expanding on this cautionary perspective, several studies delve into key aspects of knowledge diffusion's influence on sustainable development in sub-Saharan Africa. For instance, Amankwah-Amoah et al. (2023) address persistent institutional challenges encountered in international joint ventures by proposing a four-phase model to illustrate these interactions. The phases encompass pre-formation resource mobilization, initial formation challenges, decoupling and rebranding, and eventual phasing out. In another dimension, Widera (2021) assesses the thermal comfort of vernacular dwellings, and Genovese and Zoure (2023) advocate an adaptive approach to locally sustainable buildings. Additionally, Bender et al. (2021) introduce the photovoltaic index as a tool for evaluating investments in decentralized photovoltaic energy, underscoring the complexities involved in these investment decisions.

Further studies contribute unique insights into sustainable energy: Ijoma et al. (2022) explore the energy potential of wastewater treatment facilities, while Mulopo (2022) analyzes challenges in renewable energy interventions. Lastly, Djoumessi (2022) emphasizes the critical role of agricultural productivity in poverty reduction, underscoring the need for investments in human capital and agricultural technology. Collectively, these research efforts illuminate multiple facets of sustainable development in the region, offering valuable perspectives to inform more effective and inclusive policies and practices.

2.3. Effects of the Interaction between Financial Inclusion and Knowledge Diffusion on the Green Growth

The literature examining the interaction between financial inclusion and knowledge diffusion in driving green growth presents diverse perspectives. On one hand, previous studies suggest that this interaction tends to be beneficial; for example, Allen et al. (2014) and Moser and Urban (2017) argue that the synergy between financial inclusion and knowledge diffusion can enhance access to green financing and strengthen the impact of environmental policies. By equipping stakeholders in the green economy with financial information and relevant skills, this interaction fosters a more efficient transition to sustainable practices. On the other hand, some researchers, such as Lehmann et al. (2018) and Banerjee and Cáceres (2019) highlight potential risks, including unsustainable investments and practices like financial greenwashing. These cautions underscore the importance of weighing both the potential advantages and drawbacks of this interaction to design balanced policies that support both environmental and economic sustainability.

Adding to this discourse, recent research sheds light on the institutional and socio-cultural challenges faced by African countries in diffusing knowledge critical to their green economy transition. For example, Kolade et al. (2022) underscore the role of perceived ease of use as a factor in overcoming these barriers. A comprehensive synthesis by Persaud and Thaffe (2023) of 183 studies on financial inclusion in developing countries outlines four main themes: the conceptualization and impacts of financial inclusion, user perceptions, the role of financial innovation and private institutions, and the contributions of institutions and public policies. They emphasize a cautious and context-sensitive approach in applying financial inclusion models in diverse regions. Meanwhile, studies examining the impacts of ICT, economic growth, and energy consumption on GHG emissions in Malaysia yield varied insights, with recommendations to encourage renewable energy adoption (Raihan, 2023). The emergence of bioclimatic architecture in sub-Saharan Africa is explored, along with the role of International Collaborations for the Green growth in environmental and industrial governance (Aisbett, Raynal, Steinhauser, & Jones, 2023; Genovese & Zoure, 2023). Research also reveals divergent trends in the impact of digital financial inclusion on the environment and economic growth, as well as the potential for biogas production in sub-Saharan Africa (Ijoma et al., 2022; Oanh, 2024). Renewable energy interventions in the region highlight persistent challenges such as decentralization and financing (Mulopo, 2022) while research examines the impact of financial inclusion and FinTech lending on economic growth, emphasizing the moderating role of energy poverty (Rahman, 2024).

3. METHODOLOGY

3.1. Data and Sources

All data are secondary and quantitative in nature. The data on CO2 emissions intensity relative to production come from the OECD (2023). The financial inclusion index is computed based on penetration, measured by the number of bank accounts per 1,000 adults (Sarma & Pais, 2011); availability, captured by the number of bank branches per 100,000 adults (Sarma, 2015); and usage, reflected by outstanding loans with commercial banks (% of GDP) (Lenka & Bairwa, 2016). The data used to construct the financial inclusion index are sourced from the World Bank (2023) for account and loan figures, and from the Financial Access Survey for usage. Data on other explanatory variables are sourced from World Bank (2023). Due to the limited longevity of available data, quarterly data covering the period from 2004 to 2018 are used, based on an availability sample of 36 Sub-Saharan African countries.

The dependent variable, CO2 intensity based on production, serves as a vital indicator for evaluating the environmental impact of economic activities, especially in developing regions such as Sub-Saharan Africa. By measuring carbon dioxide emissions per unit of production, this metric provides a clear assessment of energy efficiency and the sustainability of economic processes. This indicator is particularly relevant when analyzing the role of financial inclusion policies and knowledge diffusion in reducing CO2 emissions while supporting economic growth. Stern (2004) highlights its importance in studying the Environmental Kuznets Curve, while Pardini (2021) demonstrates its strong connection to economic performance in developing countries. Furthermore, Aldy and Stavins (2012) use CO2 intensity to assess the effectiveness of carbon pricing mechanisms, and Kalkuhl and Edenhofer (2013) apply it to measure the impact of global climate policies.

Turning to the independent variables, the Financial Inclusion Index (FII) is critical for investigating green growth in Sub-Saharan Africa, as it fosters access to financial services for both individuals and businesses, thereby facilitating investments in sustainable technologies that can lower CO2 intensity. For example, Beck et al. (2007) illustrate how banking access is essential for mobilizing green finance, while Karlan and Zinman (2010) find that credit expansion encourages the adoption of eco-friendly technologies, contributing to emissions reductions. Additionally, Giné and Townsend (2004) demonstrate that financial literacy enhances this dynamic by improving resource management. Chakraborty and Kumbhakar (2021) further show that financial inclusion stimulates green technology investments in emerging markets, leading to emission reductions.

Other key variables that capture knowledge diffusion encompass education (edu), research and development (R&D), and internet usage (Rogers, 2003). Education (edu) stands as a significant factor, as Grossman and Krueger (1995) point out that higher education levels foster environmental awareness and support eco-friendly policies that mitigate CO2 emissions. Similarly, Marrero (2010) notes that countries with higher education levels adopt green technologies more swiftly, while Borensztein, De Gregorio, and Lee (1998) emphasize that education enhances the benefits of R&D investments, resulting in emissions-reducing innovations. Moreover, studies by Romer (1990) and Aghion, Hemous, and Veugelers (2009) argue that R&D investments are essential drivers of technological innovations critical to reducing CO2 intensity. Internet usage also plays a vital role by accelerating the spread of sustainable practices and green innovations. In support, Grossman and Krueger (1995) and Romer (1990) suggest that technological progress, facilitated by internet access, contributes to emissions reduction, as confirmed by Shahbaz, Nasir, Hille, and Mahalik (2020). Collectively, these studies underscore the importance of internet usage, R&D, education, and financial inclusion in the transition toward a green economy in Sub-Saharan Africa.

For control variables, population growth (pop), GDP growth (gdpc), trade openness (trade), foreign direct investment (FDI), and governance efficiency (govindex) are significant determinants of green growth, as measured by CO2 intensity based on production. A rising population increases energy demand and infrastructure needs, which can heighten CO2 emissions (Bongaarts, 1992; Ehrlich & Holdren, 1971). Similarly, the relationship between economic growth and emissions is often depicted as an inverted U-shaped environmental Kuznets curve, where emissions initially rise with growth but later decrease as cleaner technologies are adopted (Grossman & Krueger, 1991). Trade openness and FDI also have mixed impacts: they may either increase emissions by supporting polluting sectors or reduce them through clean technology transfer (Copeland & Taylor, 2004; Pao & Tsai, 2011). Finally, effective governance is pivotal in enforcing environmental policies and attracting green investments, as noted by Acemoglu, Aghion, Bursztyn, and Hemous (2012) and Shafik (1994).

Table 1 on descriptive statistics reveals significant variability across the analyzed variables. CO_2 emissions intensity (green) varies widely, with a relatively low mean but high dispersion, indicating substantial differences between countries. The financial inclusion index (fii) is generally low, with a wide range of values, reflecting disparities in access to financial services. Population growth (pop) is moderate on average, though some countries experience a decline. GDP growth (gdpc) shows high volatility, ranging from periods of economic contraction to strong growth. Trade openness (trade) is high on average but exhibits considerable variation among countries. Foreign direct investment (fdi) also varies greatly, with occasional negative values. Education levels (edu) and internet usage (internet) display notable differences, indicating significant gaps in access to education and technology. R&D expenditure (research) and governance efficiency (govindex) show broad dispersion as well, with extreme values reflecting different contexts. The coefficients of variation fluctuate across multiple values, indicating significant relative variability in the distributions and an apparent heterogeneity. These variations highlight the diversity of economic, social, and political conditions in the sample studied. The fact that all values fall between less than one unit and several tens suggests non-anomalous estimates.

Table 1. Descriptive statistics.

Variables	Obs.	Mean	Std. dev	Min.	Max.	Coefficient of variation
Green	2160	0.802	1.432	0.022	8.447	1.786
fii	2160	0.121	0.098	0.006	0.650	0.813
pop	2160	2.534	0.843	-0.402	5.078	0.333
gdpc	2160	4.719	4.282	-20.49	33.63	0.907
trade	2160	68.17	27.41	22.24	165.0	0.402
fdi	2160	3.992	5.284	-10.04	38.94	1.324
edu	2160	42.65	12.50	16.20	82.80	0.293
Internet	2160	10.41	12.77	0.155	62.40	1.227
Research	2160	4.321	1.825	-0.994	9.505	0.422
govindex	2160	-2.5e-09	2.202	-4.176	5.805	-0.139
Sample countries	Angola (AGO), Botswana (BWA), Burkina Faso (BFA), Burundi (BDI), Cape Verde (CPV), Cameroon (CMR), Chad (TCD), Comoros (COM), the Republic of Congo (COG), Ivory Coast (CIV), Ethiopia (ETH), Gabon (GAB), Gambia (GMB), Ghana (GHA), Guinea (GIN), Guinea-Bissau (GNB), Kenya (KEN), Lesotho (LSO), Madagascar (MDG), Malawi (MWI), Mali (MLI), Mauritania (MRT), Mauritius (MUS), Mozambique (MOZ), Namibia (NAM), Niger (NER), Nigeria (NGA), Rwanda (RWA), Senegal (SEN), Sierra Leone (SLE), South Africa (ZAF), Tanzania (TZA), Togo (TGO), Uganda (UGA), Zambia (ZMB), and Zimbabwe (ZWE).					

Figure 1 illustrates the bilateral relationships between green growth and financial inclusion, as well as between green growth and various aspects of knowledge diffusion, including education, internet usage, and scientific publications. The observed relationships show that financial inclusion has a positive influence on green growth. This observation challenges the findings of Kumar and Managi (2009) who demonstrate that financial inclusion promotes the adoption of clean technologies in developing countries, and Beck et al. (2007) who highlight how increased access to financial services can foster more sustainable economic behaviors. Regarding knowledge diffusion, studies indicate that internet usage and scientific publications are positively correlated with green growth. Bertoldi and Atanasiu (2007) show that information technologies, such as the internet, increase resource consumption, while Zhang and Liu (2013) find that increased internet usage can also deteriorate companies' environmental performance. However, education presents a negative relationship with green growth. This observation warrants further exploration to understand the specific contexts where higher and qualitative education could immediately translate into green growth gains.

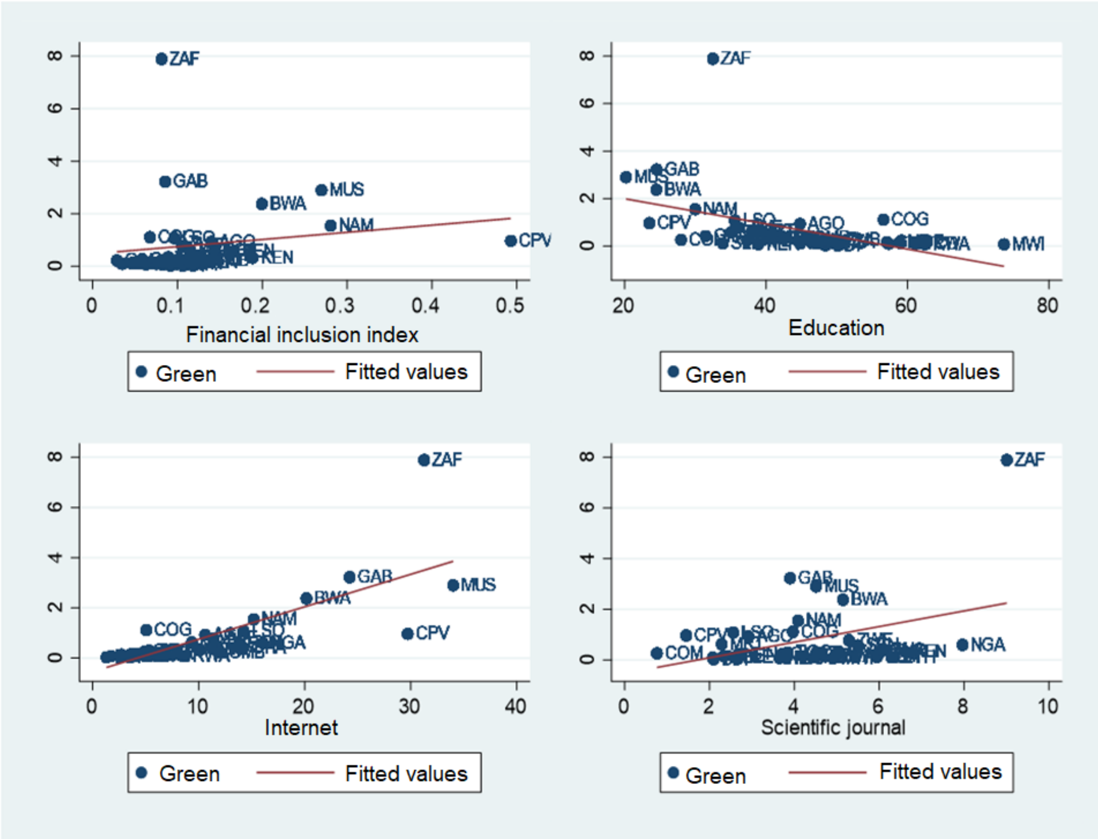

Figure 1. Correlation graph.

Table 2 of correlations reveals several significant relationships between green growth and the studied variables. Financial inclusion (fii) shows a weak positive correlation (0.1507*), suggesting a slight association with green growth. The population growth rate (Pop) and GDP growth rate (gdpc) are negatively correlated with green growth, at -0.4576* and -0.1474*, respectively, indicating that rapid demographic growth and high economic growth may be associated with higher CO_2 emission intensity. Trade openness (Trade) and governance efficiency (govindex) are positively correlated with green growth, at 0.2434* and 0.4633*, respectively, suggesting that these factors contribute to better environmental performance. Internet usage (internet) is strongly positively correlated (0.5038*), while research and development (research) is also positively correlated (0.3721*), indicating that internet access and R&D investments support green growth. In contrast, education (Edu) is negatively correlated (-0.4118*), which may reflect a complexity in the relationship between education level and environmental performance. However, this table only provides an overview of the various relationships and does not account for conditional correlations.

Table 2. matrix of correlation.

Variables	Green	Fii	Pop	gdpc	Trade	fdi	edu	Internet	Research	govindex
Green	1.000									
Fii	0.151*	1.000								
Pop	-0.458*	-0.410*	1.000							
Gdpc	-0.147*	-0.040	0.194*	1.000						
Trade	0.243*	0.284*	-0.386*	-0.037	1.000					
Fdi	-0.054	0.044	0.046	0.062	0.294*	1.000				
Edu	-0.412*	-0.540*	0.572*	0.229*	-0.375*	0.001	1.000			
Internet	0.504*	0.457*	-0.417*	0.156*	0.221*	-0.054	-0.537*	1.000		
Research	0.372*	0.300*	-0.055	0.042	-0.201*	-0.105*	-0.040	0.278*	1.000	
Govindex	0.463*	0.556*	-0.513*	0.013	0.288*	0.058	-0.509*	0.436*	0.210*	1.000

Note: * $p<0.1$.

3.2. Model Presentation and Estimation Strategy

3.2.1. Model Specification

The aim of this paper is to examine the joint and interactive effects of financial inclusion and knowledge diffusion on green growth in Sub-Saharan Africa. Fundamentally, financial inclusion promotes the adoption of eco-friendly technologies, while education enhances environmental awareness (Beck et al., 2007; Mazzucato & Semieniuk, 2017). Based on these foundations, the study investigates the following functional relationship:

$$green = F(ifi, knowledge\ diffusion, control\ variables) \quad (1)$$

where green represents green growth, fii is the financial inclusion index, and F is the functional operator. Knowledge diffusion, from production to usage, is measured here through education level, research and development, and internet usage. Specifically, our analysis focuses on the following equations:

$$green_{it} = \beta_0 + \beta_1 \cdot ifi_{it} + \beta_2 \cdot pop_{it} + \beta_3 \cdot gdpc_{it} + \beta_4 \cdot trade_{it} + \beta_5 \cdot fdi_{it} + \beta_6 \cdot edu_{it} + \beta_7 \cdot govindex_{it} + \beta_8 \cdot (ifi \times edu)_{it} + \mu_i + \lambda_t + \epsilon_{it} \quad (2)$$

$$green_{it} = \beta_0 + \beta_1 \cdot ifi_{it} + \beta_2 \cdot pop_{it} + \beta_3 \cdot gdpc_{it} + \beta_4 \cdot trade_{it} + \beta_5 \cdot fdi_{it} + \beta_6 \cdot R\&D_{it} + \beta_7 \cdot govindex_{it} + \beta_8 \cdot (ifi \times R\&D)_{it} + \mu_i + \lambda_t + \epsilon_{it} \quad (3)$$

$$green_{it} = \beta_0 + \beta_1 \cdot ifi_{it} + \beta_2 \cdot pop_{it} + \beta_3 \cdot gdpc_{it} + \beta_4 \cdot trade_{it} + \beta_5 \cdot fdi_{it} + \beta_6 \cdot internet_{it} + \beta_7 \cdot govindex_{it} + \beta_8 \cdot (ifi \times internet)_{it} + \mu_i + \lambda_t + \epsilon_{it} \quad (4)$$

Where $green_{it}$ is dependent variable, measuring CO_2 intensity based on production for country i in year t. β_0 is Constant. β_1, β_2, …, β_8 are coefficients of the independent variables. μ_i is country-specific fixed or random effect for country i. λ_t istime-specific fixed or random effect for year t. ϵit is error term for country i in year t.

The financial inclusion index (fii) is expected to have a negative coefficient in relation to CO_2 intensity reduction, as increased access to finance enables the adoption of sustainable and clean technologies (Beck et al., 2007; Mazzucato & Semieniuk, 2017). Population growth (Pop), on the other hand, is expected to have a positive sign, as a growing population increases energy and natural resource demand, thereby raising CO_2 emissions if sustainable development policies are not implemented (Dietz & Rosa, 1994; Ehrlich & Holdren, 1971). The expected sign for GDP growth (gdpc) is ambiguous due to the complex interactions between economic growth and CO_2 emissions. A positive sign may indicate industrial production intensification, while a negative sign may reflect the adoption of cleaner technologies (Chakravarty & Tavoni, 2013; Grossman & Krueger, 1995). Trade openness (trade) can have a mixed effect depending on whether it promotes polluting industries or facilitates access to ecological technologies (Antweiler, Copeland, & Taylor, 2001; Cole & Elliott, 2003). Similarly, foreign direct investment (FDI) can either increase emissions by supporting polluting industries or reduce them by facilitating the import of clean technologies (Blomström & Kokko, 1998; Zhang, 2006).

In addition, a higher level of education (edu) correlates with increased environmental awareness and a greater tendency to adopt green technologies, supporting an anticipated negative sign for this variable (Gordon, 1998; Jaffe, Newell, & Stavins, 2003). Similarly, effective governance (govindex) allows for more stringent environmental regulations, thus contributing to lower CO_2 emissions (Kaufmann, Kraay, & Mastrorillo, 2011; Stern, 2004).

Furthermore, the interaction between financial inclusion (fii) and education (edu) is also expected to have a negative impact on CO_2 intensity. This is because financial access promotes investments in green technologies, while higher education levels enhance both the adoption of these technologies and foster greater environmental consciousness (Beck et al., 2007; Kumar & Managi, 2009). The synergy between financial inclusion and education thus reinforces the effectiveness of environmental policies (Goulder & Schneider, 1999; Nguyen & Van, 2020) leading to a notable reduction in CO_2 emissions (Jenkins & Thomas, 2002).

Additionally, the "Research and Development" (R&D) variable is anticipated to exhibit a negative sign as it plays a vital role in promoting clean technology innovation and improving energy efficiency, ultimately leading to a reduction in CO_2 emissions (Newell, Jaffe, & Stavins, 1999; Popp, 2002). Research shows that investments in R&D contribute to the development of green technologies, thus lowering CO_2 intensity (Acemoglu et al., 2012; Griliches, 1992). Moreover, the interaction between financial inclusion and R&D is expected to amplify this effect, as it facilitates funding for technological innovations and accelerates the adoption of environmentally friendly practices (Mazzucato, 2013; Zhu & Wang, 2017).

Internet usage (internet) is also expected to have a negative sign, as it improves resource management and promotes more sustainable practices, reducing CO_2 intensity (Bertoldi & Atanasiu, 2007; Zhang & Liu, 2013). Similarly, the interaction between financial inclusion and internet usage should have a synergistic impact, facilitating the diffusion of green technologies and the adoption of sustainable practices, further enhancing CO_2 emission reductions (Bertoldi & Atanasiu, 2007; Mazzucato, 2013).

3.3. Estimation Strategy

Preliminary analyses to verify the properties of our time series were conducted beforehand. These include tests for cross-sectional dependence and unit root. Specifically, this study tests cross-sectional dependence (CD) using the CD test developed by Pesaran (2004). The Cross-sectionally Augmented Dickey-Fuller (CADF) test (Pesaran, 2007) is applied to assess stationarity. Multicollinearity is evaluated using the Variance Inflation Factor (VIF), a widely employed measure to detect multicollinearity. Typically, a VIF exceeding 10 is considered indicative of significant multicollinearity issues (Gujarati & Porter, 2009). According to Wooldridge (2010) endogeneity arises when one or more explanatory variables are correlated with the error term, leading to biased coefficient estimates. Hansen (1982) proposes the orthogonality conditions test (GMM C statistic: Generalised Method of Moments Cross-sectional statistic) to test for endogeneity, with the null hypothesis stating that the variables are exogenous.

The analysis is based on the combined use of estimation methods such as POLS, Newey and West, and Driscoll and Kraay, justified by their complementary advantages in handling panel data in the absence of cross-sectional dependence. The POLS (Pooled Ordinary Least Squares) method is valued for its simplicity and ease of interpretation, providing direct initial regression coefficient estimates (Greene, 2011). However, it is limited by its inability to address heteroscedasticity and autocorrelation. To overcome these limitations, the Newey and West (1987) method adjusts standard errors by correcting for heteroscedasticity and autocorrelation, ensuring more reliable inferences when residuals exhibit non-identical and non-independent dependencies (Newey & West, 1987).

The Driscoll and Kraay (1998) method offers additional robustness by adjusting standard errors for complex temporal and spatial dependencies, which is crucial for panel data exhibiting such characteristics (Arellano, 2003; Driscoll & Kraay, 1998). By combining POLS with these correction methods, we obtain more robust estimates and reliable inferences, thereby enhancing the credibility of the results and ensuring an appropriate adjustment of standard errors tailored to the specificities of the data (Driscoll & Kraay, 1998; Newey & West, 1987).

4. RESULTS

As mentioned above, the issue of cross-sectional dependence leads to biased and inconsistent results. Therefore, we analyze whether the cross-sections are independent using the Pesaran (2004) test to determine the presence of cross-sectional dependence in the variables. The results presented in Table 3 indicate that the null hypothesis of cross-sectional independence is significantly rejected at the 1% level.

Table 3. CD dependence test.

Variable	Test	p-value	corr	abs(corr)
Green	54.35	0.000	0.987	0.987
Fii	42.97	0.000	0.770	0.806
Pop	48.68	0.000	0.881	0.881
Gdpc	3.91	0.000	0.071	0.229
Trade	47.71	0.000	0.865	0.865
Fdi	22.40	0.000	0.406	0.416
Edu	44.69	0.000	0.939	0.939
Internet	41.64	0.000	0.873	0.873
Research	46.06	0.000	0.967	0.967
Govindex	44.38	0.000	0.931	0.931

Following the results of the cross-sectional dependence test, second-generation unit root tests, specifically PURT tests, are employed to verify the presence of a unit root in the series. These tests are utilized as they account for cross-sectional dependence and heterogeneity among the series. The results of the PURT (Panel Unit Root Test), reported in Table 4, indicate that all variables are stationary at level.

Table 4. PURT (Stationary in level).

Variables	No trend		With trend	
	Stat.	Prob.	Stat.	Prob.
Green	-15.921	0.000	-14.939	0.000
Fii	-12.716	0.000	-11.614	0.000
Pop	-17.072	0.000	-16.867	0.000
Gdpc	-14.143	0.000	-12.908	0.000
Trade	-12.328	0.000	-9.792	0.000
Fdi	-16.068	0.000	-15.346	0.000
Edu	-6.876	0.000	-4.673	0.000
Internet	-16.065	0.000	-15.303	0.000
Research	-17.415	0.000	-16.526	0.000
Govindex	-13.759	0.000	-12.092	0.000

The null hypothesis in a multicollinearity test states that there is no severe multicollinearity between the explanatory variables in the model. In Table 5, the VIF values range from 3.85 to 7.04, with an average of 5.616. However, none of the variables exceed the critical threshold for multicollinearity, indicating that the model is sufficiently stable to produce reliable estimates (Wooldridge, 2010). In Table 3 and 4, which present all variables in our study, the chi2 statistic for the endogeneity test ranges from 67.75 to 104.85, with all p-values exceeding the 1% threshold. This implies that the null hypothesis of exogeneity cannot be rejected. Therefore, in line with Hayashi (2000) recommendations, there is no evidence of endogeneity, and the explanatory variables can be considered exogenous in our equations, ensuring the validity of orthogonality conditions and the robustness of the estimates.

Table 5. Test of multicolinearity.

Variables	Green	fii	pop	govindex	gdpc	Trade	fdi	edu	Internet	Research	Mean VIF
VIF	7.04	6.76	5.46	6.06	4.74	3.85	5.39	6.22	4.76	5.86	5.616
1/VIF	0.142	0.149	0.183	0.165	0.211	0.26	0.186	0.161	0.21	0.171	

The diverse variability of our data, as observed in Table 1 of descriptive statistics, suggests a heterogeneity within our panel. This led us to adopt a Pooled Ordinary Least Squares (POLS) estimation, which takes this potential heterogeneity into account and has the advantage of providing efficient estimators in the absence of autocorrelation or heteroskedasticity, as long as the basic regression assumptions hold. After the POLS estimation, two options are available to verify the robustness of the results: either conducting post-estimation tests for autocorrelation and heteroskedasticity, or applying a method that corrects for the potential presence of these issues, such as the Newey and West (1987) approach. We opted for the second option, as the Newey and West (1987) method appears more optimal, providing a way to verify the consistency of the estimated coefficients. Since the first two estimations do not account for cross-sectional dependence in the panel—and the null hypothesis of cross-sectional independence was rejected—the Driscoll and Kraay (1998) test provides efficient estimators under such circumstances. The stability of the results across these different estimation methods attests to their robustness.

According to Table 6, financial inclusion (fii) has a positive and significant impact on green growth, measured by CO2 intensity from production, at the 1% level. A higher level of financial inclusion appears to deteriorate green growth. This is because increased financial inclusion also implies a greater diversity of financial products and services, including those typically associated with pollution. While financial inclusion (fii) has the potential to be crucial for green growth by facilitating access to sustainable financial products and improving the efficiency of green investments, as Banerjee and Duflo (2014) suggest, and Allen, Carletti, and Marquez (2016) highlight its role in diversifying financial products to include ecological options, Chen, Li, and Zeng (2019) note that fii can direct resources towards promising ecological projects, and Allen et al. (2014) argues it supports the implementation of environmental policies by easing access to capital. In summary, green financial inclusion would theoretically support green growth by enhancing access to ecological financing and optimizing resource allocation for sustainable projects.

Education (Edu) has a negative and significant effect on green growth (Green), measured by CO2 intensity from production, at the 5% level in Sub-Saharan Africa. As education improves, green growth becomes less significant. This reflects a higher level of pollution associated with educated individuals who often engage in more polluting activities that can spread across various sectors, including those with a larger ecological footprint, such as the industrial sector. However, education can also potentially improve green growth by reducing CO2 intensity from production. Grossman and Krueger (1995) suggest that better education can reduce pollution as educated individuals often access less polluting jobs. Cole and Elliott (2005) and Kuznets (1955) highlight that in developing countries, increased environmental education can limit concentration in carbon-intensive industries. Lucas (2004) and Beckerman (1992) confirm that education can decrease pollution by directing workers to low-impact sectors. Although education is generally beneficial, it can temporarily hinder green growth if it leads to employment in more polluting industries. The interaction between financial inclusion and education negatively and significantly influences green growth at the 1% level. Improved education results in a positive effect of financial inclusion on green growth. This interaction may be beneficial for green growth in Sub-Saharan Africa. Education can reduce pollution by directing individuals towards less polluting sectors (Grossman & Krueger, 1995; Kuznets, 1955) supported by effective financial policies (Beckerman, 1992; Lucas, 2004; Mazzucato, 2013). However, if not aligned with sustainability, this combination can negatively impact green growth (Welsch, 2004).

Table 6. Financial inclusion and education for green economy in SSA.

Variables	(1)	(2)	(3)	(4)	(5)	(6)
	POLS	NEWEY	driscoll-kraay	POLS	NEWEY	driscoll-kraay
Pop	-0.613***	-0.613***	-0.613***	-0.607***	-0.607***	-0.607***
	(0.146)	(0.146)	(0.164)	(0.129)	(0.129)	(0.180)
Gdpc	-0.013	-0.013	-0.013	-0.014	-0.014	-0.014
	(0.016)	(0.016)	(0.017)	(0.014)	(0.014)	(0.014)
Trade	-0.001	-0.001	-0.001	-0.002	-0.002	-0.002
	(0.004)	(0.004)	(0.011)	(0.004)	(0.004)	(0.012)
Fdi	-0.020*	-0.020*	-0.020*	-0.021*	-0.021*	-0.021*
	(0.011)	(0.011)	(0.012)	(0.011)	(0.011)	(0.011)
govindex	0.265***	0.265***	0.265**	0.276***	0.276***	0.276**
	(0.042)	(0.042)	(0.128)	(0.039)	(0.039)	(0.116)
fii	4.619***	4.619***	4.619***	4.719***	4.719***	4.719***
	(1.047)	(1.047)	(1.250)	(1.046)	(1.046)	(1.230)
Edu	-0.016**	-0.016**	-0.016**	-0.016**	-0.016**	-0.016**
	(0.007)	(0.007)	(0.007)	(0.007)	(0.007)	(0.007)
c.fii#c.edu				-0.171***	-0.171***	-0.171***
				(0.037)	(0.037)	(0.053)
Constant	3.680***	3.680***	3.680	3.306***	3.306***	3.306
	(0.781)	(0.781)	(2.416)	(0.738)	(0.738)	(2.317)
Observations	2160	2160	2160	2160	2160	2160
R-squared	0.415		0.415	0.419		0.419
Number of groups			60			60
Endog chi2(1)	97.43	81.34	79.43	67.85	95.45	77.34
Endog p-value	0.457	0.466	0.326	0.664	0.485	0.644

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

According to Table 7, internet usage (internet) positively and significantly impacts green growth (Green), measured by CO2 intensity, at the 1% level in Sub-Saharan Africa. As internet usage increases, pollution also rises. This reflects greater internet utilization in resource-intensive sectors, given the fragile industrial base in most African countries.

Internet usage negatively affects green growth in Sub-Saharan Africa by diminishing energy efficiency and promoting less ecological practices. Jorgenson and Wilcoxen (1990) demonstrate that limited access to environmental information increases CO2 emissions. Chau and Tam (1997) find that poor resource management due to lack of transparency hampers green growth. Kumar and Kumar (2019) show that the internet discourages effective energy practices in developing countries with low environmental education. Choi and Lee (2016) emphasize that the internet can stimulate less polluting sectors, and Shahbaz et al. (2020) illustrate that it facilitates natural resource management and the adoption of clean technologies when environmental information is easily accessible. These studies suggest that increased internet usage can conditionally support green growth in Sub-Saharan Africa.

The interaction between financial inclusion and internet usage (c.fii#c.internet) positively and significantly influences green growth at the 5% level. Improved internet usage leads to a reduction in the effect of financial inclusion on green growth. Indeed, internet use is more pronounced in the service sector in Sub-Saharan Africa. The interaction between financial inclusion and internet usage delays green growth in Sub-Saharan Africa. Beck et al. (2007) argue that this combination could enhance financial service efficiency when coupled with ecological practices. Claessens and Feijen (2007) and Jorgenson (2001) note that the internet facilitates access to a wide range of financial services, necessitating sustainable resource management. Madden and McMillan (2004) add that the internet could promote less polluting service sectors, while Shahbaz, Khan, and Schmitz (2018) confirm that this interaction could improve green financial practices. These studies suggest that enhanced internet usage combined with financial inclusion could support green growth.

Table 7. Financial inclusion and internet for green economy in SSA.

Variables	(1)	(2)	(3)	(4)	(5)	(6)
	POLS	NEWEY	Driscoll-Kraay	POLS	NEWEY	Driscoll-Kraay
Pop	-0.397***	-0.397***	-0.397***	-0.460***	-0.460***	-0.460***
	(0.106)	(0.106)	(0.132)	(0.117)	(0.117)	(0.169)
Gdpc	-0.020	-0.020	-0.020	-0.029	-0.029	-0.029
	(0.110)	(0.110)	(0.110)	(0.112)	(0.112)	(0.112)
Trade	-0.005	-0.005	-0.005	-0.006	-0.006	-0.006
	(0.013)	(0.013)	(0.013)	(0.012)	(0.012)	(0.012)
Fdi	-0.014*	-0.014*	-0.014*	-0.025***	-0.025***	-0.025***
	(0.008)	(0.008)	(0.008)	(0.009)	(0.009)	(0.009)
Govindex	0.248***	0.248***	0.248**	0.230***	0.230***	0.230**
	(0.039)	(0.039)	(0.116)	(0.032)	(0.032)	(0.102)
fii	4.932***	4.932***	4.932***	4.961***	4.961***	4.961***
	(1.048)	(1.048)	(1.298)	(1.044)	(1.044)	(1.300)
Internet	0.034***	0.034***	0.034***	0.035***	0.035***	0.035***
	(0.009)	(0.009)	(0.013)	(0.008)	(0.008)	(0.012)
c.fii#c.internet				0.038**	0.038**	0.038**
				(0.018)	(0.018)	(0.019)
Constant	1.921***	1.921***	1.921	1.958***	1.958***	1.958
	(0.530)	(0.530)	(1.726)	(0.526)	(0.526)	(1.821)
Observations	2160	2160	2160	2160	2160	2160
R-squared	0.418		0.418	0.317		0.317
Number of groups			60			60
Endog chi2(1)	86.35	93.33	71.24	88.44	77.35	96.46
Endog p-value	0.844	0.564	0.456	0.546	0.651	0.745

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

From Table 8, it is observed that research and development (R&D) positively and significantly impacts green growth (Green), measured by CO2 intensity, at the 1% level in Sub-Saharan Africa. As knowledge production expands, green growth deteriorates. This reflects a lower adoption of innovative solutions increasingly misaligned with Sustainable Development Goals (SDGs). R&D hampers green growth in Sub-Saharan Africa by failing to promote ecological innovation. Innovations are not sufficiently green in the region. However, Romer (1990) and Aghion et al. (2009) demonstrate that R&D investments can direct innovation toward sustainable technologies. Acemoglu et al. (2012) and Popp (2006) confirm that R&D generates clean technologies and it is crucial role for the SDGs. Thus, enhancing R&D focused on green innovations would foster green growth in Sub-Saharan Africa.

The moderating effect of R&D on financial inclusion (c.fii#c.research) significantly influences CO2 intensity, also at the 1% level. Improved R&D leads to a negative impact of financial inclusion on green growth. Indeed, knowledge production aligned with sustainable development realities is more innovative, leading to outputs that balance environmental preservation with growth—a global reality that Sub-Saharan African countries should align with. R&D amplifies the adverse effects of financial inclusion on green growth through various mechanisms. According to

Romer (1990) R&D stimulates innovation, but this is not sufficiently ecological in Sub-Saharan Africa. Aghion and Howitt (1998) show that favorable financial conditions, like financial inclusion, would strengthen this impact if the financial inclusion were green.

Regarding control variables, most results are significant except for GDP growth and trade openness, which have non-significant effects (see Table 6, 7, and 8). Population growth (pop), as noted by Malthus (1798) and Stern (2004) is negatively related to green growth at the 1% level, indicating that a larger population does not necessarily lead to a proportional increase in CO_2 production, although human activities, both domestic and professional, contribute to environmental degradation, with productive activities being more polluting. Foreign direct investment (FDI), as highlighted by Jenkins and Thomas (2002) and Rodrik (1998) negatively and significantly impacts green growth, reflecting an inverse relationship with CO_2 intensity, although multinational corporations increasingly invest in ecological practices to enhance their image and social responsibility. Paradoxically, governance quality (govindex), according to Kaufmann et al. (2011) positively and significantly influences CO_2 emissions, suggesting that despite efforts to strengthen environmental policies, governance in Sub-Saharan Africa still does not sufficiently address environmental issues, limiting the impact of green growth policies. Thus, while education improves green growth, knowledge production through R&D deteriorates green growth through its interaction with financial inclusion. Similarly, internet usage, when interacting with financial inclusion, also deteriorates green growth.

Table 8. Financial inclusion and Scientific research for green economy in SSA.

Variables	(1) POLS	(2) NEWEY	(3) driscoll-kraay	(4) POLS	(5) NEWEY	(6) driscoll-kraay
Pop	-0.464*** (0.098)	-0.464*** (0.098)	-0.464*** (0.132)	-0.432*** (0.110)	-0.432*** (0.110)	-0.432*** (0.136)
Gdpc	-0.030 (0.111)	-0.030 (0.111)	-0.030 (0.112)	-0.028 (0.111)	-0.028 (0.111)	-0.028 (0.114)
Trade	-0.011 (0.012)	-0.011 (0.012)	-0.011 (0.012)	-0.004 (0.020)	-0.004 (0.020)	-0.004 (0.012)
Fdi	-0.016** (0.007)	-0.016** (0.007)	-0.016** (0.008)	-0.023*** (0.008)	-0.023*** (0.008)	-0.023*** (0.009)
Govindex	0.195*** (0.026)	0.195*** (0.026)	0.195** (0.072)	0.216*** (0.034)	0.216*** (0.034)	0.216** (0.095)
fii	3.058*** (0.712)	3.058*** (0.712)	3.058*** (0.831)	3.067*** (0.613)	3.067*** (0.613)	3.067*** (0.732)
Research	0.267*** (0.048)	0.267*** (0.048)	0.267*** (0.066)	0.273*** (0.039)	0.273*** (0.039)	0.273*** (0.057)
c.fii#c.research				0.120*** (0.017)	0.120*** (0.017)	0.120*** (0.033)
Constant	0.747** (0.315)	0.747** (0.315)	0.747 (0.909)	1.899*** (0.547)	1.899*** (0.547)	1.899 (1.867)
Observations	2160	2160	2160	2160	2160	2160
R-squared	0.445		0.445	0.310		0.310
Number of groups			60			60
Endog chi2(1)	104.85	98.42	80.44	76.43	67.75	88.45
Endog p-value	0.853	0.667	0.756	0.476	0.574	0.493

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

5. CONCLUSION

This study examines the associated and interactive effects of financial inclusion and knowledge diffusion, measured by research and development (R&D), internet usage, and education on green growth in Sub-Saharan Africa. Using a sample of 36 countries and quarterly data from 2004 to 2018, based on data availability and accessibility, and employing a combination of POLS (Pooled Ordinary Least Squares), Newey and West (1987) and Driscoll and Kraay (1998) estimation methods, the following results were obtained. These results indicate that financial inclusion, R&D, and internet usage negatively impact green growth by increasing CO_2 intensity related to production. These negative impacts may stem from either inefficient applications of green technologies or an intensified focus on polluting sectors. By contrast, education positively contributes to reducing CO_2 intensity, as better-educated individuals tend to adopt sustainable practices and gravitate towards eco-friendly sectors, ultimately promoting green growth. In terms of knowledge diffusion, while education appears to bolster green growth, the production of knowledge via R&D (when combined with financial inclusion) appears to hinder it. Similarly, internet usage, in conjunction with financial inclusion, shows a negative effect on green growth.

These insights underscore the need to better align financial inclusion, R&D, and digital development policies with environmental sustainability objectives. Education, however, emerges as a key tool for reducing ecological footprints and supporting green growth. To maximize the benefits of sustainable development, Sub-Saharan African countries should consider refining their strategies by integrating eco-friendly practices within the frameworks of financial inclusion, R&D, and digital technology initiatives. Supporting green growth in this region requires promoting high-quality environmental education, incorporating sustainability themes into educational curricula, and encouraging continuous environmental training within industrial sectors. Financial inclusion policies should incorporate green initiatives, offering eco-friendly financial products such as green loans, possibly supported by tax incentives. Additionally, R&D investments should prioritize sustainable innovation, while internet and FinTech developments could help channel responsible financing into ecological projects. Future research might delve into whether energy limitations contribute to these adverse effects of financial inclusion, R&D, and internet usage on green growth in Sub-Saharan Africa.

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