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Money talks, green walks: Does financial inclusion promote green sustainability in Africa?

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ABSTRACT

This study explores the dynamic relationship between financial inclusion and green sustainability across 38 African countries. We construct an environmental pollution index and a financial inclusion index covering the period 2000–2021 to account for the several dimensions within both indicators and employ them in the System GMM approach. We also test for intra-regional heterogeneity in Africa. Our empirical results show that financial inclusion, while economically beneficial, poses a significant risk of environmental degradation and has a distinctive inverted U-shaped relationship. A direct link between increases in financial inclusion and pollution alters at a turning point, beyond which further financial inclusion increases enhance green sustainability. The same pattern is observed for aggregate output. The results hold even when we control for a score of macro-level determinants. Our analysis highlights intra-regional heterogeneity, revealing differences in impact across income levels and regional groups within Sub-Saharan Africa. These results remain robust for alternative proxies of green sustainability. We offer valuable insights for policymakers to promote sustainability through inclusive financial practices and policies in Sub-Saharan Africa.

1. Introduction

In recent years, climate change, global warming, and other environmental threats have forced the world, including Africa, towards sustainability (Udeagha & Muchapondwa, 2022). Forward-looking countries focused on sustainable growth are already looking into the opportunity of advancing the “E” component in their environmental, social, and governance (ESG) approach. The African continent, endowed with rich natural resources and diverse ecosystems, faces this dual challenge of fostering economic growth while safeguarding its environmental heritage (Opoku, Acheampong, Dzator, & Kufuor, 2022). These challenges include high carbon emissions levels, enormous environmental pollution, and an increasing dependence on energy sources. As such, the intersection of economic development and environmental degradation presents a critical area of study in financial inclusion. Grounded in the Theory of Financial Intermediation (Allen & Santomero, 1997), financial inclusion is pivotal in mobilizing funds from a broader population and channeling those funds into productive investments. Since fund accessibility influences the income and consumption patterns of individuals or organizations (Ait Lahcen & Gomis-Porqueras, 2021), we question whether it supports environmental sustainability or worsens environmental challenges. Financial inclusion already significantly supports the social component of ESG by contributing to

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eight of the seventeen Sustainable Development Goals (SDGs) (Kaur, Ahmad, Hari, & Kattumuri, 2024). Hence, in this paper, we seek to investigate the impact of financial inclusion on green sustainability in Africa, where green sustainability reflects the extent of environmental pollution. By examining this relationship, we aim to provide insights into how financial inclusion can be leveraged to promote sustainable development across the continent.

The term "green sustainability" denotes a concept that primarily emphasizes environmental consciousness, practices, and adopting eco-friendly products and services to minimize negative impacts on ecosystems and safeguard the environment for future generations. It is often synonymous with environmental sustainability (Udeagha & Muchapondwa, 2023). Environmental sustainability encompasses a range of practices, including sustainable transportation, investing in waste-to-energy projects, green building designs, reducing greenhouse gas emissions, conserving biodiversity, promoting renewable energy, and adopting sustainable production and consumption patterns. However, the extent to which financial inclusion can influence this pursuit remains a subject of empirical inquiry. Financial inclusion, in essence, provides affordable and accessible financial products and services to a broader cross-section of society, including individuals traditionally excluded from the formal financial system. The increase in financial accessibility and usage promotes reduced transaction costs, the development of innovative financial products, and the increased coverage of financial services (Kumar, Thrikawala, & Acharya, 2022).

According to Le, Le, and Taghizadeh-Hesary (2020), the impact of financial inclusion on the environment could either take a positive or negative trajectory. The positive facet is evident in how financial inclusion provides access to funds for investments in green technologies, fostering sustainable agricultural practices, clean-energy innovations, and energy-efficient infrastructure like solar panels and wind turbines (Usman, Makhdum, & Kousar, 2021). These endeavors reduce reliance on fossil fuels, mitigate greenhouse gas emissions, and strengthen overall environmental sustainability (Chen, Cheng, Lee, & Wang, 2021; Ji et al., 2021). On the other hand, as financial inclusion increases, the environment suffers from its negative externalities. Le et al. (2020), Frankel and Romer (1999), and Jensen (1996) argue that access to financial services stimulates manufacturing, industrialization, and economic activities, which increases carbon dioxide (CO2) emissions, heightens consumption of energy-intensive consumer goods, and augments demand for polluting energy sources. To mitigate these negative impacts, Wang, Tong, Takeuchi, and George (2016) advocate for the integration of Corporate Social Responsibility (CSR) activities, which can reduce production costs, environmental damage, and waste associated with financial inclusion.[1] Today, financial institutions are not only focused on providing financial products and services but are also held accountable for environmental performance (Li, Kuo, Mir, & Omar, 2022).[2]

Previous research has explored how financial inclusion or financial development affects carbon emissions in countries like China, Asia, BRICS, and Organization for Economic Co-operation and Development (OECD) countries (Le et al., 2020; Liu, Zhang, Hafeez, & Ullah, 2022; Qin et al., 2021; Wang, Wang, Ren, & Wen, 2022; Zaidi, Hussain, & Uz Zaman, 2021). Wang, Wang, Sun, Han, and Chen (2022) indicate in their study in China that the development of financial inclusion has a non-linear effect on environmental quality and sustainability, implying that only after reaching a certain degree of development can financial inclusion improve sustainability outcomes as such financial inclusion observes the Environmental Kuznets Curve (EKC) hypothesis in China. However, in the broader Asian region, Hussain, Ahmad, and Shahzad (2021) and Le et al. (2020) suggest a potential negative impact on sustainability. Ahmad, Khan, and Magda (2022) reveal that financial inclusion contributes to environmental pollution in the BRICS countries. Dou and Li (2022) extend this understanding by establishing a positive impact of financial inclusion on emissions. However, in the context of energy, where green sustainability is accounted for as an element of energy efficiency. Dai, Qian, and Zhang (2022) show that financial inclusion positively impacts renewable energy efficiency for Regional Comprehensive Economic Partnership (RCEP) economies. Notably, digital financial inclusion also supports green sustainability and development by driving technological innovation and the advancement of industrial structures (Wang, Wang, Ren, & Wen, 2022).

To the best of our knowledge, no study has delved into the role of financial inclusion in environmental pollution within the unique context of Africa, specifically Sub-Saharan Africa (SSA). Moreover, when it comes to environmental sustainability, few studies have considered its multidimensionality, such as carbon footprint, ecological footprint, and air quality, and how these factors collectively contribute to overall sustainability. Fig. 1 underlines the considerable variations in emission intensity levels among African nations and the startling fact that carbon emissions from energy sources record an average annual growth rate of 1.4 % from 2012 to 2022 (Energy Institute, 2023).[3] Furthermore, financial inclusion is expanding with regional integration and globalization (Demirgüç-Kunt, Klapper, Singer, & Ansar, 2022). As of 2021, almost 55 % of Sub-Saharan adults have access to financial accounts (Demirgüç-Kunt et al., 2022).[4] This assertion is further illustrated in Fig. 2, highlighting the varying levels of financial inclusion across different regions. Given these economic and financial shifts, it becomes imperative to explore the role of financial inclusion in shaping the environment within the SSA landscape.

We apply the System Generalized Methods of Moments (GMM) to test our hypothesis and account for potential endogeneity. We

[1] CSR represents both direct investments and indirect initiatives that contribute to sustainable development by generating economic, social, and environmental benefits.

[2] Regulatory authorities increasingly require institutions to meet environmental standards to maintain ISO certifications (Li et al., 2022).

[3] Third highest region in the world after Middle East (1.9 %) and Asia Pacific (1.7 %).

[4] From 2017 to 2021, the average rate of account ownership in developing economies increased by 8 percentage points, from 63 % of adults to 71 % of adults (Demirgüç-Kunt et al., 2022).

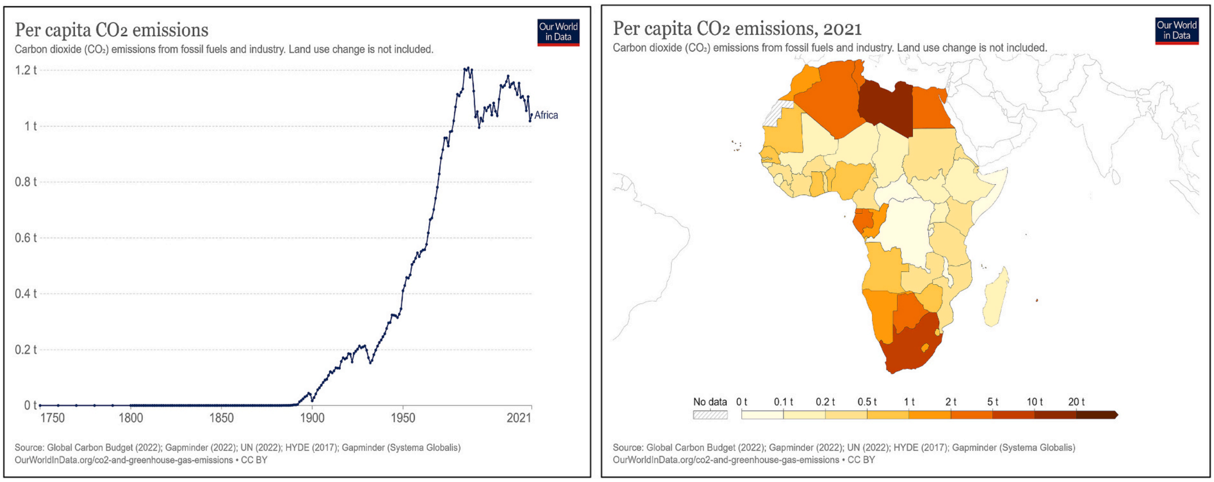

Fig. 1. Carbon emission trend in Africa.
Source: Our World in Data.

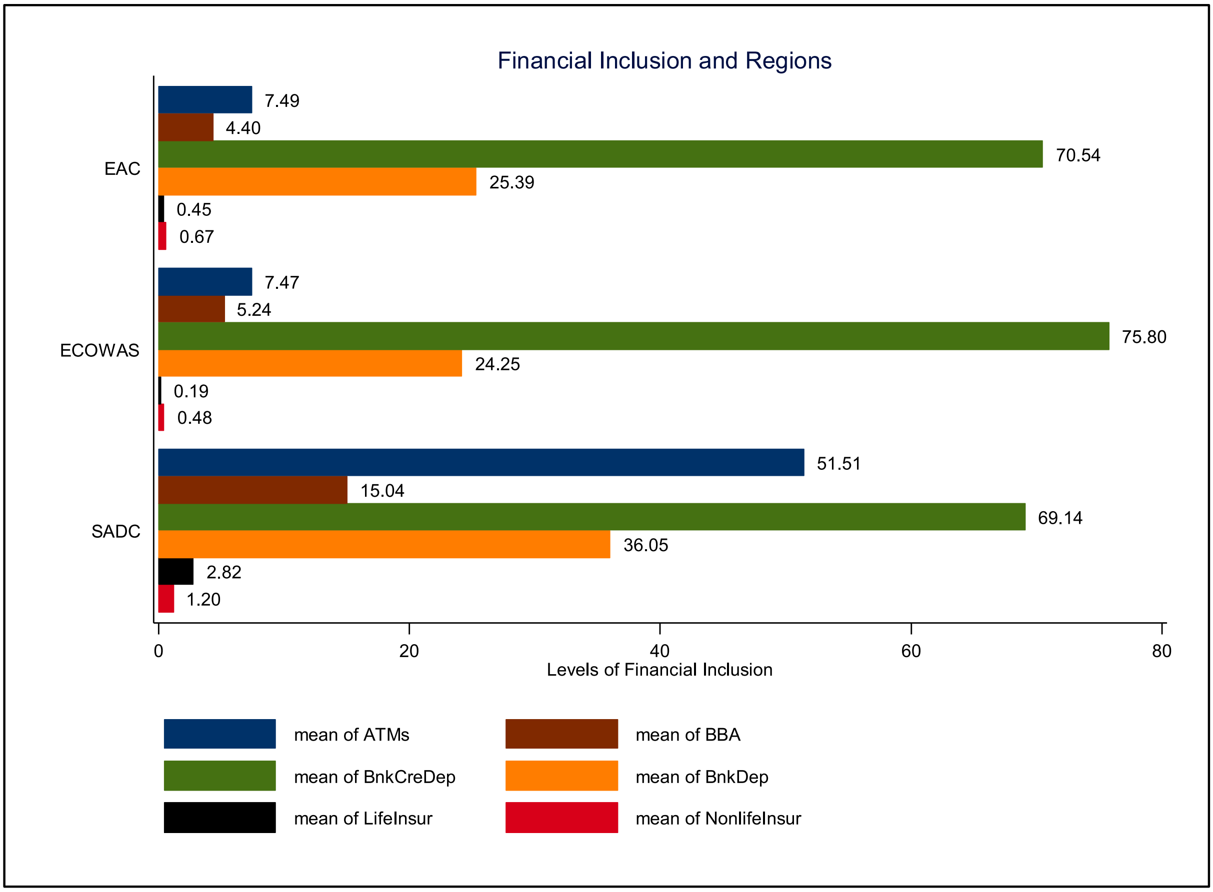

Fig. 2. Intra-regional financial inclusion comparison.
Source: Global Financial Development Database, 2000-2021.

employ annual macro-level data from 2000 to 2021 using 38 SSA countries.[5] We use the Principal Component Analysis (PCA) to construct an environmental pollution index to measure Green Sustainability. Following the example of Opoku, Acheampong, et al. (2022), the index captures four (4) environmental pollutants, including Particulate Matter (PM) 2.5, CO2 emission, methane emission, and nitrous oxide emission. We employ a multidimensionality of financial inclusion to create a financial inclusion index. Our findings suggest that financial inclusion poses an unfavorable influence on the environment by facilitating the demand for more disposable goods and encouraging rapid expansion, leading to more waste generation and environmental pollution.

Our research contributes significantly to literature as it provides a novelty in the case of SSA. First, we assess how financial inclusion can be leveraged to create a sustainable environment and further combat climate change. As such, we include a composite measure of green sustainability, which has not been employed as a factor in previous research and test a non-linear relationship between financial inclusion and environmental pollution levels. Second, we provide a more focused analysis of the regions and income groups (based on the World Bank income classification)[6] in SSA by conducting an intra-regional heterogeneity test to assess how this impact of financial inclusion on the environment differs among the various regions and income groups. Third, we provide more robust outcomes by controlling for innovative variables affecting the environment, such as urbanization, trade openness, energy use, and human development. Fourth, we provide a clear insight into the magnitude of each financial inclusion indicator on the separate covariates of the environmental pollution index, as one indicator may affect the environment differently. The same insight is provided for separate pollutants that primarily impact climate change. Lastly, we provide policy recommendations on how financial inclusion could be applied by adopting innovative products like green loans, green bonds, and green credit score models to promote and strengthen the environment in SSA.

The paper is structured as follows: the next section reviews the theoretical and empirical literature on financial inclusion and green sustainability, Section 3 describes the data and measurement methods, Section 4 explains the methodology and model specifications, Section 5 presents and discusses the main empirical results, Section 6 presents the results of robustness tests, and finally, Section 7 concludes and offers policy directions and suggestions for future research.

2. Literature review

2.1. *Theoretical literature*

We explore key theories underpinning the relationship between financial inclusion and green sustainability. The discussion focuses on the Theory of Financial Intermediation (Allen & Santomero, 1997), Behavioral Finance Theory (Barberis & Thaler, 2003), and the Resource Mobilization Theory (McCarthy & Zald, 1977). These theories explain how access to financial services influences environmental outcomes through resource allocation to individual decision-making processes.

2.1.1. *Theory of financial intermediation*

The relationship between financial inclusion and green sustainability is grounded in the Theory of Financial Intermediation by Allen and Santomero (1997). The theory posits that by expanding access to financial services, a larger population can actively participate in economic activities and enhance the mobilization of financial resources. Financial intermediaries, such as banks and microfinance institutions, are instrumental in channeling funds from savers to borrowers. Hence, the influence of financial inclusion on environmental pollution can be understood through its impact on funding channels. For instance, broader access to credit enables companies to finance large-scale projects, which may involve importing heavy machinery (Ozturk & Ullah, 2022). Likewise, individuals may use financing to purchase luxury items or energy-intensive appliances (Ozturk & Acaravci, 2013) and increase consumption and production levels (Hafeez et al., 2019). Each of these channels bears an environmental impact, emphasizing how financial inclusion, when expanded, can both support and challenge sustainable practices.

The theory of financial intermediation also underscores the potential for financial institutions to innovate and offer products such as green bonds and sustainability-linked loans that specifically fund environmentally sustainable projects. These products attract sustainability-focused investors and furnish capital for companies and individuals to undertake green initiatives, thus linking financial intermediation with environmental goals.

2.1.2. *Behavioral Finance Theory*

The Behavioral Finance Theory put forth by Barberis and Thaler (2003) explains that cognitive limitations, psychological biases, and social influences significantly shape financial decisions. This perspective is vital in understanding the effects of financial inclusion—defined as the provision of accessible, affordable financial services—on green sustainability, particularly efforts to reduce environmental pollution and carbon emissions. As financial inclusion expands, a broader range of individuals enters the formal

[5] We do not perform estimation at micro-level as insights from such study would serve as further studies in a different paper with different research questions. This decision also stems from limitations in micro-level data accessibility, necessitating a different approach to data collection and analysis.

[6] The World Bank classifies countries into four income groups based on their gross national income (GNI) per capita. As of 2023, low-income countries have a GNI per capita of $1145 or less. Lower-middle-income countries have a GNI per capita between $1146 and $4515, while upper-middle-income countries fall between $4516 and $14,005. High-income countries have a GNI per capita exceeding $14,005 (World Bank Income Classification FY24)

financial system, many of whom may lack familiarity with complex financial products and may, therefore, make suboptimal long-term decisions regarding environmental sustainability. This is where financial institutions often act on their CSR, educating new participants about how responsible finance can support environmental sustainability (Hamid, Saeed, Farooq, & Alnori, 2022).

As financial inclusion expands, the Concept of Present Bias explains that there is a tendency for newly financially included individuals to prioritize immediate rewards over long-term benefits. (Laibson, 1997; O'Donoghue & Rabin, 2015). However, financial inclusion also has the potential to cultivate sustainable financial practices within communities through Peer Effects (Beshears, Choi, Laibson, Madrian, & Milkman, 2015) and CSR (Jiménez-Parra, Alonso-Martínez, & Godos-Díez, 2018; Li et al., 2022). The concept of peer effect in finance shows that people frequently imitate the financial choices of their peers or social groups based on conformity and their desire to fit in (Ali-Rind, Boubaker, & Jarjir, 2023). Hence, as certain community members adopt green financial products, they may set an example that encourages others to follow—a phenomenon called Social Proof (Cialdini, 2001).

2.1.3. Resource Mobilization Theory (RMT)

Resource Mobilization Theory (RMT), developed by McCarthy and Zald (1977), highlights the importance of acquiring and utilizing resources to drive social change. The theory asserts that successful social initiatives rely not just on ideological support but significantly on the effective mobilization of financial resources (Edwards & McCarthy, 2004). Financial inclusion plays a critical role in this context by providing access to formal financial services, which creates the necessary infrastructure for resource mobilization that RMT identifies as essential for social transformation. Thus, RMT posits that the success of green sustainability efforts is closely linked to the availability and effective utilization of funds. Despite that the RMT comes from the field of sociology, it complements the two more economics-grounded strands of theories.

2.2. Empirical literature and hypothesis development

The empirical investigation of financial inclusion's relationship with environmental pollution has garnered increasing attention in recent years as researchers examine its varied impacts across regions. Numerous studies have explored how financial inclusion affects green sustainability, particularly in terms of environmental pollution and CO_2 emissions.

2.2.1. The financial inclusion and environmental pollution nexus

Empirical evidence from Sub-Saharan Africa (SSA) often associates financial inclusion with increased CO_2 emissions. This relationship is attributed to economic growth, industrialization, income inequality, and trade expansion (Liu et al., 2022; Ogede & Tiamiyu, 2023; Rasheed, Adeneye, & Farooq, 2024). Some studies also propose that education, innovation, green investments, and CSR could offset these environmental impacts (Jiménez-Parra et al., 2018; Musah, Gyamfi, Kwakwa, & Agozie, 2023). Liu et al. (2022) and Mukalayi and Inglesi-Lotz (2023) find that financial inclusion in African countries contributes to rising emissions. In a study of 23 SSA countries from 2004 to 2019, Said (2024) concludes that while financial inclusion increases CO_2 emissions, it also promotes renewable energy use, which can mitigate some environmental harm. Similarly, Musah et al. (2023) argue that financial inclusion can reduce greenhouse gas emissions when paired with green investments and technological advancements.

Studies from other regions offer a broader perspective on financial inclusion's environmental effects. Fareed et al. (2022) find that increased financial inclusion levels correlate with higher CO_2 emissions in the Eurozone. Zaidi et al. (2021) also observe this trend in OECD nations. In Asia, Le et al. (2020) argue that greater access to financial services fuels higher consumption and production, contributing to CO_2 emissions. Similarly, Lei, Chen, Xu, Qiu, and Zhang (2024) note that increasing digital financial inclusion in China reduces carbon emissions by optimising industrial structure and promoting technological innovation. They link this contribution to higher physical capital investment, higher education, more mature economic development, and more resources and technologies for developing and transforming a low-carbon economy. Mehmood (2022) reports that financial inclusion exacerbates CO_2 emissions in South Asia. The study suggests that the environmental costs may outweigh the social benefits. Ahmad et al. (2022) reiterates these findings in the ASEAN countries, showing that financial inclusion could increase environmental degradation. Such diverse findings underscore the importance of regional factors when assessing how financial inclusion impacts environmental outcomes.

H1. Financial inclusion has a negative effect on environmental pollution levels in SSA.

2.2.2. Non-linear U-shaped relationship between financial inclusion and environmental pollution levels

The hypothesis of a non-linear, U-shaped relationship between financial inclusion and environmental pollution aligns with the Environmental Kuznets Curve (EKC) hypothesis introduced by Grossman and Krueger (1995) in the context of economic development. According to the EKC hypothesis, environmental degradation occurs during the early development phase. Beyond a certain level of development, the economic benefit of growth becomes more affluent for environmental preservation. Though the EKC hypothesis is in the context of economic growth, it allows for relevant macroeconomic variables that are theorized to influence environmental sustainability (Qin et al., 2021), including financial inclusion (Qin et al., 2021; Renzhi & Baek, 2020; Wang, Wang, Ren, & Wen, 2022).

Cai and Wei (2023) and Mukalayi and Inglesi-Lotz (2023) observe that financial inclusion can increase environmental degradation in the early stages of economic growth, but as economies mature, financial inclusion can contribute to environmental improvements. Yang, Yang, Zhang, Kassim, and Wang (2024) documented mixed effects of financial inclusion on air quality in Asian countries, noting that higher levels of digital financial inclusion are associated with better air quality in the long term. They further suggest that the environmental impact of financial inclusion may evolve. Additionally, Said (2024) confirms that the effect of financial inclusion on CO_2 emissions varies with the economic development level in SSA, providing evidence for an Environmental Kuznets Curve (EKC) hypothesis between financial inclusion and environmental pollution. Based on the empirical discourse, we develop this hypothesis to suggest that while financial inclusion initially exacerbates environmental degradation during early development stages, it may eventually improve environmental quality as economies transition to sustainable practices.

H2. There exists a negative non-linear relationship between financial inclusion and environmental pollution levels in SSA.

2.2.3. Intra-regional effect of financial inclusion on green sustainability in sub-Saharan Africa

The environmental impact of financial inclusion varies within SSA, with some regions experiencing heightened ecological footprints while others see less impact (Ali, Jianguo, & Kirikkaleli, 2022). For instance, Musah et al. (2023) report that financial inclusion and green investments strongly influence environmental quality in West Africa. Ali et al. (2022) find that financial inclusion has a detrimental impact on environmental quality within ECOWAS countries. This study also emphasizes that West Africa faces unique challenges, including limited access to financial services and heavy reliance on fossil fuels and biomass, which shape the relationship between financial inclusion and the environment. Meanwhile, Said and Acheampong (2024) find that financial inclusion is associated with reduced CO_2 emissions in the Middle East and North Africa (MENA), suggesting that environmental effects may differ across regions within SSA due to economic structure and energy reliance. The variability in these findings underscores the importance of customized financial inclusion policies that address SSA's distinct economic and environmental conditions.

H3. Financial inclusion has a negative heterogeneous impact on pollution across SSA regions.

3. Sample and data

We use panel data with annual frequencies covering 38 Sub-Saharan African (SSA) countries from 2000 to 2021 to investigate the role of financial inclusion on green sustainability, along with other country-level information detailed later in this section. The countries included in our study are listed in Appendix Table B1. The chosen period is motivated by the need to capture long-term trends, economic changes such as how financial inclusion has evolved and deepened to include more focus on sub-national data mostly since 2000, and environmental concerns in SSA, including the oil spills in Nigeria and the discovery of oil in Ghana. The data are sourced from the World Development Indicators, Global Financial Development, and Our World in Data. Appendix Tables B2, B3, and B4 list all the data used in our study.

3.1. Measure of green sustainability and financial inclusion

We measure green sustainability and financial inclusion by constructing an environmental pollution index (EPI) and a financial inclusion index (FII) to account for the several dimensions of both variables. Specific dimensions are defined with the help of relevant variables in Appendix Tables B3 and B4. We further introduce macro-level dependent variables to serve as controls.

3.1.1. Green sustainability measure

Following the example of Opoku, Dogah, and Aluko (2022), we measure green sustainability to depict the level of pollution intensity using an environmental pollution index. The index is constructed using four environmental pollution variables, namely CO2 emissions, Particulate Matter (PM) 2.5, methane emissions, and nitrous oxide emissions. These variables are carefully selected to capture different facets of pollution, such as ecological footprint, carbon footprint, and air quality. We also avoid the issue of double-counting various pollution indicators.

CO2 emissions reflect the release of carbon oxide gas into the atmosphere primarily from activities like burning fossil fuels, solid waste, and trees. CO2 emission is measured in metric tons per capita, and by dividing the total emissions by population, it captures the contribution of the average citizen of each country. CO2 emissions are associated with increased global warming and climate change concerns, making it a crucial indicator for evaluating environmental sustainability (Wang, 2023). Mitigating CO2 emissions is vital for curbing the adverse impacts of climate change, including extreme weather events and rising sea levels.

PM assesses the local level of air pollution and air quality. We employ PM as a variable to measure the concentration of small airborne particles, including dust, dirt, soot, smoke and liquid droplets. It primarily originates from various sources, including industrial processes, bushfires, pollens, sea spray, dust storms and motor vehicle engines (Isphording & Pestel, 2021). However, our empirical analysis focuses on PM 2.5 to measure particles up to a diameter of 2.5 μm. PM 2.5 is a commonly employed key indicator in literature to measure exposure to air pollution, and it stands as the fifth most significant risk factor contributing to global mortality (Cui, Huang, & Wang, 2023). High levels of air pollution are detrimental to human health and the environment (Roy, Nguyen, & Visaltanachoti, 2023), making it an essential aspect of environmental sustainability.

Further, methane emission captures the emissions from agricultural activities, livestock farming, and waste management. Methane emission has implications for climate change due to the high heat-trapping ability of methane (CH4) compared to carbon dioxide. As is common in environmental research, the CH4 variable is measured as an equivalent of the metric tons of CO2 per capita. Finally, nitrous oxide emission captures emissions from agriculture and wastewater containing organic-based nitrogen materials. It is essential to note that not all types of nitrous emissions are considered. Instead, we focus specifically on one subset—nitrous oxide (N2O), which is a greenhouse gas with a longer atmospheric lifetime than other greenhouse gases. The primary source of N2O is the agricultural sector (Krüger & Tarach, 2022). While nitrous oxide is present in substantially smaller concentrations than carbon dioxide, nitrous oxide emission represents a much higher global warming potential (Paolini et al., 2018). Again, the N2O variable is measured in metric tons of CO2 equivalent per capita to provide a comparative perspective when assessing the impact of different greenhouse gases.

As a robustness check, we separate the pollutants that impact urban air quality (such as PM2.5) from those that primarily impact climate change (CO2, CH4, N2O). In order to use the latter as a single measure, we construct an index termed the climate footprint index (CFI). The equation for the index is described in Section 3.1.3. We adopt this approach due to the distinct origins of our emissions variables—specifically, CO2, methane, and nitrous oxide emissions. These variables have been weighted based on their Global Warming Potential and differ slightly from PM2.5. Our approach is also to help gain insight into how financial inclusion impacts climate change in SSA. Finally, we perform another test examining the impact of financial inclusion on individual pollution indicators.

3.1.2. Financial inclusion measure

We assess financial inclusion by constructing a comprehensive Financial Inclusion Index (FII) comprising six variables. The index considers the multidimensional nature of financial inclusion, encompassing accessibility, usage, and the quality of financial services and products. Appendix Table B4 summarizes the dimension defined with the help of relevant variables. Our rationale for this multifaceted approach is rooted in the understanding that true financial inclusion is not fully realized unless all these dimensions are effectively addressed. For instance, the mere presence of ATMs in proximity to individuals is unsatisfactory if those ATMs are non-functional or inaccessible (Nguyen, 2021).

To measure the accessibility dimension, we employ two key variables: ATMs per 100,000 adults and bank branches per 100,000 adults. These factors account for the physical availability of financial service points provided by financial institutions (Cámara & Tuesta, 2014; Ugwuanyi et al., 2022) and the country's banking infrastructure development. Although financial technology like mobile money can enhance access to financial services, mobile money typically relies on having a registered mobile device, a registered number, and a reliable internet connection. Such prerequisites favor wealthier, urban regions with developed infrastructure, while underserved, rural areas face challenges (Eshun & Kočenda, 2024).

As previously mentioned, the significance of financial access becomes apparent when it is actively utilized. Utilization includes various financial activities such as saving, investing, borrowing, and making deposits and withdrawals. Building upon this concept, we utilize bank deposits and bank credits as indicators to quantify the extent of utilization within the dimension of financial usage.

To measure the quality dimension, we employ two indicators: Life Insurance, captured as the ratio of life insurance premiums to a country's GDP, and Non-Life Insurance, measured as the ratio of non-life insurance premiums to a country's GDP. As denoted by the stated indicators, the quality dimension assesses the financial products or services that address financial needs and reduce financial burdens.

3.1.3. Principal Component Analysis

Further, we construct the Environmental Pollution and Financial Inclusion Indexes using the Principal Component Analysis (PCA).[7] The PCA method helps to gauge the aggregate effect of the four (4) and six (6) variables related to environmental pollution and dimensions of financial inclusion, respectively (Sharma & Changkakati, 2022). The application of PCA has three advantages: we avoid the problem of weight assignment and arbitrary weights using statistical weights (Cámara & Tuesta, 2014). PCA creates a linear combination of the original variables (principal components), which are orthogonal to each other. After the dimension reduction, statistical weights are applied to the various components based on the contribution of each principal component to the overall index. The weights are determined based on the eigenvalues of the covariance matrix of the standardized variables. We normalize the indices to ensure that all variables contribute equally to the analysis, preventing those with larger scales and variances from dominating the principal components. As such, the higher the eigenvalue, the more significant the variance and importance. We avoid the correlation between different individual indicators and can analyze the aggregate impact of the various factors without omitting any particular one (Iwasaki, Kočenda, & Shida, 2022). To ensure coherent and consistent results, we normalize the various indicators to provide a comparable impact of green sustainability and financial inclusion independently of their original scale.

Hence, we employ the principal component methodology in line with the approach of Sharma and Changkakati (2022) and for every country *i* and period *t*, we develop an environmental pollution index (EPI) and a financial inclusion index (FII). We use the same approach to construct the Climate Footprint Index (CFI). All the indexes ($Index_{it}$) are defined in a similar way as follows:

$$Index_{it} = \sum_{n=1}^{N} \varnothing_n Z_{it} + \varepsilon_{it}, \tag{1}$$

where Z_{it} represents the dimensions associated with both financial services and products and also the dimensions of environmental pollution. The variable N represents the number of factors contributing to the index and the loadings $\varnothing_n$ represents the respective weights for each principal component. The term ε_{it} accounts for errors in the model. The index is constructed so that an increase in financial inclusion increases emissions and, therefore, reduces green sustainability since the function of the index captures environmental pollutants.

The PCA results are presented in Appendix Table B5. The eigenvalues of the first two components explain the majority of variance in the data. The first two components of the environmental pollution and financial inclusion indexes account for 75 % and 82 % of the total variation, respectively. For the environmental pollution index, variables with higher absolute coefficients (Methane emission, nitrous oxide emission) have a more substantial influence on the first principal component, indicating that changes in these variables

[7] The PCA approach utilizes the summation of weighted contributions from various dimensions associated with variables (in this case, financial services/products and environmental pollution) to create both indices. The use of the principal components ensures that the indices capture the most important variations in the underlying data.

contribute more to the variability captured by the first component. Variables with lower coefficients (PM25, CO2 emission) have a weaker influence on the first principal component. However, all variables are significant in determining environmental pollution levels.

All original variables have positive coefficients in the first component of the financial inclusion index, indicating that an increase in any of these variables contributes positively to the financial inclusion index.

3.2. Control variables

Following the standard economic literature, we also account for other variables such as energy use (Sinha, Shahbaz, & Balsalobre, 2017; Usman et al., 2021), human development[8] (Opoku, Acheampong, et al., 2022), natural resource dependency (Li, Dong, Wang, & Dong, 2023), trade openness (Ali, Law, & Zannah, 2016; Ozturk & Acaravci, 2013), government expenditure (Halkos & Paizanos, 2016; Pirgaip, Bayrakdar, & Kaya, 2023), and urbanization (Ali et al., 2016) as control covariates. As these controls in the equation successfully account for the factors explaining the rise in pollution, we also account for economic growth (GDP) (Ali et al., 2016; Usman et al., 2021).

We further present the descriptive statistics of variables in Appendix Table B6 and the results of our correlation analysis among variables in Appendix Table B7. The variation in the number of observations across our estimation results is due to missing data for some variables in certain countries and years. While the theoretical number of observations is 836, data availability constraints, particularly for financial inclusion indicators and environmental pollution metrics, result in fewer observations in the estimation. The Environmental Pollution Index and Financial Inclusion Index are standardized with a means of zero to ensure comparability. The negative minimum values observed in the descriptive analysis result from the normalization employed in our PCA. The standardization process centers the data around 0, forming a symmetric distribution where values can be both positive and negative. Hence, the negative values indicate observations that fall below the mean level of environmental pollution or financial inclusion within the dataset. The minimum EPI of −1.438 indicates an observation where pollution levels are lower compared to the mean pollution level after considering the variance in the data. Similarly, the minimum FII of −2.083 shows a financial inclusion below the average. These negative values do not imply the absence or a reverse state of the financial inclusion or pollution levels but rather reflect relative positions within the normalized scale.

The Macroeconomic controls demonstrate considerable heterogeneity - trade openness averages 71.16 % of GDP, while GDP growth averages approximately 4.01 %. Natural resource endowments average 10.76 % but reach as high as 59.68 % in resource-rich nations. The human development indicator (mean: 8.64) suggests substantial room for socioeconomic progress. Urbanization levels in SSA average 39.56 %. This urbanization level indicates a predominantly rural population, though some nations have achieved substantial urban development (maximum: 90.42 %). Of particular note is the inflation variable, which exhibits extreme variation with a mean of 10.43 % and a maximum level of 557.20 %, reflecting episodes of significant monetary instability in certain economies. Government expenditure across the region averages 15.14 % of GDP.

We use the pairwise correlation test to determine the magnitude and linear direction between the variables. Our results show no evidence of or concern for multicollinearity in our model.[9] The independent variables have a correlation coefficient of less than 0.7 (Krehbiel, 2004).

4. Methodology

4.1. Model specification

We estimate the effect of financial inclusion on green sustainability through a dynamic panel model. The model is based on the assumption that the present value of our selected variable, reflecting environmental pollution, exhibits a strong dependence on its own lagged values (Li, Ding, Hu, & Wan, 2021). Pollution cumulates and generates damage over time with persistence (Calzolari, Casari, & Ghidoni, 2018). Consistent with Li et al. (2021), we adopt a dynamic panel model for country i at time t of the form:

$$\mathrm{Y}_{\mathrm{it}} = \alpha + \sum_{s} \rho_s Y_{i,t-s} + \beta X_{it} + (u_i + \mathcal{E}_{it}); (t = 2, 3, \dots, T), \tag{2}$$

where s = 1, 2 …, and $Y_{i,t-1}$, $Y_{i,t-2}$ are the values of the lagged dependent variable that affect X_{it}. The coefficient ρ_s captures the autocorrelation in Y, and β measures the effect of X on Y.

The lagged dependence stems from the fact that present environmental pollution levels are shaped by past practices, regulations, or environmental conditions and their likely evolution in the future (Sadorsky, 2010). This recognition emphasizes the inherent link between environmental pollution or sustainability and its past values. We further estimate three equations to help test our hypothesis. Following the Theory of Financial Intermediation, and akin to Ozturk and Ullah (2022) and Sadorsky (2010), we break and specify our model assessing the impact of financial inclusion on environmental pollution as:

[8] We do not use the Human Development Index as a proxy for human development as it is highly correlated with urbanization. We employ one of the single indicators of its composite dimensions to avoid the issue of multicollinearity.

[9] The Correlations between green sustainability, financial inclusion, energy use, human development, trade openness, natural resource, economic growth, government expenditure and urbanization ranges between 0.02 and 0.53 and do not lead to problem of multi-collinearity.

$$EPI_{it} = \beta_1 EPI_{it-1} + \beta_2 FII_{it} + \sum_{i=1}^{n} \beta_i Z_{it} + \nu_i + \mathcal{E}_{it}, \quad (3)$$

In the above specification, the EPI represents the environmental pollution index, FII denotes the financial inclusion index, $\sum Z$ represents a vector of control variables, ν represents the time-invariant country-specific fixed effects, and $\mathcal{E}$ denotes the residual disturbance in the model estimation. The environmental pollution index and financial inclusion index encompass various specific dimensions, as detailed in Section 3.1, while Section 3.2 defines the control variables used.

We further modify the model to account for a potential non-linear relationship between financial inclusion and pollution. Recognizing that the linear regression might not capture the non-linearity of financial inclusion, we opted for the non-linear equation to capture the impact of financial inclusion on pollution at different levels. The adapted model incorporating this hypothesis is

Table 1
Effect of financial inclusion on environmental pollution.

	Linear	Non-linear (FII)	Non-linear (GDP)
	(Model 3)	(Model 4)	(Model 5)
Lag of Environmental Pollution Index	0.948***	0.898***	0.956***
	(0.000)	(0.000)	(0.000)
Financial Inclusion	0.052***	0.125***	0.049***
	(0.004)	(0.000)	(0.009)
Financial Inclusion_squared		−0.019***	
		(0.000)	
Economic Growth			0.014***
			(0.000)
Economic Growth_squared			−0.004***
			(0.000)
Controls			
Energy Use	0.050***	0.065**	0.061***
	(0.008)	(0.017)	(0.002)
Human Development	−0.011***	0.001	−0.009***
	(0.000)	(0.753)	(0.001)
Natural Resources	0.001	0.004*	0.004*
	(0.311)	(0.067)	(0.062)
Trade Openness	−0.001**	−0.005***	−0.000
	(0.047)	(0.000)	(0.269)
Economic Growth	0.009***	0.004***	
	(0.001)	(0.014)	
Government Expenditure	−0.023***	0.031***	−0.024***
	(0.002)	(0.000)	(0.000)
Urbanization	0.004**	0.005***	0.002
	(0.029)	(0.002)	(0.242)
Constant	0.289***	−0.444***	0.368***
	(0.001)	(0.000)	(0.000)
Diagnostics			
Wald Test	4280.39	27,225.80	14,173.76
Prob. (Wald)	0.000	0.000	0.000
AR1 (*p*-value)	0.231	0.227	0.224
AR2 (p-value)	0.365	0.363	0.363
Hansen-J (*p*-value)	0.592	0.316	0.548
Sargan (p-value)	0.347	0.285	0.439
DHT for instrument			
a. Instruments in levels			
H excluding group	0.242	0.625	0.267
b. IV (years, eq(diff))			
H excluding group	0.706	0.312	0.41
Number of groups	33	33	33
Number of instrumental	30	30	30
Observations	162	162	162

Statistical significance at the 1 %, 5 %, and 10 % level is indicated by ***, **, and *, respectively. P-values in parentheses. Model 3 reflects the baseline model. Model 4 uses the financial inclusion index as a test of a non-linear pattern, while Model 5 utilizes GDP as a battery test of the typical EKC hypothesis. Environmental pollution index represents a statistical index of CO2 emissions, Particulate Matter 2.5 (PM), methane emissions, and nitrous oxide emissions. Financial inclusion represents a comprehensive index (FII) based on six variables: ATMs, bank branches, credit-to-deposit ratio, bank deposits, life insurance, and non-life insurance. Control variables include energy use, human development, natural resources, trade openness, economic growth, government expenditure, and urbanization. The diagnostics section presents the values of the Wald test, probability values of the Wald test, z-values of AR(1) and AR(2), probability of z-values of AR(1) and AR(2), probability of the Sargan test, the number of groups and instruments, and the number of observations.

expressed as:

$$EPI_{it} = \beta_1 EPI_{it-1} + \beta_2 FII_{it} + \beta_3 FII_{it}^2 + \sum_{i=1}^{n} \beta_i Z_{it} + \nu_i + \varepsilon_{it}, \tag{4}$$

here, FII^2 captures the quadratic term of financial inclusion, accommodating the non-linear relationship postulated by the EKC hypothesis. Further, consistent with the mainstream literature, we modify our specification to include economic growth and its square as core components of the typical EKC model to assess the dynamics of financial inclusion's impact. We specify the model as:

$$EPI_{it} = \beta_1 EPI_{it-1} + \beta_2 FII_{it} + \beta_3 GDP_{it} + \beta_4 GDP_{it}^2 + \sum_{i=1}^{n} \beta_i Z_{it} + \nu_i + \varepsilon_{it}, \tag{5}$$

where GDP and GDP^2 capture the linear and quadratic terms of economic growth in the EKC hypothesis, respectively.

In our robustness test, we re-estimate the model using the climate footprint index (CFI) as a proxy for our dependent variable. We specify the model as follows:

$$CFI_{it} = \beta_1 CFI_{it-1} + \beta_2 FII_{it} + \sum_{i=1}^{n} \beta_i Z_{it} + \nu_i + \varepsilon_{it}, \tag{6}$$

where CFI represents the Carbon Footprint Index, as described in Sections 3.1.1 and 3.1.3.

Given the dynamic nature of the models, we employ the System Generalized Method of Moments (GMM) as our estimation technique to address endogeneity concerns. For further technical details on the full estimation procedure, refer to Appendix 1 A.

5. Results and discussion

We present the results of our system GMM model, as detailed in Table 1, which examines the influence of financial inclusion on green sustainability in Sub-Saharan Africa (SSA). Our initial hypothesis (H_1) states that financial inclusion has a negative effect on environmental pollution levels in SSA. However, our analysis reveals a positive association between financial inclusion and environmental pollution levels, which rejects our hypothesis. The results, thus, show that increased financial inclusion levels are strongly linked to increased pollution levels in SSA.

The findings align with the Theory of Financial Intermediation, which suggests that increased financial inclusion facilitates access to funds for acquiring more big-ticket items such as automobiles, refrigerators, air-conditioners, electricity generators, and plants (Le et al., 2020). The widespread use of these items accelerates the consumption of domestic fossil fuels, resulting in increased CO2 emissions and higher pollution levels (Zaidi et al., 2021). Zaidi et al. (2021) further confirm that financial inclusion contributes to higher energy consumption and carbon emissions.

Additionally, our findings resonate with the concept of present bias explained by Behavioral Finance Theory, where newly financially included individuals prioritize immediate consumption over long-term environmental considerations. Financial inclusion increases purchasing power and consumption (Addury, 2019). While this can stimulate economic growth, it results in higher demand for disposal goods, leading to more waste generation and environmental pollution.

By comparing our results to existing literature, our finding aligns with Usman et al. (2021) in the Eurozone. Similarly, Popescu, Gibon, Hitaj, Rubin, and Benetto (2023) confirm that Socially Responsible Investing (SRI) funds may not exhibit lower climate exposure than market indexes. They explain that funds labeled sustainable (SRI) remain exposed to highly emitting companies, particularly those with high indirect carbon intensity. However, our results contrast the findings of Shahbaz, Li, Dong, and Dong (2022) and Renzhi and Baek (2020), who observe that financial inclusion reduces carbon emissions. These differing outcomes may be attributed to variations in the level of development of financial inclusion, industrialization, technological advancement, innovation, and the preference for advanced gadgets in these countries. Nonetheless, in a region like SSA, where financial inclusion is still in its early stages, a significant increase in financial inclusion creates the urge for rapid infrastructure development for growth, rapid urbanization in search of economic opportunities, expansion of industries, and increased demand for energy. These activities could destroy habitats and disrupt natural ecosystems, causing environmental harm.

We further extend our analysis to capture the potentially evolving dynamics of the relationship between financial inclusion and green sustainability (measured by the environmental pollution index). Specifically, we conduct a decade-based analysis, comparing the period before 2010 with that from 2011 onwards. Our findings reveal that financial inclusion is associated with decreased green sustainability in both decades. However, the magnitude of the effect was higher in the pre-2010 period (coefficient of 0.05, 5 % significance) compared to the post-2010 period (coefficient of 0.04, 5 % significance). The results suggest that the negative impact of financial inclusion linked to green sustainability is slightly slowing down over time. This finding can be considered as indirect evidence of a small learning effect.

5.1. Control for other macroeconomic determinants

We control for other determinants that can collaboratively influence environmental pollution by employing control variables of energy use, human development, natural resource dependency, trade openness, economic growth, government expenditure, and urbanization. Our findings reveal a significant contribution of energy use (proxied by electricity from oil) in increasing environmental pollution levels. This adverse effect is evident in its negative coefficient and may be attributed to the extensive reliance on fossil fuels like oil for energy generation, transportation, and manufacturing (Le et al., 2020).

Further, we note that higher levels of human development significantly decrease environmental pollution. Human development improves awareness and behavior change through education, contributing to adopting eco-friendly practices and policies. Our findings are consistent with Opoku, Dogah, and Aluko (2022).

Our analysis suggests that trade openness is linked to decreased environmental pollution levels. The presence of trade liberalization encourages the alignment of environmental standards and policies with international norms, which fosters collective efforts to reduce pollution across borders. As noted by Le et al. (2020), trade agreements can enhance the capacity of governments to tackle environmental issues by eliminating trade barriers to environmental goods and services. Trade openness often facilitates technology and innovation transfer (Usman et al., 2021) to provide easier access to environmentally friendly technologies and renewable energy sources.

Also, increasing economic growth contributes to high environmental pollution levels. Our result highlights how increased production of goods and services and overall economic expansion can contribute to environmental depletion. Rapid economic growth is associated with elevated energy consumption, intensified industrial activities, and heightened transportation, all contributing to environmental stress. In response to such adverse impacts from economic growth, Yuan, Zou, and Feng (2023) suggest adopting and establishing environmental courts, as seen in China. These specialized courts can reduce emissions without hindering economic growth. They achieve this by employing efficient judicial methods to address local environmental pollution problems and establish a sustainable mechanism for environmental governance (Yuan et al., 2023).

We further highlight that government expenditure is linked with a decreasing impact on environmental pollution in SSA economies. An increasing number of government policies and regulations lead to increased government spending and efficient resource allocation, predominantly improving environmental efforts in SSA. According to Magacho, Espagne, Godin, Mantes, and Yilmaz (2023), government expenditures are necessary to promote green industries either through direct fiscal stimulus or investment in renewable energy and other green technologies, which effectively reduces pollution. Moreover, many SSA countries are involved in international agreements, including the African Union Agenda 2063, the United Nations Framework Convention on Climate Change (UNFCCC), and the Paris Agreement. These agreements and intergovernmental environmental cooperation foster the advocacy of the Clean Development Mechanism (CDM) (Cui, Wang, & Yu, 2022) and encourage governments to invest in activities to curb greenhouse gas emissions, conserve biodiversity, and mitigate climate change.

Also, urbanization contributes to increasing environmental deterioration in the sampled SSA economies. Urbanization intensifies environmental effects, impacting air quality, ecosystems, land utilization, natural cycles, water purity, waste handling, and the climate (Bai et al., 2017).

Finally, we show that the influence of natural resource dependence on environmental pollution is statistically irrelevant. The environmental impact of natural resource dependence may not be solely attributed to the region itself but may be dispersed globally due to the nature of the supply chain (OECD, 2023). The dispersion chain could account for the observed insignificant effect. Countries may export raw materials for processing elsewhere, influencing where pollution occurs in the supply chain. The insignificant effect may also stem from the varied environmental impacts of different natural resources (OECD, 2021). For instance, sustainable forestry may have less impact than oil or minerals. According to OECD (2019, 2021), the environmental impacts of other metals like aluminium, iron, and manganese are projected to remain constant or decrease over time due to the decarburization of energy in production and the increased use of secondary materials, which tend to have lower overall environmental impacts compared to primary materials.

5.2. *Test of a non-linear relationship*

We also examine the existence of a non-linear relationship between financial inclusion and green sustainability in Sub-Saharan Africa. We hypothesize (H_2) that there exists a negative, non-linear U-shaped relationship. Our findings, detailed in Table 1, support this hypothesis by revealing an inverted U-shaped pattern. The results show a positive initial coefficient of financial inclusion on environmental pollution, indicating its contribution to increasing pollution levels. The effect is not straightforward, though. Since the coefficient of the quadratic term of financial inclusion is negative and statistically significant, it confirms the presence of a non-linear U-shaped relationship between financial inclusion and environmental pollution in SSA.

These findings suggest that financial inclusion is linked with increasing environmental pollution. Further, the inverted U-shaped effect implies that in the early stages of increased financial inclusion, pollution level increases until it reaches an optimal level. Beyond the turning point, further increments in financial inclusion notably enhance sustainability. The behavior of individuals and businesses can explain the U-shaped phenomenon during different stages of expansion of financial inclusion. Specifically, according to Renzhi and Baek (2020), people primarily focus on improving their living standards and expanding their businesses at the initial stages of increased financial inclusion. Such pursuit often leads to higher consumption and increased environmental degradation. However, at the later stage, individuals and corporations gain the capacity to invest in cleaner technologies, enhance their corporate social responsibility (CSR) efforts and explore greener innovations. CSR efforts, when financial access increases, help move beyond more compliance (Liang & Renneboog, 2020) to proactive environmental stewardship. As a result, environmental sustainability sees a significant improvement during these later stages of financial inclusion. The shift aligns with Musah et al. (2023) and Youssef, Boubaker, and Omri (2020) and outlines the importance of reaching an optimal level of financial inclusion for achieving environmental sustainability in SSA.

Additionally, our result underscores the importance of considering financial inclusion and economic growth dynamics in fostering environmental sustainability. Our findings in Table 1 show that the quadratic term for GDP growth exhibits a negative impact, implying a curvilinear relationship between GDP growth and environmental pollution. Our result supports the typical Environmental Kuznets Curve (EKC) hypothesis (Hlongwane & Daw, 2022; Li, 2023) and serves as a battery test, indicating that our results align with the mainstream literature.

5.3. Test of intra-regional heterogeneity with respect to environmental pollution

In investigating the heterogeneous effects of financial inclusion on environmental pollution across regions in Sub-Saharan Africa (SSA), we hypothesize (H_3) that financial inclusion has a negative heterogeneous impact on pollution across SSA regions, reflecting regional and income-group-specific differences. To test this hypothesis, we examine the intra-regional heterogeneity among three SSA regions: Western Africa, Eastern Africa and Southern Africa,[10] alongside an income-group analysis based on the World Bank classification—low-income, lower-middle-income, upper-middle-income, and high-income countries. Given that Southern Africa has relatively higher levels of financial inclusion than West and East Africa (Sulemana & Dramani, 2022) and that CO_2 emission levels vary among these regions (as shown in Fig. 1), we evaluate the differential impact of financial inclusion on pollution across these groups.

Our analysis, presented in Tables 2 and 3, supports the hypothesis of intra-regional heterogeneity. Table 2 results indicate a distinct intra-regional heterogeneity in SSA. First, we note that financial inclusion's impact on environmental pollution is 1.52 % lower in Southern Africa than in Eastern Africa, which is consistent with the findings of Barut, Kaya, Bekun, and Cengiz (2023) for South Africa alone. Further, we show that given a 1 % increase in financial inclusion in SSA, environmental pollution levels are 1.13 % less in Western Africa than in Eastern Africa. Our finding aligns with Musah et al. (2023), showing that financial inclusion reduces environmental pollution in the Western African region. Specifically, the impact of financial inclusion in Southern Africa and Western Africa on environmental pollution is smaller than that of Eastern Africa. Hence, the two former regions seem to be in better shape regarding environmental sustainability.

This intra-regional heterogeneity reflects varying financial inclusion strategies and environmental policies across regions, which aligns with Resource Mobilization Theory's (RMT) assertion that access to resources can facilitate different social outcomes. Southern and Western African regions may be leveraging geographical advantages and investment incentives to promote sustainable practices.

Analyzing across income groups, we observe a distinct pattern in the environmental impact of financial inclusion. Using low-income countries as the reference group for our analysis, the results in Table 3 show that financial inclusion in upper-middle-income countries is associated with a 0.69 % increase in pollution levels relative to low-income countries. Similarly, lower-middle-income countries exhibit a 0.40 % pollution increase over low-income countries, though this effect is smaller than in upper-middle-income countries. Interestingly, high-income countries show a much lesser impact on environmental pollution, and this effect is statistically insignificant. Perhaps a higher increase in financial inclusion at this level could eventually contribute to environmental sustainability in these economies.

These findings highlight the varied environmental effects of financial inclusion across different financial development stages within SSA. The stronger positive coefficient observed for upper-middle-income countries likely reflects a phase of rapid industrialization and consumption growth, where environmental considerations are often secondary. The magnitude of this effect decreases as financial development increases. This pattern aligns with the non-linear relationship discussed in Section 5.2, where environmental degradation initially rises with financial and economic development but potentially declines at higher income levels as sustainable practices become more accessible.

6. Robustness tests

In addition to our baseline estimation, we perform various robustness checks to verify the validity of our results. We explore alternative green sustainability and financial inclusion measures consistent with the approaches outlined in our base model (3). We present the results of our robustness tests in Appendix Section C, which we find to be consistent and not materially different from our baseline results. Finally, we also re-estimate our baseline model and report results based on alternative sets of instruments. We present the additional information in Appendix Table C6. The results show similarities with those reported in Table 1. The probability values of the Sargan test indicate no rejection of the null hypothesis that the instruments as a group are exogenous. Therefore, the instruments used in each GMM model estimation are valid with appropriate exclusion restrictions.

6.1. Robustness test I: single alternative measures of financial inclusion and green sustainability

We re-estimate our results using various individual measures of environmental pollution (CO2, N2O, CH4, PM 2.5) as a dependent variable and used various individual measures of financial inclusion as the regressors. Given the use of highly aggregated data, this robustness approach helps to identify the mechanisms through which each financial inclusion covariate impacts emissions and the magnitude of estimated effects. We avoid the issue of multicollinearity by not including all the financial inclusion covariates in the

[10] The three regions represent countries that are members of the formal arrangements: the Economic Community of West African States (ECOWAS), the East African Community (EAC), and the Southern African Development Community (SADC). The last one is dubbed as Southern Africa and comprises sixteen members, including (the Republic of) South Africa.

Table 2
Intra-regional heterogeneity with respect to environmental pollution.

	Intra-regional
Lag of Environmental Pollution Index	0.720***
	(0.000)
Financial Inclusion	0.145***
	(0.001)
Intra-regional heterogeneity	
Financial Inclusion in Southern Africa	−1.515***
	(0.000)
Financial Inclusion in Western Africa	−1.133***
	(0.000)
Controls	
Energy Use	−0.076***
	(0.001)
Human Development	−0.018***
	(0.007)
Natural Resources	−0.009***
	(0.003)
Trade Openness	−0.001
	(0.391)
Economic Growth	0.033***
	(0.000)
Government Expenditure	0.024***
	(0.008)
Urbanization	−0.003
	(0.541)
Constant	0.982***
	(0.000)
Diagnostics	
Wald Test	3544.37
Prob. (Wald)	0.000
AR1 (p-value)	0.217
AR2 (p-value)	0.368
Hansen-J (p-value)	0.338
Sargan (p-value)	0.252
DHT for instrument	
a. Instruments in levels	
H excluding group	
b. IV (years, eq(diff))	
H excluding group	0.501
Number of groups	33
Number of instrumental	30
Observations	162

Statistical significance at the 1 %, 5 %, and 10 % level is indicated by ***, **, and *, respectively. P-values in parentheses. Financial Inclusion in Southern Africa represents a dummy variable of 1 for countries belonging to Southern Africa or 0 otherwise. Financial Inclusion in Western Africa represents a dummy variable of 1 for countries belonging to the West African States or 0 otherwise. Financial Inclusion in Eastern Africa represents a dummy variable of 1 for countries belonging to Eastern Africa or 0 otherwise and serves as the reference category. All the other variables in this table are the same as previously defined in Table 1.

same model to prevent overlapping results. We present our results in Appendix Tables C1 to C4.

Our findings indicate that access to ATMs and bank branches reduces environmental pollution in SSA. Their contribution is evidenced by a negative coefficient associated with CO2 emission. Similarly, bank credit and bank deposits are linked to reduced pollution levels. This result is intuitively correct as higher deposits could indicate a greater propensity for saving and a reduced need for immediate consumption, resulting in lower overall resource consumption and, subsequently, lower emissions. Moreover, banks may have substantial financing as deposits increase to support sustainable projects promoting environmental sustainability. Conversely, life and non-life insurance exhibit positive associations with CO_2 emissions, particularly non-life insurance. Insurance coverage might encourage more carbon-intensive activities as risks are transferred to insurers.

Further analysis highlights the negative impact of bank branches in reducing environmental pollution. This observation could be potentially linked to their role in promoting sustainable agricultural practices. According to Chen et al. (2021), establishing

Table 3
Income bloc heterogeneity with respect to environmental pollution.

	Income bloc
Lag of Environmental Pollution Index	0.787***
	(0.00)
Financial Inclusion	0.057**
	(0.039)
Income Bloc heterogeneity	
High-income countries (HIC)	0.101
	(0.804)
Upper-medium income countries (UMIC)	0.690**
	(0.024)
Lower-medium income countries (LMIC)	0.401*
	(0.057)
Controls	
Energy Use	0.106***
	(0.003)
Human Development	−0.025**
	(0.025)
Natural Resources	0.010**
	(0.020)
Trade Openness	0.003
	(0.106)
Economic Growth	−0.004
	(0.539)
Government Expenditure	−0.030*
	(0.074)
Urbanization	−0.018***
	(0.002)
Constant	0.781***
	(0.000)
Diagnostics	
Wald Test	1328.78
Prob. (Wald)	0.000
AR1 (p-value)	0.218
AR2 (p-value)	0.370
Hansen-J (p-value)	0.491
Sargan (p-value)	0.104
DHT for instrument	
c. Instruments in levels	
H excluding group	
d. IV (years, eq(diff))	
H excluding group	0.585
Number of groups	33
Number of instrumental	30
Observations	162

Statistical significance at the 1 %, 5 %, and 10 % level is indicated by ***, **, and *, respectively. P-values in parentheses. “HIC” denotes a dummy variable equal to 1 for high-income countries (as defined by the World Bank) and 0 otherwise. “UMIC” represents a dummy variable equal to 1 for upper-middle-income countries, and “LMIC” represents a dummy variable equal to 1 for lower-middle-income countries based on World Bank classifications. “LIC” denotes lower-income countries and serves as the reference category. All the other variables in this table are the same as previously defined in Table 1.

commercial banks significantly reduces regional pollution due to innovation-promoting and FDI-attracting effects. However, the positive contribution of the other financial inclusion measures - particularly bank credit, non-life insurance, and ATMs can be attributed to their role in expanding agricultural and industrial activities, which are primary sources of N2O emissions in developing economies.

As seen in Appendix Table C3, bank branches enhance environmental sustainability by reducing the release of methane. These results could be due to their role in promoting sustainable practices through direct monitoring, as observed for nitrous oxide emission (Appendix Table C2). Conversely, the other financial inclusion measures positively contribute to environmental pollution through methane emission. Life insurance shows the most substantial positive contribution (0.290), followed by bank deposits (0.135), bank credit and non-life insurance (both 0.099), and ATMs (0.040). Their positive contribution could be explained through the facilitation and expansion of activities that are major sources of methane in Africa – agriculture and waste management (Delmas, Tathy, & Cros, 1992; Robert & Adonye, 2021).

Our results show that bank credits are associated with increased air pollution, as evidenced by a positive coefficient with PM 2.5. Higher bank credit could indicate increased lending activities that might support industrial expansion and urban development, contributing to air pollution. Interestingly, we highlight the positive impact of life insurance in reducing environmental pollution, particularly in air pollution. The results suggest that individuals with life insurance coverage tend to adopt practices or behaviors leading to reduced pollution. Conversely, non-life insurance, mainly covering assets and properties, contributes to increased environmental pollution, as indicated by the positive coefficient on PM2.5 emissions. We can infer that non-life insurance may indirectly incentivize behaviors or practices that lead to air pollution. Physical banking infrastructure (ATMs, bank branches) and bank deposits show statistically insignificant effects, suggesting their limited direct influence on particulate matter emissions.

6.2. Robustness test II: climate footprint index as a measure of green sustainability

Finally, as another measure of green sustainability, we focused on pollutants that primarily impact climate change (CO_2, N_2O, CH_4) as a dependent variable. The results, outlined in Appendix Table C5, consistently support our initial findings, indicating that financial inclusion contributes to environmental pollution, as indicated by the climate footprint index. Specifically, we show that ATMs, bank branches, and non-life insurance contribute to heightened levels of environmental pollution. The increase in these variables often signifies the expansion of industrialization and infrastructure development, which jointly contribute to environmental pollution and the release of emissions through both direct and indirect mechanisms (Liu et al., 2022). On the other hand, bank credit, bank deposits, and life insurance play a vital role in reducing environmental pollution in the SSA. This observation is intuitively straightforward, as these variables are expected to provide credit to facilitate the adoption of green technologies and practices and even reduce the long-term impact of environmental hazards.

Upon completing our robustness test, the results from the robustness analysis are not materially different from our baseline results. The results emphasize the reliability of our methodology, as they remain consistent even when alternative variables are employed to measure green sustainability and financial inclusion.

7. Conclusion and policy implications

We explore the relationship between financial inclusion and green sustainability in Africa and its link to environmental challenges. This relationship can have positive or negative effects. While it enables investments in green technologies and eco-friendly practices, it can also promote carbon emissions and energy-intensive consumption. To better understand this relationship, we develop three hypotheses to address the research objective. We use a comprehensive empirical analysis spanning 38 Sub-Saharan African (SSA) countries from 2000 to 2021. We further develop an environmental pollution index and a financial inclusion index to account for the several dimensions of both variables. We also use the System GMM dynamic panel data estimation to address endogeneity and potential reverse causality issues.

Contrary to our first hypothesis, our results align with the notion that financial inclusion facilitates more accessible access to funds, fueling swift expansions in infrastructure, urbanization, and increased energy consumption. However, this poses a significant risk of environmental degradation and a surge in waste generation. The results hold even when we control for a set of macro-level determinants such as energy use, human development, natural resource dependency, trade openness, government expenditure, and urbanization. We further confirm that financial inclusion has a negative heterogeneous impact on pollution across SSA regions, thus confirming an intra-regional heterogeneity within SSA. We observe that while financial inclusion's effect on environmental pollution is positive overall, the magnitude of this effect varies less across regions within SSA. Southern Africa and Western Africa exhibit lower pollution levels than Eastern Africa. Further, the impact of financial inclusion on environmental pollution is more pronounced in upper-middle-income countries, followed by lower-middle-income countries, compared to low-income countries. In high-income countries, however, this effect is insignificant. The variation suggests diverse categorical strategies potentially influenced by varying financial inclusion per income groups and geographical factors.

Our empirical analysis also validates a negative non-linear (inverted U-shaped) relationship between financial inclusion and environmental pollution, consistent with the Environmental Kuznets Curve (EKC) hypothesis. We highlight the need to strike a balance in expanding financial services, emphasizing the importance of reaching an optimal level of financial inclusion for fostering sustainable practices in the region. Perhaps we can conclude that promoting green sustainability tends to be more feasible for those with ample financial resources. Cultivating a culture of environmental awareness requires access to a diverse range of funds at an optimal level.

It is conventional to suggest that governments should continue promoting financial inclusion initiatives and encourage financial institutions to integrate environmental criteria into their lending policies and risk assessment processes. Financial institutions can be incentivized or charged to develop eco-innovations or adopt eco-friendly practices that prioritize investments in green technologies and projects as part of their CSR initiatives. Such a policy may enable financial inclusion to be environmentally beneficial rather than unfavorable. It may involve providing incentives, subsidies, or reduced interest rates for loans and investments related to eco-friendly technologies like green bonds, green loans, green funds, and Sustainability-linked loans (SLLs). It is also worth noting that developing green credit score models that can evaluate financial institutions and their role in financing green sustainable projects compliance helps them get their commitment to financing and developing innovative products to guide investors towards genuinely eco-friendly initiatives. Lastly, policymakers are encouraged to develop long-term sustainability education and awareness programs tailored to different stages of financial inclusion. Recognizing the U-shaped relationship between financial inclusion and green sustainability, they could focus on establishing basic environmental standards and gradually introduce more stringent regulations as financial inclusion progresses, ensuring that sustainable practices are integrated into business operations at an optimal stage of development. The financial market will also gradually respond to the opportunities embedded within these regulations. Strengthening environmental policies can potentially relocate capital towards green private sector investment, establishing a win-win benefit for all (Kruse, Mohnen, & Sato, 2023).

Further research could assess the political and economic institutions that affect green sustainability in Sub-Saharan Africa and provide deeper insights into how certain factors, such as property rights and political stability, could impact green sustainability. Also, future research could assess this relationship at the micro-level to understand the behavioral aspects of individual financial inclusion levels and their impact on green sustainability.

CRediT authorship contribution statement

Samuel Fiifi Eshun: Conceptualization, Methodology, Data curation, Formal analysis, Writing – original draft, Writing – review & editing, Visualization. **Evžen Kočenda:** Conceptualization, Resources, Writing – original draft, Writing – review & editing, Supervision, Funding acquisition.

Declaration of competing interest

The authors report there are no competing interests to declare.

Data availability

Data will be made available on request.

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Appendix A. Estimation technique

In line with our model specifications and consistent with existing literature, our dependent variable, green sustainability, proxied by EPI, is considered endogenous. Endogeneity arises from the fact that green sustainability is influenced by its lag values, leading to a dynamic relationship (Law and Azman-Saini, 2012). Endogeneity can also occur in the dynamic model when there is a reverse causality among the independent variables and a reverse causality between the independent variable and financial inclusion (Francois, 2023).

We employ the System Generalized Methods of Moments (GMM) to estimate our results and address the endogeneity issue. The estimation strategy is efficient in handling endogeneity bias, particularly when appropriate instruments are available (Raftis, Karpetis, Papadamou, and Spyromitros, 2024). The GMM technique, introduced by Blundell and Bond (1998) and Arellano and Bond (1991), is an instrumental variable method that combines a system of two equations, a model estimated in differences with a model estimated in levels for its estimation. Our data is stationary for the mean differences to be used as informative instruments, ensuring reliable estimation. Mathematically, the levels equation for computing the system GMM, according to Li, Ding, Hu, and Wan (2021), is computed as:

$$Y_{it} = aY_{it-t} + bX_{it} + yZ_{it} + \varepsilon_{it}, \tag{7}$$

where Y_{it} is the dependent variable, X_{it} is the matrix of the exogenous variables, Z_{it} is the matrix of instruments (lagged levels and first differences of endogenous variables and exogenous variables), a and b are the parameters to be estimated, ε_{it} and is the error term.

Subsequently, the first difference equation is specified as:

$$Y_{it} = m\Delta Y_{it-1} + n\Delta X_{it} + q\Delta Z_{it} + \mu_{it}, \tag{8}$$

where $\Delta Y_{it} = Y_{it} - Y_{it-1}$ is the first difference of the dependent variable; $\Delta X_{it} = X_{it} - X_{it-1}$ is the matrix of the first differences of exogenous variables; $\Delta Z_{it} = Z_{it} - Z_{it-1}$ is the matrix of the first differences of instruments; m and n are the parameters to be estimated, and μ_{it} and is the error term.

The System GMM uses moment conditions based on the instrumental variables. These moment conditions are used to construct the weighting matrix of the estimation. For each period t, the moment conditions are given by:

$$E[\Delta Z_{it} . \mu_{it}] = 0, \tag{9}$$

where, for every t and i in the sample period, the expected value of the idiosyncratic error given the explanatory variables in all periods and the unobserved effect is 0 (Li, Ding, Hu, and Wan, 2021).

Again, we adopted a panel estimation strategy as it is suitable in two (2) ways: (1) when the cross-sectional (N) units are more than the time series (T) units (Abeka et al., 2022); (2) when there is a tendency for persistence in the lagged differences of the dependent variable using a rule of thumb of 0.80 (Agyei, Marfo-Yiadom, Ansong, and Idun, 2020). Thus, the coefficient of the lagged dependent variable should be close to 1.

In our study, T=22 and N=38. From our correlation analysis, the lag value of the dependent variable shows a correlation coefficient of 0.918, which is close to 1 and confirms the presence of lagged persistence. We employed the approach of Roodman (2009) to reduce the possibility of bias from instrument proliferation by restricting the moment conditions to a maximum of two lags of the dependent variable. The number of instruments should be less than or equal to the number of groups to avoid instrument proliferation (David, Diallo, and Nilsson, 2023).

We assess the adequacy of our System GMM results and the validity of our instruments by reporting on the Sargan test of over-identifying restrictions (OIR) and Hansen test of over-identifying restrictions (OIR). Similarly, we test for the absence of autocorrelation using the Arellano and Bond serial correlation test. These tests require that the null hypothesis be rejected for the test to be valid. It is usually expected that the null hypothesis for the first order (AR1) will be rejected. Nevertheless, the second order (AR2) is more important because it will detect autocorrelation in levels and therefore, its null hypothesis should not be rejected. As Asongu and De Moor (2017) recommended, we further analyze and report on the difference-in-hansen test (DHT) for the exogeneity of instruments to assess the results of the Hansen OIR test. Fischer's test for the joint validity of estimated coefficients evaluates the validity of the estimated GMM model.

Appendix B. Section B

Appendix Table B1
List of the sample of 38 Sub-Saharan (SSA) economies

SUB-SAHARAN AFRICA COUNTRIES	
Eastern Africa	Western Africa
Burundi	Benin
Congo	Burkina Faso
Congo Republic	Cape Verde
Kenya	Cameroon
Madagascar	Chad
Mauritius	Cote d'Ivoire
Mozambique	Gabon
Rwanda	The Gambia
Sudan	Ghana
Tanzania	Guinea
Uganda	Mali
	Mauritania
Southern Africa	Niger
Angola	Nigeria
Botswana	Senegal
Eswatini	Sierra Leone
Lesotho	Togo
Malawi	
Namibia	
Seychelles	
South Africa	
Zambia	
Zimbabwe	

Appendix Table B2
Description of variables and measurement

Variable	Measurement	Data Source
Environmental Pollution Index	Principal Component Analysis of four (4) variables: CO2 emission, PM 2.5, Methane emission, Nitrous oxide emission	See Appendix Table B3
Financial Inclusion Index	Principal Component Analysis of six (6) variable estimates measuring access, usage, and quality of product	See Appendix Table B4
Energy Use	Per capita electricity generation from oil (kWh)	Our World in Data 2000 - 2021

(continued on next page)

Appendix Table B2 (*continued*)

Variable	Measurement	Data Source
Human Development	School enrollment, Tertiary	World Development Indicators 2000 - 2021
Trade Openness	Sum of exports and imports of goods and services as a share of gross domestic product.	World Development Indicators 2000 - 2021
Natural Resource Dependency	Total national resource rents (% of GDP)	World Development Indicators 2000 - 2021
Economic Growth	Gross Domestic Product (GDP) (% growth)	World Development Indicators 2000 - 2021
Government Expenditure	Annual percentage growth of general government final consumption expenditure (% of GDP)	World Development Indicators 2000 - 2021
Urbanization	Urban Population (% of total population)	World Development Indicators 2000 - 2021

Appendix Table B3
Component variables of the Environmental Pollution Index

Components	Individual indicator(s)	Source of Data
CO2 emissions	CO2 emission per capita (metric tons)	World Development Indicators 2000 – 2021
Particulate Matter (PM) 2.5	PM 2.5 (particles with a diameter of 2.5 micrometres or less)	World Development Indicators 2000 – 2021
Methane emissions	Methane emission (metric tons of CO2 equivalent per capita)	World Development Indicators 2000 – 2021
Nitrous oxide emission	Nitrous oxide emission (metric tons of CO2 equivalent per capita)	World Development Indicators 2000 – 2021

Appendix Table B4
Component variables of the Financial Inclusion Index

Components	Individual indicator(s)	Source of Data
ATM per 100,000 adults	Number of ATMs per 100,000 adults.	Global Financial Development, 2000-2021
Bank Branches per 100,000 adults	Number of commercial bank branches per 100,000 adults.	Global Financial Development, 2000-2021
Bank Deposits	Money deposited in banks as a share of GDP.	Global Financial Development, 2000-2021
Bank Credit to Bank Deposit	Credit provided by domestic money banks as a share of total deposits.	Global Financial Development, 2000-2021
Life Insurance Premium	Ratio of life insurance premium volume to GDP.	Global Financial Development, 2000-2021
Non-Life Insurance Premium	Ratio of non-life insurance premium volume to GDP	Global Financial Development, 2000-2021

Appendix Table B5
Estimation results of the principal component analysis

Eigenvalue of the correlation matrix				Eigenvectors of the first component	
Component no.	Eigenvalue	Eigenvalue Difference	Cumulative percentage of total variance	Variables	Eigenvector
(a) Environmental Pollution Index					
1	1.649	0.310	0.412	CO2 emission	0.237
2	1.338	0.692	0.747	Particulate Matter (PM) 2.5	0.301
3	0.646	0.280	0.909	Methane emissions	0.674
4	0.366		1.000	Nitrous oxide emission	0.632
(b) Financial Inclusion Index					
1	3.956	3.000	0.659	ATMs	0.450
2	0.953	0.347	0.818	BBA	0.449
3	0.606	0.292	0.919	Bank credit to Bank deposit	0.221
4	0.314	0.193	0.971	Bank Deposit	0.365
5	0.120	0.068	0.991	Life Insurance	0.451
6	0.052		1.000	Non-life Insurance	0.458

Environmental pollution index represents a statistical index of CO2 emissions, Particulate Matter 2.5 (PM), methane emissions, and nitrous oxide emissions. Financial inclusion represents a comprehensive index (FII) based on six variables: ATMs, bank branches, credit-to-deposit ratio, bank deposits, life insurance, and non-life insurance.

Appendix Table B6
Descriptive statistics

Variable	Observation	Mean	Standard Deviation	Minimum	Maximum
Environmental Pollution Index (EPI)	380	0	1.284	-1.438	7.567
Financial Inclusion Index (FII)	427	0	1.989	-2.083	9.120
Energy Use	814	193.607	624.345	0	5352.816
Human Development	537	8.637	7.691	0.318	43.959
Trade Openness	805	71.161	35.800	0.757	225.023
Natural Resource	836	10.761	10.435	0.002	59.684
GDP Growth	836	4.012	4.573	-20.599	33.629
Government Expenditure (GE)	769	15.140	6.907	0.952	43.484
Urbanization	836	39.564	16.562	8.246	90.423

Environmental pollution index represents a statistical index of CO2 emissions, Particulate Matter 2.5 (PM), methane emissions, and nitrous oxide emissions. Financial inclusion represents a comprehensive index (FII) based on six variables: ATMs, bank branches, credit-to-deposit ratio, bank deposits, life insurance, and non-life insurance. Energy use represents per capita electricity generation from oil. Human Development represents tertiary school enrolment. Trade Openness represents the sum of exports and imports as a share of GDP. Natural Resource Dependency represents the total national resource rents as a percentage of GDP. Economic Growth represents GDP growth. Government Expenditure represents the annual growth of government consumption as a percentage of GDP. Urbanization represents the urban population as a percentage of the total population.

Appendix Table B7
Pairwise correlations analysis

	Environmental Pollution Index	Renewable Energy	Financial Inclusion	Energy Use	Human Development	Trade	Natural Resource	Economic Growth	Gov't Expenditure	Urbanization
Environmental Pollution Index	1.000									
Financial Inclusion	0.129	-0.301	1.000							
Energy Use	0.054	-0.147	0.201	1.000						
Human Development	0.162	-0.193	0.534	0.218	1.000					
Trade	0.006	-0.092	0.315	-0.244	0.250	1.000				
Natural Resources	-0.065	0.196	-0.264	-0.223	-0.279	-0.007	1.000			
Economic Growth	0.070	0.034	-0.160	-0.125	-0.208	0.086	0.153	1.000		
Gov't Expenditure	0.081	0.143	0.314	-0.175	0.163	0.503	-0.212	-0.095	1.000	
Urbanization	0.265	-0.280	0.467	0.238	0.512	0.399	0.032	-0.167	0.140	1.000

*significance at 10% level; **significance at 5% level; ***significance at 1% level.
Environmental pollution index represents a statistical index of CO2 emissions, Particulate Matter 2.5 (PM), methane emissions, and nitrous oxide emissions. Financial inclusion represents a comprehensive index (FII) based on six variables: ATMs, bank branches, credit-to-deposit ratio, bank deposits, life insurance, and non-life insurance. Energy use represents per capita electricity generation from oil. Human Development represents tertiary school enrolment. Trade Openness represents the sum of exports and imports as a share of GDP. Natural Resource Dependency represents the total national resource rents as a percentage of GDP. Economic Growth represents GDP growth. Government Expenditure represents the annual growth of government consumption as a percentage of GDP. Urbanization represents the urban population as a percentage of the total population.

Appendix C. Section C. Results of Robustness Test

Appendix Table C1
Robustness Test I - Single alternative measures of financial inclusion and green sustainability

	CO2 EMISSION (Model 3a)	CO2 EMISSION (Model 3a)	CO2 EMISSION (Model 3a)	CO2 EMISSION (Model 3a)	CO2 EMISSION (Model 3a)	CO2 EMISSION (Model 3a)
Lag of environmental pollutants	0.991***	0.970***	0.984***	0.989***	0.966***	0.950***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
ATMs	-0.030***					
	(0.000)					
Bank Branches		-0.033**				
		(0.025)				
Bank Credit to Deposit			-0.014***			
			(0.000)			
Bank Deposit				-0.011***		
				(0.000)		
Life Insurance					0.025*	
					(0.092)	
Non-Life Insurance						0.029***

(*continued on next page*)

Appendix Table C1 (*continued*)

	CO2 EMISSION (Model 3a)	CO2 EMISSION (Model 3a)	CO2 EMISSION (Model 3a)	CO2 EMISSION (Model 3a)	CO2 EMISSION (Model 3a)	CO2 EMISSION (Model 3a)
						(0.009)
Controls						
Energy Use	0.006	-0.008	0.006	0.004	-0.006	-0.024***
	(0.135)	(0.302)	(0.180)	(0.441)	(0.292)	(0.008)
Human Development	0.002***	0.005***	0.003***	0.003***	0.005***	0.003***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Natural Resources	-0.001*	-0.003***	0.001***	0.002***	0.003***	-0.000
	(0.080)	(0.000)	(0.006)	(0.000)	(0.010)	(0.576)
Trade Openness	0.001***	0.002***	0.001***	0.001***	0.002***	0.001***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Economic Growth	0.003***	0.009***	0.001**	0.002***	0.001*	-0.007***
	(0.000)	(0.000)	(0.039)	(0.000)	(0.075)	(0.000)
Government Expenditure	-0.004***	-0.004***	-0.001	0.002***	-0.011***	-0.008***
	(0.000)	(0.005)	(0.530)	(0.000)	(0.000)	(0.001)
Urbanization	0.002***	0.001	-0.001***	-0.001***	-0.003***	0.000
	(0.000)	(0.004)	(0.000)	(0.000)	(0.000)	(0.872)
Constant	-0.102***	-0.134***	-0.043**	-0.120***	0.136***	0.124***
	(0.000)	(0.000)	(0.014)	(0.000)	(0.000)	(0.008)
Diagnostics						
Wald Test	1.22e+06	3.39e+06	1.67e+06	3.66e+06	69166.31	182115.67
Prob. (Wald)	0.000	0.000	0.000	0.000	0.000	0.000
AR1 (p-value)	0.063	0.055	0.035	0.037	0.040	0.040
AR2 (p-value)	0.491	0.273	0.857	0.735	0.767	0.545
Hansen-J (p-value)	0.574	0.758	0.680	0.453	0.547	0.477
Sargan (p-value)	0.254	0.164	0.420	0.117	0.293	0.951
DHT for instrument						
Instruments in levels						
H excluding group	0.379	0.417	0.225	0.543	0.579	0.634
IV (years, eq(diff))						
H excluding group	0.591	0.704	0.627	0.466	0.491	0.427
Number of groups	35	35	37	37	35	35
Number of instruments	30	30	30	34	30	30
Observations	341	381	446	446	390	415

Statistical significance at the 1%, 5%, and 10% level is indicated by ***, **, and *, respectively. P-values in parentheses. Model 3 uses the baseline model. Financial inclusion is measured by proxies such as ATMs, bank branches, bank credit to deposit, bank deposits, life insurance, and non-life insurance. Control variables include energy use, human development, natural resources, trade openness, economic growth, government expenditure, and urbanization. The diagnostics section presents the values of the Wald test, probability values of the Wald test, z-values of AR(1) and AR(2), probability of z-values of AR(1) and AR(2), probability of the Sargan test, the number of groups and instruments, and the number of observations.

Appendix Table C2
Robustness Test I - Single alternative measures of financial inclusion and green sustainability

	N2O EMISSION (Model 3b)	N2O EMISSION (Model 3b)	N2O EMISSION (Model 3b)	N2O EMISSION (Model 3b)	N2O EMISSION (Model 3b)	N2O EMISSION (Model 3b)
Lag of environmental pollutants	0.780***	0.805***	0.709***	0.699***	0.675***	0.655***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
ATMs	0.046***					
	(0.000)					
Bank Branches		-0.043***				
		(0.000)				
Bank Credit to Deposit			0.086***			
			(0.000)			
Bank Deposit				0.038**		
				(0.021)		
Life Insurance					0.024***	
					(0.001)	
Non-Life Insurance						0.051***
						(0.005)
Controls						
Energy Use	-0.008**	-0.018***	-0.044***	-0.009	0.003	0.025*
	(0.050)	(0.000)	(0.000)	(0.477)	(0.754)	(0.061)

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Appendix Table C2 (*continued*)

	N2O EMISSION (Model 3b)	N2O EMISSION (Model 3b)	N2O EMISSION (Model 3b)	N2O EMISSION (Model 3b)	N2O EMISSION (Model 3b)	N2O EMISSION (Model 3b)
Human Development	-0.011***	-0.004***	-0.003***	-0.004***	-0.006***	-0.007***
	(0.000)	(0.000)	(0.001)	(0.014)	(0.000)	(0.000)
Natural Resources	-0.001*	-0.003***	-0.004***	-0.000	0.000	0.000
	(0.055)	(0.000)	(0.002)	(0.914)	(0.716)	(0.920)
Trade Openness	-0.000***	0.000**	-0.001***	-0.002***	-0.001***	-0.002***
	(0.004)	(0.033)	(0.000)	(0.000)	(0.000)	(0.000)
Economic Growth	-0.001**	0.006***	0.011***	0.004**	0.004***	0.005***
	(0.054)	(0.001)	(0.001)	(0.021)	(0.000)	(0.008)
Government Expenditure	-0.003***	0.002*	0.012***	-0.006**	-0.005**	-0.004
	(0.000)	(0.065)	(0.007)	(0.030)	(0.017)	(0.202)
Urbanization	0.001	0.001***	0.001	0.002**	0.001	0.001
	(0.143)	(0.000)	(0.144)	(0.029)	(0.195)	(0.595)
Constant	0.274***	0.042**	0.050	0.279***	0.289***	0.358***
	(0.000)	(0.026)	(0.485)	(0.002)	(0.000)	(0.000)
Diagnostics						
Wald Test	48035.17	2.47e+06	4366.17	83.85	1059.89	626.65
Prob. (Wald)	0.000	0.000	0.000	0.000	0.000	0.000
AR1 (p-value)	0.296	0.292	0.291	0.252	0.276	0.270
AR2 (p-value)	0.333	0.336	0.351	0.236	0.315	0.264
Hansen-J (p-value)	0.510	0.500	0.333	0.761	0.340	0.347
Sargan (p-value)	0.155	0.690	0.878	0.389	0.326	0.360
DHT for instrument						
Instruments in levels						
H excluding group	0.327	0.671	0.327	0.522	0.299	0.427
IV (years, eq(diff))						
H excluding group	0.582	0.507	0.330	0.720	0.288	0.395
Number of groups	35	35	37	37	35	35
Number of instruments	34	34	30	30	30	30
Observations	341	381	446	446	391	415

Statistical significance at the 1%, 5%, and 10% level is indicated by ***, **, and *, respectively. P-values in parentheses. Model 3 uses the baseline model. Financial inclusion is measured by proxies such as ATMs, bank branches, bank credit to deposit, bank deposits, life insurance, and non-life insurance. Control variables include energy use, human development, natural resources, trade openness, economic growth, government expenditure, and urbanization. The diagnostics section presents the values of the Wald test, probability values of the Wald test, z-values of AR(1) and AR(2), probability of z-values of AR(1) and AR(2), probability of the Sargan test, the number of groups and instruments, and the number of observations.

Appendix Table C3

Robustness Test I - Single alternative measures of financial inclusion and green sustainability

	METHANE (Model 3c)	METHANE (Model 3c)	METHANE (Model 3c)	METHANE (Model 3c)	METHANE (Model 3c)	METHANE (Model 3c)
Lag of environmental pollutants	0.861***	0.961***	0.711***	0.804***	0.835***	0.832***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
ATMs	0.040***					
	(0.000)					
Bank Branches		-0.161*				
		(0.068)				
Bank Credit to Deposit			0.099***			
			(0.000)			
Bank Deposit				0.135***		
				(0.000)		
Life Insurance					0.290***	
					(0.000)	
Non-Life Insurance						0.099***
						(0.000)
Controls						
Energy Use	-0.023***	-0.022***	-0.059***	0.025***	0.032***	0.016**
	(0.006)	(0.000)	(0.000)	(0.009)	(0.000)	(0.034)
Human Development	-0.005***	0.000	-0.003***	-0.007***	-0.009***	-0.005***
	(0.000)	(0.229)	(0.000)	(0.004)	(0.000)	(0.007)
Natural Resources	-0.001*	-0.003***	-0.002**	0.004***	0.009***	0.008***
	(0.074)	(0.000)	(0.048)	(0.010)	(0.000)	(0.000)
Trade Openness	0.001***	0.001***	0.001***	-0.001**	0.002***	-0.001***
	(0.002)	(0.000)	(0.000)	(0.016)	(0.000)	(0.000)

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Appendix Table C3 (*continued*)

	METHANE (Model 3c)	METHANE (Model 3c)	METHANE (Model 3c)	METHANE (Model 3c)	METHANE (Model 3c)	METHANE (Model 3c)
Economic Growth	-0.002*	0.007***	0.001	-0.004***	-0.015***	0.003
	(0.072)	(0.000)	(0.140)	(0.010)	(0.000)	(0.172)
Government Expenditure	-0.010***	-0.004***	-0.006***	-0.012***	-0.029***	-0.010***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.002)
Urbanization	0.000	0.000	0.003***	-0.002	-0.003***	0.003***
	(0.938)	(0.660)	(0.000)	(0.259)	(0.014)	(0.000)
Constant	0.274***	0.052*	0.256***	0.512***	0.621***	0.176***
	(0.000)	(0.088)	(0.000)	(0.000)	(0.000)	(0.003)
Diagnostics						
Wald Test	3.15e+06	148827.72	47539.71	14647.73	10918.88	56580.49
Prob. (Wald)	0.000	0.000	0.000	0.000	0.000	0.000
AR1 (p-value)	0.291	0.287	0.295	0.289	0.276	0.285
AR2 (p-value)	0.314	0.312	0.321	0.319	0.306	0.303
Hansen-J (p-value)	0.696	0.588	0.344	0.337	0.753	0.319
Sargan (p-value)	0.233	0.997	0.178	0.260	0.242	0.236
DHT for instrument						
Instruments in levels						
H excluding group	0.376	0.456	0.222	0.487	0.585	0.179
IV (years, eq(diff))						
H excluding group	0.718	0.535	0.312	0.289	0.788	0.298
Number of groups	35	35	37	37	35	35
Number of instruments	34	34	34	34	34	34
Observations	341	381	446	446	391	415

Statistical significance at the 1%, 5%, and 10% level is indicated by ***, **, and *, respectively. P-values in parentheses. Model 3 uses the baseline model. Financial inclusion is measured by proxies such as ATMs, bank branches, bank credit to deposit, bank deposits, life insurance, and non-life insurance. Control variables include energy use, human development, natural resources, trade openness, economic growth, government expenditure, and urbanization. The diagnostics section presents the values of the Wald test, probability values of the Wald test, z-values of AR(1) and AR(2), probability of z-values of AR(1) and AR(2), probability of the Sargan test, the number of groups and instruments, and the number of observations.

Appendix Table C4

Robustness Test I - Single alternative measures of financial inclusion and green sustainability

	PM 2.5 (Model 3d)	PM 2.5 (Model 3d)	PM 2.5 (Model 3d)	PM 2.5 (Model 3d)	PM 2.5 (Model 3d)	PM 2.5 (Model 3d)
Lag of environmental pollutants	0.938***	0.940***	0.972***	0.888***	0.939***	1.048***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
ATMs	-0.045					
	(0.178)					
Bank Branches		-0.043				
		(0.100)				
Bank Credit to Deposit			0.063***			
			(0.010)			
Bank Deposit				0.035		
				(0.113)		
Life Insurance					-0.073*	
					(0.060)	
Non-Life Insurance						0.060*
						(0.079)
Controls						
Energy Use	-0.049***	-0.057***	-0.064**	-0.116***	-0.046***	-0.009
	(0.000)	(0.000)	(0.018)	(0.001)	(0.002)	(0.693)
Human Development	-0.018***	-0.023***	-0.020***	-0.012**	-0.001	-0.008***
	(0.014)	(0.000)	(0.000)	(0.027)	(0.407)	(0.001)
Natural Resources	-0.005***	-0.006***	-0.006***	-0.010***	-0.003	0.000
	(0.002)	(0.000)	(0.003)	(0.004)	(0.322)	(0.912)
Trade Openness	-0.002***	-0.001	-0.002***	-0.004***	-0.002*	0.000
	(0.008)	(0.105)	(0.013)	(0.000)	(0.063)	(0.962)
Economic Growth	-0.030***	-0.033***	-0.030***	-0.037***	-0.025***	-0.018***
	(0.000)	(0.000)	(0.006)	(0.000)	(0.000)	(0.000)
Government Expenditure	0.015*	0.016**	0.009	0.025***	0.011**	-0.004
	(0.081)	(0.026)	(0.167)	(0.001)	(0.019)	(0.486)
Urbanization	0.001	0.004	0.003	0.002	0.000	0.001
	(0.676)	(0.210)	(0.252)	(0.407)	(0.821)	(0.650)
Constant	0.289***	0.205**	0.317*	0.373**	0.169***	0.228
	(0.012)	(0.023)	(0.097)	(0.018)	(0.010)	(0.121)

(*continued on next page*)

Appendix Table C4 (*continued*)

	PM 2.5 (Model 3d)	PM 2.5 (Model 3d)	PM 2.5 (Model 3d)	PM 2.5 (Model 3d)	PM 2.5 (Model 3d)	PM 2.5 (Model 3d)
Diagnostics						
Wald Test	10585.39	15073.32	2573.36	19302.21	346345.17	1847.12
Prob. (Wald)	0.000	0.000	0.000	0.000	0.000	0.000
AR1 (p-value)	0.015	0.015	0.016	0.020	0.023	0.024
AR2 (p-value)	0.112	0.116	0.110	0.125	0.110	0.100
Hansen-J (p-value)	0.726	0.706	0.699	0.901	0.559	0.440
Sargan (p-value)	0.974	0.973	0.958	0.964	0.976	0.840
DHT for instrument						
Instruments in levels						
H excluding group	0.292	0.338	0.259	0.536	0.145	0.203
IV (years, eq(diff))						
H excluding group	0.682	0.654	0.664	0.891	0.387	0.424
Number of groups	35	35	35	35	35	34
Number of instruments	34	34	34	34	34	31
Observations	191	191	194	194	165	177

Statistical significance at the 1%, 5%, and 10% level is indicated by ***, **, and *, respectively. P-values in parentheses. Model 3 uses the baseline model. Financial inclusion is measured by proxies such as ATMs, bank branches, bank credit to deposit, bank deposits, life insurance, and non-life insurance. Control variables include energy use, human development, natural resources, trade openness, economic growth, government expenditure, and urbanization. The diagnostics section presents the values of the Wald test, probability values of the Wald test, z-values of AR(1) and AR(2), probability of z-values of AR(1) and AR(2), probability of the Sargan test, the number of groups and instruments, and the number of observations.

Appendix Table C5

Robustness Test II - Climate Footprint Index as a measure of green sustainability

	CLIMATE FOOTPRINT INDEX (Model 6a)	CLIMATE FOOTPRINT INDEX (Model 6b)
Lag of Climate Change Index	0.763***	0.677***
	0.000	(0.000)
Financial Inclusion	0.071***	
	(0.000)	
ATMs		0.005***
		(0.006)
Bank Branches		0.023**
		(0.025)
Bank Credit to Deposit		-0.007***
		(0.009)
Bank Deposit		-0.019***
		(0.003)
Life Insurance		-0.271***
		(0.000)
Non-Life Insurance		0.654***
		(0.000)
Controls		
Energy Use	0.044***	0.132***
	(0.000)	(0.007)
Human Development	-0.013***	0.018
	(0.000)	(0.141)
Natural Resources	-0.015***	-0.010**
	(0.000)	(0.040)
Trade Openness	0.004***	0.002
	(0.000)	(0.297)
Economic Growth	0.025***	0.021***
	(0.000)	(0.011)
Government Expenditure	-0.047***	-0.048***
	(0.000)	(0.001)
Urbanization	-0.001	-0.008
	(0.609)	(0.270)
Constant	0.580***	1.182***
	(0.000)	(0.010)
Diagnostics		
Wald Test	20558.89	30400.00
Prob. (Wald)	0.000	0.000
AR1 (p-value)	0.279	0.262
AR2 (p-value)	0.305	0.304
Hansen-J (p-value)	0.847	0.534

(*continued on next page*)

Appendix Table C5 (*continued*)

	CLIMATE FOOTPRINT INDEX (Model 6a)	CLIMATE FOOTPRINT INDEX (Model 6b)
Sargan (p-value)	0.183	0.238
DHT for instrument		
Instruments in levels		
H excluding group	0.401	0.254
IV (years, eq(diff))		
H excluding group	0.875	0.623
Number of groups	34	34
Number of instruments	34	34
Observations	289	289

Statistical significance at the 1%, 5%, and 10% level is indicated by ***, **, and *, respectively. P-values in parentheses. Model 6a uses the financial inclusion index as a regressor, while Model 6b utilizes individual financial inclusion indicators. Climate change index represents a statistical index of pollutants that primarily impact climate change: CO2 emissions, methane emissions, and nitrous oxide emissions. All the other variables in this table are the same as previously defined in Table 1.

Appendix Table C6
Effect of Financial Inclusion on Environmental Pollution - based on alternative sets of instruments

	LINEAR (Model 3)	NON-LINEAR (FII) (Model 4)
Lag of Environmental Pollution Index	0.949***	0.766***
	(0.000)	(0.000)
Financial Inclusion	0.016*	0.409***
	(0.062)	(0.000)
Financial Inclusion_squared		-0.048***
		(0.000)
Controls		
Energy Use	0.024	-0.052**
	(0.118)	(0.004)
Human Development	0.003*	-0.022***
	(0.098)	(0.000)
Natural Resources	0.001	0.014***
	(0.307)	(0.000)
Trade Openness	-0.001**	-0.012***
	(0.053)	(0.000)
Economic Growth	0.006**	0.003
	(0.002)	(0.192)
Government Expenditure	-0.024***	0.031***
	(0.000)	(0.000)
Urbanisation	0.003**	0.019***
	(0.026)	(0.000)
Constant	0.284***	-0.111
	(0.000)	(0.487)
Diagnostics		
Wald Test	10498.07	93763.17
Prob. (Wald)	0.000	0.000
AR1 (p-value)	0.229	0.221
AR2 (p-value)	0.369	0.343
Hansen-J (p-value)	0.613	0.505
Sargan (p-value)	0.310	0.220
DHT for instrument		
Instruments in levels		
H excluding group	0.256	0.369
IV (years, eq(diff))		
H excluding group	0.573	0.482
Number of groups	33	33
Number of instrumental	30	30
Observations	162	162

Statistical significance at the 1%, 5%, and 10% level is indicated by ***, **, and *, respectively. P-values in parentheses. Model 3 uses the baseline model. Model 4 uses the financial inclusion index as a test of a non-linear pattern. Environmental pollution index represents a statistical index of CO2 emissions, Particulate Matter 2.5 (PM), methane emissions, and nitrous oxide emissions. Financial inclusion represents a comprehensive index (FII) based on six variables: ATMs, bank branches, credit-to-deposit ratio, bank deposits, life insurance, and non-life insurance. Control variables include energy use, human development, natural resources, trade openness, economic growth, government expenditure, and urbanization. The diagnostics section presents the values of the Wald test, probability values of the Wald test, z-values of AR(1) and AR(2), probability of z-values of AR(1) and AR (2), probability of the Sargan test, the number of groups and instruments, and the number of observations.

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