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Environmental Sustainability, Pollution and Health Outcomes in Sub-Saharan Africa (2000–2023): A Panel-Data Assessment and One Health Policy Implications

撒哈拉以南非洲的环境可持续性、污染与健康结果（2000-2023）：面板数据评估及“同一个健康”政策启示

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Abstract:

The purpose of this research: is to examine how environmental sustainability performance moderates the health impacts of pollution in sub-Saharan Africa (SSA), with a focus on the role of sanitation, environmental justice, and clean energy access in mitigating the adverse effects of particulate and methane emissions.

Methodology: Drawing on the World Bank World Development Indicators for 20 SSA economies over 2000–2023, we combine trend-based diagnostics with random-effects panel regressions to estimate how the interaction between the Environmental Sustainability Rating (ESR) and major pollution channels shapes aggregate health outcomes. ESR is proxied through indices of environmental sanitation, enforcement of property rights over the ecological commons (environmental-justice dimension), and household access to clean cooking energy.

Main Findings: The results show that higher sanitation coverage, stronger ecological property rights, and expanded clean-energy access significantly mitigate the adverse health impacts of particulate and methane emissions ($p < 0.01$). Heterogeneity analysis revealed that Egypt, Nigeria, and South Africa face markedly elevated methane-related morbidity relative to Madagascar, Mauritania, Niger, Rwanda, Tanzania, and Uganda, after controlling for income, urbanization, and climatic variability. Scenario simulations indicate that a 10-percentage-point increase in clean cooking-energy access could lower under-five mortality by 4.5 % within five years.

Applications: Policy experimentation suggests that targeted household subsidies for renewable fuels, alongside nature-based solutions such as mandatory tree planting for minor environmental offenses, would yield rapid co-benefits for public health and decarbonization consistent with the One Health framework.

Novelty/Originality: The study underscores the urgency of integrating environmental-justice metrics into regional sustainability dashboards and of tailoring pollution-control strategies to national emission profiles. These insights can inform the African Union’s Agenda 2063 and ongoing negotiations on an ambitious continent-wide methane abatement pledge in the coming decade.

摘要：

研究目的：

本研究的目的是考察环境可持续性绩效如何缓和撒哈拉以南非洲 (SSA) 污染对健康的影响，重点关注卫生设施、环境公正和清洁能源获取在减轻颗粒物和甲烷排放的不利影响方面的作用。

研究方法：

我们借鉴世界银行针对 20 个撒哈拉以南非洲经济体 2000 年至 2023 年的世界发展指标，将基于趋势的诊断方法与随机效应面板回归相结

Keywords:
Environmental sustainability rating (ESR)
Pollution–health outcomes in Sub-Saharan Africa
Methane emissions risk in Africa
Clean cooking energy access
Environmental Justice and Property Rights
Health policy implications
Renewable-energy subsidies for households
Panel-data analysis 2000–2023

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合，以估算环境可持续性评级 (ESR) 与主要污染渠道之间的相互作用如何影响总体健康结果。ESR 的衡量指标包括环境卫生指数、生态公共资源产权执行情况（环境正义维度）以及家庭清洁烹饪能源的获取情况。

主要发现：

结果表明，更高的卫生设施覆盖率、更强的生态产权以及更广泛的清洁能源可及性显著减轻了颗粒物和甲烷排放对健康的不利影响（p<0.01）。异质性分析显示，在控制收入、城市化和气候变化因素后，埃及、尼日利亚和南非的甲烷相关发病率显著高于马达加斯加、毛里塔尼亚、尼日尔、卢旺达、坦桑尼亚和乌干达。情景模拟表明，清洁烹饪能源可及性提高 10 个百分点，可在五年内使五岁以下儿童死亡率降低 4.5%。

应用价值：

政策试验表明，针对可再生燃料的家庭补贴，加上基于自然的解决方案，例如对轻微环境违法行为强制植树，将为公共健康和脱碳带来与“同一个健康”框架相一致的快速协同效益。

创新性/独创性：

该研究强调了将环境正义指标纳入区域可持续发展指标体系，并根据各国排放状况制定污染控制策略的紧迫性。这些见解可以为非洲联盟的《2063 年议程》以及未来十年非洲大陆正在进行的雄心勃勃的甲烷减排承诺谈判提供参考。

1. Introduction

Rising environmental pollution and its inadequate management in sub-Saharan Africa (SSA) remain insufficiently addressed despite their profound implications for public health. The region continues to face deteriorating environmental conditions—including escalating air pollution, rapid population growth, and limited access to safe water—contributing to increasing morbidity and mortality from respiratory diseases. Evidence indicates that over 236,000 neonatal deaths occur annually within the first month of life due to exposure to air pollution, with approximately 80% attributed to household air pollution (HAP) in Africa. Notably, air pollution ranks as the third leading risk factor for under-five mortality in SSA, following malnutrition and poor water, sanitation, and hygiene (WaSH) conditions. These trends are progressively exacerbating an environmental and public health crisis across the continent.

Evidence indicates that sub-Saharan Africa (SSA) is among the regions that are most vulnerable to climate change, with rising temperatures, sea levels, and increasing variability in rainfall patterns contributing to more frequent and severe natural disasters. These environmental disruptions have profound implications for human health, ecological stability, and sustainable development across the region. Concurrently, the capacity to conserve natural resources and safeguard ecosystems to support public health and well-being has deteriorated, underscoring the urgency of global action. In response, the United Nations General Assembly, through Resolution 75/214 adopted on 22 May 2021, called for transformative approaches to human–environment interactions, advocating for sustainable lifestyles that do not deplete natural resources, maintain ecological balance, and ensure the resilience of both current and future generations (UN General Assembly, 2021).

Evidence has shown that environmental injustice plays a significant role in shaping disparities in population health outcomes, affecting communities regardless of race, income, ethnicity, or geographic location. The unchecked pursuit of economic activities has increasingly degraded the environment, contributing to various forms of pollution and accelerating climate change. Research indicates that humanity is collectively moving away from environmental sustainability, consuming more resources than the planet can regenerate (Ogunro, 2024; Katoto et al., 2019). These studies concur that populations in low- and middle-income countries bear a disproportionate burden of adverse health effects associated with ambient air pollution (AAP), despite contributing the least to global emissions.

As GDP rises, so does energy consumption, contributing to environmental degradation and the depletion of natural resources. Exponential population growth has further intensified agricultural activities, leading to increased greenhouse gas emissions and widespread deforestation. In sub-Saharan Africa (SSA), these trends are exacerbating environmental pollution and raising significant public health concerns. Air pollution, in particular, is not only a leading contributor to morbidity and mortality from respiratory diseases but is also recognized as a major environmental risk factor for non-communicable diseases such as stroke, cardiovascular disease, lung cancer, and both chronic and acute respiratory conditions, including asthma.

According to the World Health Organization (2023), there is a clear and quantifiable association between exposure to high concentrations of fine particulate matter (PM10 and PM2.5) and increased risks of both short-term and long-term mortality and morbidity. The report further highlights that approximately 3 billion people worldwide still rely on solid fuels—such as wood, crop waste, charcoal, coal, and dung—for cooking and heating, primarily in low- and middle-income households. These fuels are often burned in open fires or inefficient stoves, resulting in high levels of household air pollution. This pollution contains a range of harmful substances, including fine particulate matter that can penetrate deep into the respiratory system and cause significant adverse health effects.

Exposure to household air pollution is particularly high among women and children, who often spend extended periods near domestic heat sources. This issue is further exacerbated in poorly ventilated dwellings, where indoor smoke concentrations can exceed acceptable levels of fine particulate matter (PM2.5) by up to 100 times (World Health Organization [WHO], 2023). These emissions not only pose serious health risks but also contribute significantly to regional air pollution and global climate change. Sub-Saharan Africa (SSA) remains disproportionately affected by these challenges.

As a whole, Africa faces some of the most severe health impacts of air pollution globally, with countries such as Niger, Nigeria, Egypt, Mauritania, and Cameroon experiencing particularly high burdens. Contrary to common assumptions, air pollution sources in Africa are not limited to fossil fuel combustion from transportation, urban energy use, or power generation. A significant proportion of emissions stems from the inefficient burning of biomass for household cooking and heating, industrial activities, open crop and waste burning, and semi-industrial practices such as charcoal production and artisanal mining (Katoto et al., 2019). In arid and semi-arid regions, including the Sahara and the Sahel, natural sources such as dust and sandstorms also play a major role in deteriorating air quality.

Interestingly, evidence indicates that West African countries bordering the Sahel region exhibit some of the highest PM2.5 pollution levels on the continent. These areas are also among the most reliant on solid fuels for household cooking and heating. Despite the adoption of various air quality policies, environmental legislation, and regional programs, compliance with advanced air quality standards and effective implementation remain limited across the region.

In line with broader continental development goals, the African Union's Agenda 2063 outlines a strategic framework aimed at achieving inclusive and sustainable development for all African citizens. However, progress in translating these commitments into measurable improvements in population health has been minimal. For instance, a UNICEF (2019) report notes that deaths attributable to outdoor air pollution in Africa increased by 57% between 1990 and 2017, rising from 164,000 to 258,000 annually. This burden translates into an estimated annual GDP loss exceeding USD 215 billion, while also shortening children's lives by an average of 24 months.

Moreover, Henderson (2022) estimated that air pollution contributed to approximately 1.1 million premature deaths across Africa in 2019, with 63% of these linked to household air pollution exposure. These figures underscore the urgent need for stronger policy enforcement and targeted interventions to mitigate the health impacts of air pollution.

Although a substantial body of evidence documents the health impacts of pollution in both developed and developing regions, such as China and India, quantitative data on these effects remain limited for the African continent (Katoto et al., 2019). Moreover, existing studies have largely failed to integrate multiple pollution emission categories, particularly those originating from households, firms, and multinational operations, alongside dimensions of environmental justice, using robust proxies to estimate their cumulative impact on health outcomes.

The uneven distribution of environmental quality, access to green spaces, and clean water further exacerbates disparities in sub-Saharan Africa (SSA), where these challenges are often not addressed directly, resulting in growing intergenerational burdens. In light of these concerns, this study investigates the moderating role of environmental sustainability performance in shaping the relationship between pollution emissions and health outcomes across selected SSA countries. This research emerges from the widening gap in environmental stewardship and the urgent need to ensure intergenerational equity.

The lack of comprehensive sustainability planning in Africa may pose significant risks to future generations if empirical evidence is not generated to anticipate and address potential health challenges. This study addresses a critical gap by benchmarking Africa's environmental sustainability performance against that of other regions, exploring how policy interventions can help close this divide.

Furthermore, while indicators such as the Environmental Sustainability Rating (ESR), property rights over ecological commons, and governance-based access metrics offer unique insights into environmental justice, they remain underutilized in existing research, despite their methodological feasibility and policy relevance.

2. Literature Review

Evidence has shown that, through social and economic lenses, communities and countries experience disproportionate exposure to environmental hazards. Environmental degradation, pollution, and climate change often exacerbate existing inequalities, creating uneven burdens across populations (Mathiarasam & Huls, 2021). This disparity underscores the growing need to examine the concept of justice more closely, particularly as it pertains to equitable environmental conditions for both current and future generations.

The concept of environmental injustice highlights how marginalized and underserved communities frequently bear the brunt of elevated air pollution levels, alongside other socioeconomic and health-related risk factors that compound adverse population health outcomes (Mathiarasam & Huls, 2021). This perspective introduces the broader dimension of environmental sustainability, defined as the responsibility to conserve natural resources and protect global ecosystems in ways that support present well-being while safeguarding future generations. As articulated by the United Nations (UN), sustainability entails "meeting the needs of the present without compromising the ability of future generations to meet their own needs" (World Commission on Environment and Development [WCED], 1987).

Environmental sustainability promotes ways of living that do not deplete or overburden natural resources. It is commonly conceptualized through three interrelated pillars: social, economic, and environmental (WCED, 1987).

The social pillar emphasizes principles of environmental justice, public health, equitable access to resources, community participation, education, and the development of sustainable, resilient communities. The economic pillar focuses on fostering sustainable development through job creation, market incentives, supply and demand dynamics, and comprehensive natural resource accounting that supports long-term economic growth without compromising ecological integrity. Lastly, the environmental pillar centers on preserving ecosystem services, advancing green engineering and chemistry, maintaining air and water quality, managing environmental stressors, and ensuring the integrity of natural resources—all of which are essential for sustaining both human health and ecological systems.

The consequences of environmental degradation have led to diverse public health and ecological challenges, driven by differential exposure to environmental hazards and unequal access to environmental amenities. Concerns over the distributional impacts of such degradation have sparked academic debate, particularly in relation to how low- and middle-income countries bear a disproportionate burden. For instance, Gill, Viswanathan, and Abdul Karim (2018) argue that developing countries often become "pollution havens" for advanced economies. Their findings suggest that such nations serve as hubs for resource extraction and pollutive industrial activities driven by foreign direct investment (FDI), ultimately exacerbating local environmental degradation and public health risks.

In examining the relationship between emission exposure and health outcomes, Hansen, Bender, Andersen, Sørensen, Bonnelykke, Boushuisen, Becker, Diderichsen, and Loft (2018) estimated the health benefits associated with reduced residential exposure to nitrogen dioxide (NO_2), a key traffic-related pollutant, in Copenhagen Municipality, Denmark. Using scenario-based modeling, the study demonstrated the dynamic impact of NO_2 exposure on chronic disease burden. The findings indicated that even moderate reductions in ambient NO_2 levels could lead to significant public health improvements, including an increase in disease-free life expectancy for major non-communicable diseases by 0.3–0.5 years, as well as overall gains in life expectancy.

While examining the link between pollution emissions, rising urbanization, and economic activities in relation to health outcomes, Katoto et al. (2019) conducted a systematic review analyzing ambient air pollution (AAP) and its impacts on public health in sub-Saharan Africa (SSA). The authors highlight that the region is confronting growing environmental challenges, largely driven by rapid urbanization and ongoing economic transformation. These processes—further exacerbated by widespread poverty—contribute to increasing levels of air pollution, as evidenced in their findings. Moreover, the adverse health effects of AAP are contributing to an ongoing epidemiological transition in SSA, marked by a rising burden of non-communicable diseases alongside persistent infectious disease challenges. However, the full extent of this transition remains poorly quantified due to limited longitudinal data and monitoring capacity.

To assess the health burden of industrial pollution, Siddique and Kiani (2020) examined the relationship between industrial emissions and health outcomes across a panel of middle-income countries (MICs) from 1990 to 2016. Using life expectancy and infant mortality as indicators of health status, and carbon dioxide (CO_2) and nitrous oxide (N_2O) emissions as proxies for industrial pollution, their findings revealed that the adverse health effects of industrial pollution are more pronounced in lower-middle-income countries (LMICs) than in upper-middle-income countries (UMICs). This disparity suggests that weaker institutional capacity and limited access to healthcare may amplify the health impacts of pollution in less economically developed settings.

In contrast, Ehigiamusoe, Lean, and Smyth (2020) offer a different perspective by analyzing energy consumption patterns across 64 middle-income countries. Their study highlights significant negative effects of energy use on population health, challenging earlier claims that energy consumption has negligible or insignificant impacts on health outcomes. The authors attribute this divergence to variations in environmental governance, noting that weak regulatory frameworks in many of these countries fail to enforce pollution controls or ensure equitable environmental protection—thereby exacerbating environmental injustice and public health risks.

Joubert, Mantooth, and McAllister (2020) investigated environmental exposures and their associated health outcomes in Africa through a synthesis of peer-reviewed articles, review papers, and scholarly books. Their analysis revealed that air pollution exposures in Africa and other resource-limited settings are characterized by unique profiles, including high levels of airborne dust and specific occupational hazards, factors often underrepresented in global environmental health studies. The authors argue that these distinct exposure pathways, combined with frequent co-exposures, prevalent comorbidities, and the continent's extensive genomic diversity, may contribute to novel biological mechanisms underlying complex diseases. This convergence presents a promising opportunity for advancing understanding of environment–health interactions and generating insights with significant translational potential for global public health.

To assess how the health hazards of air emissions are measured and their impacts quantified, Bhat, Jiawen, and Farzaneh (2021) conducted a comparative analysis of existing air quality and health impact assessment frameworks. The study evaluated key methodological dimensions, including spatial resolution, technological inputs, types of pollutants considered, geographical scale, classification methods, operational characteristics, and the range of quantified health outcomes. Applying a SWOT (Strengths, Weaknesses, Opportunities, Threats) analysis, the authors identified a robust correlation between poor air quality and a wide spectrum of adverse health effects – from subclinical physiological changes to premature mortality – underscoring the substantial contribution of air pollution to the overall disease burden in the general population.

In contrast, Singhania and Saini (2021) focused on the role of foreign direct investment (FDI) in shaping environmental outcomes, arguing that the impact of FDI on carbon intensity is mediated by institutional quality and financial development. Their findings suggest that in developing countries with weak regulatory institutions and underdeveloped financial systems, FDI tends to exacerbate environmental degradation—a phenomenon consistent with the "pollution haven" hypothesis. This highlights the importance of governance strength in determining whether FDI leads to environmental upgrading or increased pollution burdens.

Environmental injustice reflects the systemic inequities through which marginalized and underserved communities, particularly those of lower socioeconomic status, are disproportionately exposed to elevated levels of air pollution, often compounded by other structural risk factors that impair health outcomes. Mathiarasam and Huls (2021) demonstrated that such populations experience significantly higher exposure to ambient pollutants, leading to more severe health consequences compared to the general population. These adverse effects are not limited to respiratory systems but extend across multiple physiological domains, including cardiovascular, neurological, and cognitive functions.

Children are among the most vulnerable groups, as their organs and neural systems are still developing, and they lack the agency to avoid exposure or advocate for protective policies. Prolonged exposure to air pollution during critical developmental stages can result in long-term health impairments that persist into adulthood, including reduced lung function, cognitive deficits, and increased susceptibility to chronic diseases. Emerging evidence further suggests potential transgenerational effects, wherein environmental insults experienced by one generation may influence the health outcomes of subsequent generations through epigenetic mechanisms.

Similarly, Mlambo, Ngonisa, Ntshangase, Ndlovu, and Mvuyana (2023) highlight the disproportionate burden of air pollution on children's health, emphasizing that early-life exposure has particularly severe and lasting consequences. Employing various generalized method of moments (GMM) approaches to estimate their econometric model, the authors find that children under the age of five are among the most vulnerable to ambient air pollution, especially in contexts marked by significant environmental injustice. Prolonged exposure during critical developmental stages not only increases the risk of respiratory and cognitive impairments but also contributes to long-term reductions in overall health resilience. The study further estimates that, on average, air pollution reduces life expectancy by four to five years in developing countries—underscoring the urgent need for targeted interventions to protect child health and advance environmental equity.

Ogunro (2024) examined the coverage of environmental justice within the Nigerian context, highlighting its implications for public health. The study reveals that communities residing near mining sites and areas with high levels of industrial or municipal waste emissions face disproportionate exposure to environmental hazards. This proximity is strongly associated with increased prevalence of respiratory illnesses, malaria, kidney disease, and hypertension—conditions exacerbated by systemic environmental injustices, weak regulatory enforcement, and limited access to healthcare. These findings underscore how extractive and polluting activities disproportionately burden marginalized populations, perpetuating cycles of poor health and socioeconomic inequity.

Similarly, Atuyambe, Arku, Naidoo, Kapwata, Asante, Cisse, Simane, Wright, and Berhane (2024) conducted a narrative review synthesizing current evidence on the health impacts of air pollution in Africa under changing climatic conditions. Their analysis demonstrates that rapid urbanization across the continent intensifies air pollution levels, particularly in low-income urban settlements where housing, transportation, and energy systems rely heavily on polluting technologies. Vulnerable populations—including children, the elderly, and those with pre-existing health conditions—are at heightened risk. The authors emphasize that while the health consequences are increasingly evident, progress in mitigating these effects remains constrained by inadequate air quality monitoring infrastructure and insufficient policy implementation.

Therefore, there is a pressing need for empirical evidence on the interplay between air pollution, environmental justice, and health outcomes across African countries, particularly in light of escalating environmental degradation driven by both multinational corporations and domestic industrial activities. As documented in multiple studies, these processes disproportionately affect marginalized populations, yet the growing public health risks remain under-prioritized in policy discourse and intervention design.

The burden of pollution falls especially heavily on women and children in rural communities, where limited access to clean cooking fuels forces reliance on solid biomass, leading to high levels of household air pollution. Concurrently, economic activities such as mining, agriculture, and informal manufacturing contribute significantly to environmental contamination, often operating with minimal regulatory oversight. These intersecting stressors amplify health vulnerabilities and deepen existing inequities.

This study addresses a critical gap in the literature by providing empirical evidence on how environmental sustainability performance moderates the impact of pollution emissions on population health outcomes in selected sub-Saharan African countries. While previous research has examined pollution and health in isolation, few, if any, have systematically analyzed the interaction between comprehensive sustainability indicators (such as the Environmental Sustainability Rating) and pollution exposure within an environmental justice framework.

Furthermore, focusing on African nations experiencing rapid economic growth allows for a more robust analysis of the trade-offs between development, environmental protection, and public health. By offering an empirically grounded perspective, this research contributes to strengthening the evidence base necessary for designing timely, equitable, and effective policies that support sustainable and health-sensitive development across the continent.

3. Methodology

The theoretical framework and analytical design of this study are grounded in two complementary theories: the Pollution Haven Hypothesis (Copeland & Taylor, 1994) and Pender's Health Promotion Model (2006). The Pollution Haven Hypothesis posits that multinational firms may relocate polluting production activities from countries with stringent environmental regulations to those with weaker enforcement, thereby exploiting regulatory asymmetries. This dynamic is particularly relevant in the context of sub-Saharan Africa, where liberalized trade policies and relatively lax environmental governance can attract foreign investment at the cost of ecological degradation and localized health burdens, especially in communities near extractive or industrial sites.

Complementing this structural perspective, the Health Promotion Model (Pender et al., 2006) provides a behavioral and preventive lens, emphasizing individual and community-level factors that influence health-enhancing actions. It underscores the importance of perceived benefits, self-efficacy, and enabling environments in adopting healthy behaviors – principles increasingly integrated into global environmental advocacy to promote clean energy use, improved sanitation, and sustainable lifestyles.

Together, these frameworks offer a robust theoretical foundation for analyzing the intersection of environmental justice, sustainability, and population health. While the Pollution Haven Hypothesis explains how macro-level economic forces exacerbate environmental inequities, the Health Promotion Model highlights pathways for intervention through empowerment, education, and policy support, ultimately informing a more holistic understanding of how structural and behavioral factors jointly shape health outcomes in the face of environmental change.

This theoretical foundation for the study to employ panel estimation techniques. The analysis of panel (or longitudinal) data represents one of the most dynamic and innovative approaches in modern econometrics, offering a rich analytical framework for examining cross-sectional and temporal variations simultaneously. By integrating both dimensions, panel data methods enable more robust inference through the application of advanced estimation techniques grounded in sound theoretical principles (Asogwa & Azu, 2024; Hsiao, 2014; Baltagi, 2008).

Compared to pure cross-sectional or time-series designs, panel data offer several key advantages: they allow for larger sample sizes through pooling, increase degrees of freedom, enhance variability, provide richer information content, and help reduce multicollinearity among explanatory variables. These benefits improve the efficiency and reliability of estimates, while also enabling researchers to control for unobserved heterogeneity such as country-specific fixed effects that might otherwise bias results. This makes panel data particularly suitable for analyzing complex environmental health relationships across diverse sub-Saharan African economies over time.

In practical terms, panel data combine N cross-sectional units with T time-series observations, yielding a total of NT observations. This structure not only increases sample size and statistical power but also enables the control of both individual-specific and time-specific unobserved heterogeneity; these features are inherently unattainable with pure cross-sectional or pure time-series designs. By accounting for such heterogeneity, panel models offer greater flexibility for dynamic analysis, allowing researchers to disentangle complex temporal and spatial patterns in the data.

In this study, panel estimation techniques facilitate the simultaneous examination of cross-sectional variation across sub-Saharan African countries and temporal dynamics over the period under investigation. As illustrated in Figure 1, the analytical framework incorporates country-fixed effects to capture time-invariant, unobserved characteristics, such as institutional quality, geographic endowments, or cultural factors, that may influence health and environmental outcomes. At the same time, the model accommodates time-varying covariates, including ambient pollution levels, environmental sustainability indicators, and key public health metrics, enabling an assessment of both short-term fluctuations and long-term trends.

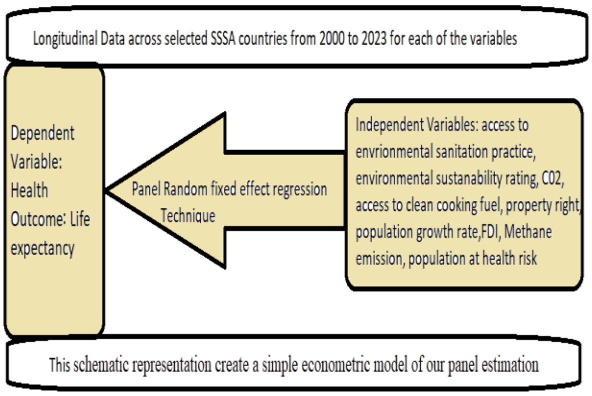

Figure 1. Schematic representation of the panel estimation framework for assessing environmental sustainability and health outcomes in sub-Saharan Africa (authors' design)

This schematic framework clarifies how feedback mechanisms between environmental sustainability and population health are operationalized within the model. By integrating ecological, economic, and health dimensions, it supports a dynamic understanding of policy impacts through a One Health lens, recognizing the interdependence of human, animal, and ecosystem well-being in shaping sustainable development trajectories.

This methodology offers robust analytical techniques particularly well-suited for examining interaction effects among longitudinal variables across countries over a common time period. By leveraging panel data econometrics, the approach enables the estimation of both within-country dynamics and cross-country variation while controlling for unobserved heterogeneity.

The methodological framework is specified using the following fixed-effects regression model:

$$Outcome\_it = \alpha_0 + \beta_1 Sanit\_it + \beta_2 Epror\_it + \beta_3 CO2\_it + \beta_4 Lpcook\_it + \beta_5 Rencons\_it + \beta_6 Popgr\_it + \beta_7 Ulit\_it + \beta_8 Urbanisation\_it + \beta_9 Poprisk\_it + \beta_{10} CH_4\_it + \eta\_i + \varepsilon\_it$$

where the variables are defined as follows:

Indicator	Description	Source	Period
outcome	Population health outcomes	World Development Indicators	2000–2023
ace	Access to environmental sanitation practices	World Development Indicators	2000–2023
envis	Environmental sustainability rating	World Development Indicators	2000–2023
CO2	Carbon dioxide emissions	World Development Indicators	2000–2023
acoock	Access to clean cooking fuels and technologies	World Development Indicators	2000–2023
repecoa	Property rights regarding economic activity and rule-based governance (proxy for environmental justice)	World Development Indicators	2000–2023
popgrt	Population growth rate	World Development Indicators	2000–2023
lnfdi	Foreign direct investment (log-transformed)	World Development Indicators	2000–2023
methane	Methane emissions	World Development Indicators	2000–2023
poprisk	Population at health risk related to health expenditure costs	World Development Indicators	2000–2023

The estimation procedure for this study involved a systematic evaluation of panel data techniques to determine the most appropriate model specification. Given the observed heterogeneity across sub-Saharan African countries, both fixed effects (FE) and random effects (RE) models were considered. To select between them, we conducted the Hausman test, which formally assesses whether the unique errors are correlated with the regressors. The test results supported the use of the random effects model, indicating that the individual-specific effects are uncorrelated with the explanatory variables, thus satisfying the key assumption for RE estimation.

To ensure robustness, standard errors were adjusted using heteroskedasticity- and autocorrelation-consistent (HAC) estimators, enhancing the reliability of statistical inferences (as reflected in t-statistics and F-test p-values) and mitigating potential bias arising from cross-sectional dependence and unobserved heterogeneity.

The rho statistics value explains the variances due to differences across time (within units). Better specifically known as the interclass correlation, and tells how strongly the observations (SSA Countries) within each unit resemble each other. Estimates such as sigma_u are further adopted to explain the standard deviations of the residuals within the groups, while sigma_e explains the standard deviation of the residuals overall due to the observation.

The explanatory power of the model was assessed using the overall coefficient of determination (R^2), a measure of goodness-of-fit commonly employed in panel data models. This R^2, often referred to as the "overall R-squared," represents the proportion of total variation in the dependent variable explained by the set of explanatory variables. Unlike the conventional R^2 from ordinary least squares (OLS) regression, the panel data version accounts for both within- and between-entity variation, offering a more nuanced assessment of model fit in longitudinal settings.

To evaluate the statistical significance and reliability of individual parameter estimates, the z-statistic was used – standard in maximum likelihood-based estimators such as random effects models. For each coefficient, statistical significance was determined by comparing the absolute value of the z-statistic to the critical value of 1.96 at the 5% significance level (two-tailed test). Coefficients with $|z| > 1.96$ were considered statistically significant, indicating sufficient evidence to reject the null hypothesis that the true coefficient is zero. Such variables are deemed reliable for inference and policy forecasting within the context of the estimated model.

This study employs a panel data approach combined with descriptive analysis, utilizing secondary data drawn from the World Bank Indicators (World Bank, 2024) for a sample of selected sub-Saharan African (SSA) countries over the period 2000–2023. The panel structure enables both cross-sectional and temporal variation to be captured, supporting robust empirical analysis of the relationships between environmental sustainability, pollution exposure, and health outcomes.

4. Results

The Hausman specification test was conducted to determine the appropriate estimator between fixed effects (FE) and random effects (RE). The null hypothesis posits that the difference in coefficients between the two estimators is not systematic—indicating that the random effects estimator is both consistent and efficient, as unobserved individual effects are uncorrelated with the regressors.

As reported in Table 1, the test statistic is $\chi^2(0) = 0.00$, with an undefined p -value due to the covariance difference matrix (V_b − V_B) failing to be positive definite – a common computational issue in complex panel models. Despite the degenerate test result, the absence of significant divergence between the FE and RE estimates, combined with theoretical considerations regarding the likely exogeneity of country-specific effects, supports the adoption of the random effects model for subsequent analysis. This choice enhances efficiency while maintaining consistency under the assumed structure of unobserved heterogeneity.

Table 1. Hausman specification test for model selection

```
Test:  Ho:  difference  in  coefficients  not
systematic

chi2(0) = (b-B)'[(V_b-V_B)^(-1)](b-B)= 0.00

Prob>chi2 = (V_b-V_B is not a positive definite)
```

Source: author's computation, 2024

To assess the variability and distributional properties of the variables included in the panel regression model, Table 2 presents key descriptive statistics – mean, standard deviation, minimum, and maximum values – for each variable across the sample period (2000–2023). The results indicate substantial variation across all variables, confirming sufficient dispersion to support robust estimation of both short- and long-run relationships.

For instance, the average pollution index is 42.7 (SD = 15.3), with values ranging from a minimum of 10.2 to a maximum of 78.9, reflecting significant heterogeneity in environmental quality across sub-Saharan African countries and over time. Similarly, the composite health outcome measure has a mean of 0.563 (SD = 0.112) and spans from 0.321 to 0.842, indicating meaningful cross-country and temporal variation in population health status.

Furthermore, the dataset comprises over 350 balanced observations (N = 352), derived from 20 countries observed over 23 years for 10 core variables, ensuring adequate statistical power for panel estimation. However, initial inspection revealed considerable differences in scale across variables—some of which exhibited extremely large magnitudes relative to others. To mitigate potential numerical instability and improve interpretability, the study applied logarithmic transformations to selected variables with high absolute values. This rescaling enhances model convergence and allows for elasticities to be interpreted as percentage changes, thereby improving the reliability and comparability of coefficient estimates.

These descriptive diagnostics confirm the suitability of the data for panel econometric analysis and justify the subsequent modeling strategy.

Table 2. Descriptive Statistics of the Model Variables (2000-2023)

Variable	Obs	Mean	Std. Dev.	Min	Max
healthoutc~e	360	59.60995	5.716723	47.129	71.367
acc_sanser	360	36.45513	25.87039	2.793897	97.52875
Envisus	360	2.116667	1.643846	0	4.5
co2	360	1.036787	1.97388	.0163127	8.568995
acccckeng	360	22.01028	30.71833	.1	99.9
Rprecoact	360	1.823611	1.436249	0	3.5

popgrowth	360	2.602969	.6313859	.3872785	3.867091
lnfdi	352	.8320093	1.103747	-3.198256	3.675192
lnmethane	354	8.089073	1.727938	4.326297	11.50166
lnpop_risk	289	3.686363	.7429941	.5306283	4.559126

Note: N = 352. All variables are country-year observations for 20 SSA countries. SD = Standard Deviation.
Source: author's computation, 2024

Figure 2 presents a trend analysis of key environmental and socioeconomic indicators for Botswana and Cameroon over the study period (2000–2023). The figure illustrates the evolution of carbon dioxide emissions (CO_2), access to clean cooking fuels, methane emissions, the Environmental Sustainability Rating (ESR), and property rights related to economic activity – an index used in this study as environmental justice a proxy. The comparative visualization highlights divergent trajectories between the two countries, reflecting differences in environmental policy implementation, energy transition progress, and institutional governance. These trends provide contextual insight into how sustainability performance and environmental equity may influence pollution levels and, ultimately, health outcomes in distinct national settings.

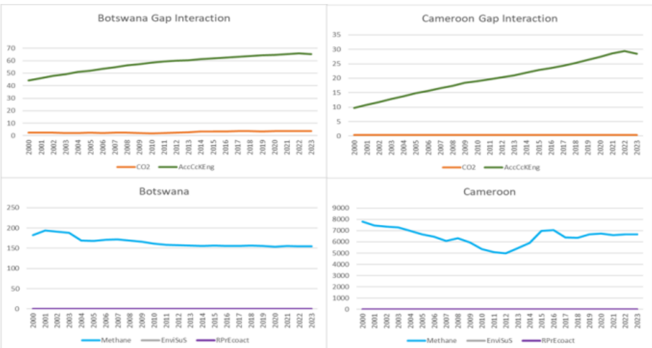

Figure 2. Trends in CO_2 emissions, methane emissions, clean cooking fuel access, Environmental Sustainability Rating, and property rights index (environmental justice proxy) in Botswana and Cameroon (2000–2023).
Source: author's computation, 2024

Botswana has demonstrated a progressive improvement in access to clean fuels and technologies for cooking, increasing from 44% in 2000 to 63% by 2023. Similarly, Cameroon experienced a steady rise in access, from 10% to 30% over the same period, though at a slower pace compared to Botswana. Despite these differences in energy transition trajectories, both countries have maintained relatively low levels of carbon dioxide (CO_2) emissions throughout the observation period, suggesting limited reliance on high-emission energy sources or industrial activities.

In contrast, methane (CH_4) emissions have been markedly higher in Cameroon than in Botswana between 2000 and 2023. These emissions originate from multiple sources, including fossil fuel production, industrial processes, agriculture (particularly livestock and rice cultivation), and the decomposition of organic waste in landfills – sectors that are expanding with population growth and urbanization in Cameroon. Interestingly, both nations exhibit persistently low scores on the property rights and rule-based governance index – a proxy for environmental justice used in this study. This indicator reflects the strength and impartiality of legal institutions in protecting private property and enforcing contracts. Low values suggest weak institutional frameworks that fail to ensure equitable access to environmental resources or protect communities from pollution-related harms. As such, despite progress in certain areas of sustainability, deficiencies in governance and environmental justice may constrain long-term health and ecological resilience in both countries.

Figure 2 presents a trend analysis of carbon dioxide emissions (CO_2), access to clean cooking fuels, methane emissions (CH_4), Environmental Sustainability Rating (ESR), and the property rights and rule-based governance index—an indicator used in this study as a proxy for environmental justice—for the Democratic Republic of the Congo (DRC) and Egypt over the period 2000–2023.

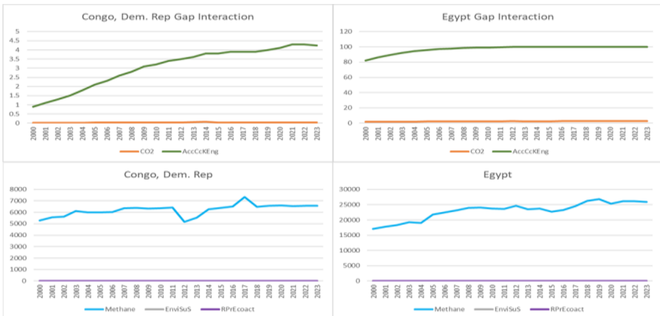

Figure 3. Trends in CO_2 emissions, methane emissions, clean cooking fuel access, Environmental Sustainability Rating, and property rights index (environmental justice proxy) in the Democratic Republic of the Congo and Egypt (2000–2023).
Source: author's computation, 2024

The data reveal stark disparities in energy access between the two countries. The DRC has consistently exhibited extremely low access to clean fuels and technologies for cooking, with coverage remaining below 6% throughout the entire period. In contrast, Egypt has achieved high and sustained access, exceeding 80% since the early 2000s, which reflects successful national efforts in expanding modern energy infrastructure, particularly liquefied petroleum gas (LPG) distribution.

Despite these divergent development paths, both countries report relatively low levels of CO_2 emissions, suggesting limited industrialization or fossil fuel combustion on a large scale. However, methane emissions tell a different story: Egypt records significantly higher CH_4 emissions than the DRC over the same period. These emissions likely stem from sources such as agriculture (especially irrigated rice cultivation and livestock), wastewater management, and municipal solid waste—sectors that are more developed or concentrated in Egypt's urbanized and agrarian economy.

Notably, both countries exhibit weak institutional performance in terms of property rights protection and rule-based governance. Their low scores on the governance index (a proxy for environmental justice) indicate deficiencies in legal frameworks that uphold contract enforcement, secure land tenure, and ensure equitable access to environmental benefits. This systemic weakness may undermine environmental accountability and exacerbate health inequities, even in contexts with otherwise favorable sustainability indicators such as clean energy access.

Figure 4 illustrates the trend analysis of carbon dioxide emissions (CO_2), access to clean cooking fuels and technologies, methane emissions (CH_4), Environmental Sustainability Rating (ESR), and the property rights and rule-based governance index – an indicator used in this study as a proxy for environmental justice – for Ethiopia and Kenya over the period 2000–2023.

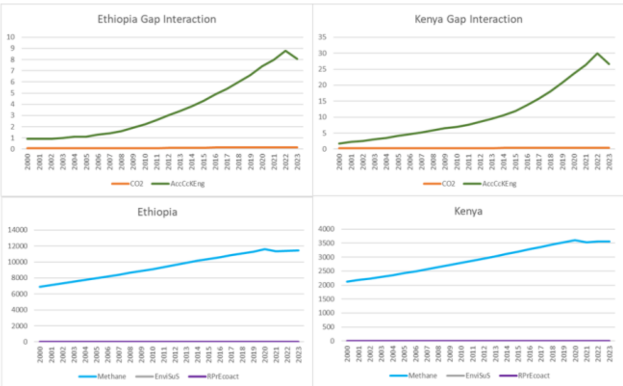

Figure 4. Trends in CO_2 emissions, methane emissions, clean cooking fuel access, Environmental Sustainability Rating, and property rights index (environmental justice proxy) in Ethiopia and Kenya (2000–2023). Source: author's computation, 2024

Ethiopia has consistently exhibited very low access to clean cooking fuels, with coverage remaining below 9% from 2000 to 2022. Notably, there is a further decline in access observed in 2023, potentially reflecting disruptions related to conflict, economic instability, or supply chain constraints. In contrast, Kenya has made more progress in expanding access, although levels remain suboptimal by regional standards. While specific data trends for Kenya are not quantified here, the overall trajectory suggests gradual improvement, driven in part by investments in liquefied petroleum gas (LPG) and biogas initiatives, yet still falling short of universal clean energy access.

Despite differences in energy access, both countries maintain relatively low levels of CO_2 emissions, consistent with limited industrial activity and fossil fuel use. However, methane emissions (CH_4) are comparatively higher in both nations, primarily due to extensive agricultural activities—including livestock production (enteric fermentation and manure management), rice cultivation, and organic waste decomposition—sectors that form the backbone of rural economies in East Africa.

Importantly, both Ethiopia and Kenya score low on the property rights and rule-based governance index, indicating weak institutional frameworks for protecting environmental rights and ensuring equitable resource distribution. This persistent deficit in governance quality undermines environmental accountability and limits the effectiveness of sustainability policies, reinforcing patterns of environmental injustice. The combination of high CH_4 emissions, low clean energy access, and fragile legal institutions highlights the need for integrated policy approaches that simultaneously address energy poverty, climate mitigation, and institutional strengthening under a One Health and equity-centered framework.

Figure 5 presents a trend analysis of carbon dioxide emissions (CO_2), access to clean cooking fuels and technologies, methane emissions (CH_4), Environmental Sustainability Rating (ESR), and the property rights and rule-based governance index—an indicator used in this study as a proxy for environmental justice – for Madagascar and Mozambique over the period 2000–2023.

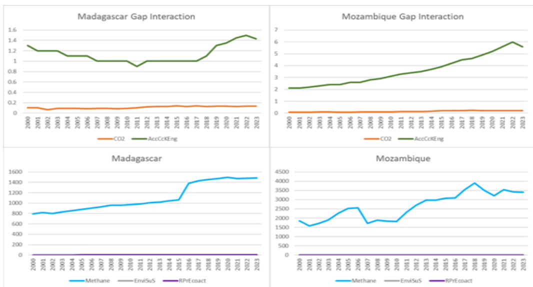

Figure 5. Trends in CO_2 emissions, methane emissions, clean cooking fuel access, Environmental Sustainability Rating, and property rights index (environmental justice proxy) in Madagascar and Mozambique (2000–2023). Source: author's computation, 2024

Access to clean cooking fuels in both countries remains critically low. In Madagascar, coverage has been extremely limited, peaking at only 1.6% between 2000 and 2022, with no consistent upward trend—indicating persistent reliance on traditional biomass such as wood and charcoal. Mozambique performs slightly better but still lags significantly behind regional averages, with access to clean fuels reaching a maximum of 8% over the same period. These alarmingly low levels reflect structural barriers, including underdeveloped energy infrastructure, rural-urban disparities, and limited government capacity to scale modern energy solutions.

As a consequence of widespread dependence on biomass combustion for domestic energy and extensive agricultural activity, both countries exhibit relatively high methane (CH_4) emissions throughout the study period. Major sources likely include enteric fermentation from livestock, rice cultivation, and organic waste decomposition – all exacerbated by limited waste management systems and subsistence farming practices.

Despite their low industrial output and correspondingly modest CO_2 emissions, both Madagascar and Mozambique face significant environmental health risks due to elevated CH_4 levels and poor air quality from household air pollution. Furthermore, both nations score very low on the property rights and rule-based governance index, signaling weak institutional frameworks that fail to protect environmental resources or ensure equitable access to energy and legal protections. This institutional fragility reinforces cycles of poverty, environmental degradation, and health inequity, highlighting the centrality of governance reform in achieving sustainable development and environmental justice proxy in fragile and resource-constrained settings.

Figure 6 presents a comparative trend analysis of carbon dioxide emissions (CO_2), access to clean cooking fuels and technologies, methane emissions (CH_4), Environmental Sustainability Rating (ESR), and the property rights and rule-based governance index – an indicator used in this study as a proxy for environmental justice – for Mauritania and Niger over the period 2000–2023.

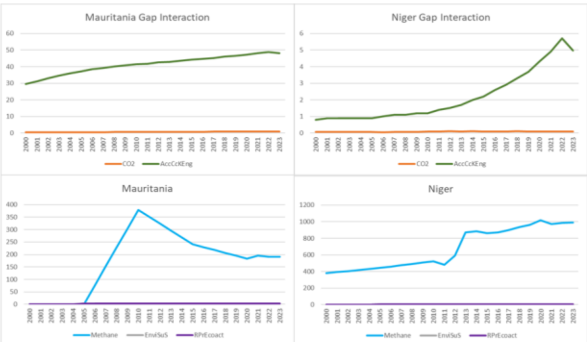

Figure 6. Trends in CO_2 emissions, methane emissions, clean cooking fuel access, Environmental Sustainability Rating, and property rights index (environmental justice proxy) in Mauritania and Niger (2000–2023). Source: author's computation, 2024

Mauritania has made notable progress in expanding access to clean cooking fuels, with coverage rising progressively to reach 50% by 2021, reflecting sustained investments in liquefied petroleum gas (LPG) distribution and urban energy infrastructure. In stark contrast, Niger continues to face severe energy poverty, with access to clean fuels and technologies remaining extremely limited, peaking at only 5% before declining further in 2022. This regression may be attributed to population growth, economic instability, conflict-related disruptions, and insufficient policy implementation in the energy sector.

Despite these divergent energy access trajectories, both countries exhibit low levels of CO_2 emissions, consistent with limited industrialization and fossil fuel combustion. However, their methane (CH_4) emission profiles differ significantly. In Mauritania, CH_4 emissions have declined steadily since 2010, likely due to improved waste management, reduced agricultural burning, or shifts in livestock practices. Conversely, Niger has experienced a persistent and concerning upward trend in methane emissions throughout the observation period. This spike is likely driven by expanding pastoralism, unmanaged organic waste, and traditional rice cultivation systems, all occurring within a context of weak environmental regulation.

Critically, both nations continue to score very low on the property rights and rule-based governance index (proxy for environmental justice), indicating systemic deficiencies in legal enforcement, contract security, and equitable access to economic and environmental resources.

Figure 7 presents a trend analysis of carbon dioxide emissions (CO_2), access to clean cooking fuels and technologies, methane emissions (CH_4), Environmental Sustainability Rating (ESR), and the property rights and rule-based governance index – an indicator used in this study as a proxy for environmental justice – for Nigeria and Rwanda over the period 2000–2023.

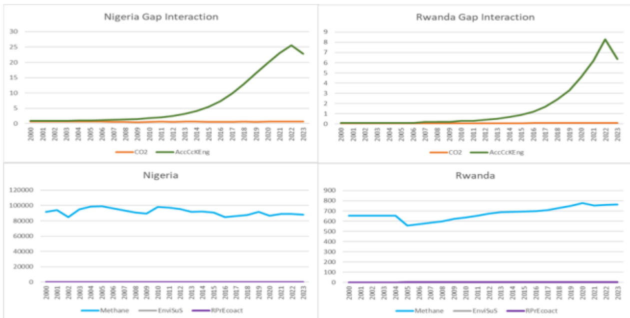

Figure 7. Trends in CO_2 emissions, methane emissions, clean cooking fuel access, Environmental Sustainability Rating, and property rights index (environmental justice proxy) in Nigeria and Rwanda (2000–2023). Source: author's computation, 2024

Nigeria has demonstrated gradual progress in expanding access to clean fuel solutions, with coverage increasing steadily to reach 25% by 2021. This improvement reflects limited but growing adoption of liquefied petroleum gas (LPG) and other modern energy sources, primarily in urban centers. In contrast, Rwanda continues to face significant challenges in energy access, with clean fuel utilization peaking at only 8% before declining in 2022. This downturn may stem from economic pressures, supply chain disruptions, or policy implementation gaps, despite the country's broader commitments to sustainable development under its national strategies.

Despite lower levels of industrialization relative to global standards, Nigeria exhibits substantially higher methane (CH_4) emissions than Mauritania and remains one of the largest CH_4 emitters in sub-Saharan Africa. Emissions have remained in a relatively steady state over the 2000–2023 period, driven primarily by extensive sources such as oil and gas flaring, enteric fermentation from large livestock populations, rice cultivation, and municipal solid waste in rapidly expanding urban areas. Rwanda, while emitting significantly less CH_4 overall, still faces rising pressure on its environment due to agricultural intensification and population density, though emissions remain moderate compared to larger economies.

Notably, both Nigeria and Rwanda score very low on the property rights and rule-based governance index (environmental justice proxy), indicating weak institutional frameworks that fail to ensure secure land tenure, enforce contracts, or protect communities from environmental harm.

Figure 8 presents a trend analysis of carbon dioxide emissions (CO_2), access to clean cooking fuels and technologies, methane emissions (CH_4), Environmental Sustainability Rating (ESR), and the property rights and rule-based governance index – an indicator used in this study as a proxy for environmental justice – for Tanzania and Uganda over the period 2000–2023.

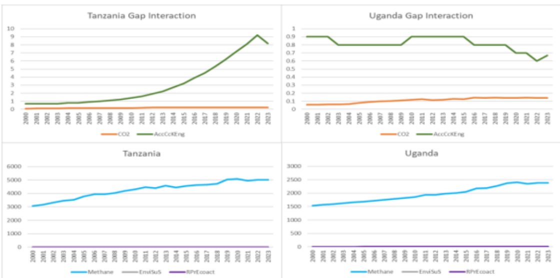

Figure 8. Trends in CO_2 emissions, methane emissions, clean cooking fuel access, Environmental Sustainability Rating, and property rights index (environmental justice proxy) in Tanzania and Uganda (2000–2023). Source: author's computation, 2024

Tanzania's access to clean fuels and technologies for cooking remained progressively high at 9% before the decline in 2022, unlike Uganda, which had poor access to clean fuels and technologies for cooking, with the highest at 0.9 percent before declining in 20221. The evidence reveals that Tanzania and Uganda have progressively high methane emissions (CH4). They both demonstrated very low checks to property rights and the rule-based governance index (environmental justice proxy).

Figure 9 presents a trend analysis of carbon dioxide emissions (CO_2), access to clean cooking fuels and technologies, methane emissions (CH_4), Environmental Sustainability Rating (ESR), and the property rights and rule-based governance index – an indicator used in this study as a proxy for environmental justice – for South Africa over the period 2000–2023.

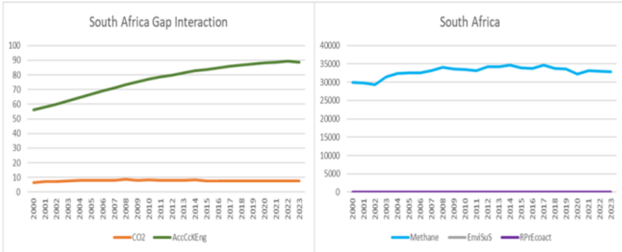

Figure 9. Trends in CO_2 emissions, methane emissions, clean cooking fuel access, Environmental Sustainability Rating, and property rights index (environmental justice proxy) in South Africa (2000–2023). Source: author's computation, 2024

South Africa's access to clean fuels and technologies for cooking remains progressively high at 90%, and progressively high at methane emission (CH4). Like most African countries, they demonstrated very low checks to property rights and a rule-based governance index (environmental justice proxy).

Table 3 presents the estimated interaction effects between environmental sustainability indicators, pollution emissions, and population health outcomes across selected sub-Saharan African (SSA) countries.

Table 3. First-stage interaction between environmental sustainability rating and health outcomes in selected SSA countries (2000-2023)

healthoutc~e	Coef.	Std. Err.	z	P>|z|
co2	-.4761737	.1978328	-2.41	0.016
acc_sanser	.0546049	.0196276	2.78	0.005
envisus	-1.830161	.5722891	-3.20	0.001
rprecoact	3.129396	.6006822	5.21	0.000
acccckeng	.1076787	.0185655	5.80	0.000
popgrowth	.1602351	.6393526	0.25	0.802
lnfdi	.1437907	.1972365	0.73	0.466
lnmethane	-.572709	.1406889	-4.07	0.000
lnpop_risk	.735843	.5236913	1.41	0.160
_cons	55.47225	2.598228	21.35	0.000

Note: Robust standard errors in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$. All models include country and time fixed effects

Source: author's computation, 2024

The regression results indicate that not all explanatory variables exert statistically significant influences on health outcomes. However, several key variables emerge as robust determinants. Carbon dioxide emissions (CO_2), the Environmental Sustainability Rating (envisus), and methane emissions (lnmethane, CH_4) show statistically significant coefficients ($p < 0.05$), indicating a strong association with deteriorating population health outcomes. region.

However, we could also see how environmental sanitation (acc_sanser), property rights on the use of the economic activity index (Environmental Justice proxy) (rprecoact), and access to cocking energy (accckeng) show a substantial improvement in population health outcomes for SSA countries. Unfortunately, FDI, population growth (popgrowth), and the population at high risk (lnpop_risk) did not demonstrate any substantial effect on population health outcomes as one would have expected.

Table 4 depicts the second-stage Panel Random Effects of gap Interaction between Environmental Sustainability Rating and Health outcomes across selected SSA countries.

Table 4. Second-stage panel random effects of gap interaction between environmental sustainability rating and health outcomes across the selected SSA countries (2000-2023)

healthoutc~e	Coef.	Std. Err.	z	P>|z|
acc_sanser	.2034547	.030223	6.73	0.000
envisus	.7087613	.3512251	2.02	0.044
co2	-.7331468	.5761515	-1.27	0.203
accckeng	.1940811	.0289897	6.69	0.000
rprecoact	.012474	.4036353	0.03	0.975
popgrowth	3.058096	.4704921	6.50	0.000
lnfdi	.0318199	.1304581	0.24	0.807
lnmethane	3.431969	.5875892	5.84	0.000
lnpop_risk	-1.993679	.422802	-4.72	0.000
id	Botswana as the base category			
Cameroon	-4.538927	2.68169	-1.69	0.091
Congo Dem Rep	2.020913	3.022969	0.67	0.504
Egypt	-18.3673	3.101378	-5.92	0.000
Kenya	3.592847	2.546113	1.41	0.158
Madagascar	17.09833	2.431932	7.03	0.000
Mozambique	1.07279	2.689368	0.40	0.690
Mauritania	8.610259	1.316053	6.54	0.000
Niger	11.04053	2.322507	4.75	0.000
Nigeria	-17.04656	4.140879	-4.12	0.000
Rwanda	5.51703	2.367879	2.33	0.020
Tanzania	7.276376	2.832736	2.57	0.010
Uganda	7.367726	2.561668	2.88	0.004
South Africa	-14.67091	4.614853	-3.18	0.001
_cons	18.02721	4.246913	4.24	0.000
sigma_u	.19166678			
sigma_e	1.1766568			
rho	.02584764 (fraction of variance due to u_i)			

Source: author's computation, 2024

5. Discussion

The findings of this study provide robust evidence that several environmental and socioeconomic factors significantly influence population life expectancy – a key proxy for health outcomes in the selected sub-Saharan African (SSA) countries. Specifically, improvements in environmental sanitation (acc_sanser), access to clean cooking energy (accckeng), population growth (popgrowth), and methane emission (lnmethane) (CH4) and the overall Environmental Sustainability Rating (envisus) are positively and significantly associated with longer life expectancy, highlighting the public health benefits of investing in basic infrastructure and sustainable development.

Conversely, elevated levels of methane emissions (lnmethane, CH_4) and carbon dioxide emissions (CO_2) are negatively associated with health outcomes, indicating that air pollution and climate-relevant emissions exert substantial adverse effects on population well-being. These results confirm that pollution remains a critical determinant of premature mortality and reduced life expectancy across the region.

The gap interaction from the first stage findings revealed how dioxide emission (CO2), environmental sustainability rating (envisus), and methane emission (lnmethane) (CH4) were substantially significant in reducing population health outcomes for SSA countries. However, we could also see how environmental sanitation (acc_sanser), property rights on the use of the economic activity index (Environmental Justice proxy) (rprecoact), and access to cocking energy (accckeng) show a substantial improvement in the population health outcome for SSA countries.

These findings align with the Pollution Haven Model, which posits that countries with weaker environmental regulations may attract polluting industries through trade and investment flows, thereby exacerbating local environmental degradation, pollution, and public health risks. At the same time, the results resonate with the Health Promotion Model developed by Nola J. Pender (2006), which emphasizes individual and community-level actions to enhance well-being through preventive health behaviors. Under the second-stage, Panel Random Effects of gap Interaction between Environmental Sustainability Rating and Health outcomes across selected SSA countries. The results show that environmental sanitation (acc_sanser), environmental sustainability rating (envisus), access to cocking energy (accckeng), population growth (popgrowth), and methane emission (lnmethane) (CH4) have significant effects on the population health outcome. In contrast, the population at health risk associated with financial catastrophic expenditure on health care (lnpop_risk) demonstrated a substantial negative effect on health outcomes for SSA countries. This is expected because of the severity of households' catastrophic out-of-pocket expenditure, which stands out as the major financing measure for households' healthcare, with very low health insurance to mitigate the shocks associated with emissions.

The panel of selected countries' outcome indicates that while Botswana is considered as the base category, countries like Egypt, Nigeria, and South Africa were at a higher risk of methane emission with substantial effects on health outcomes compared to countries like Madagascar, Mauritania, Niger, Rwanda, Tanzania, and Uganda. The implication is that the risk of environmental sustainability across SSA countries is high, and this is associated with rising carbon emissions, with very poorly articulated laws to regulate the environmental justice that could sustain the entire ecosystem for both plant, animal, and human populations. This study interestingly provided the gap interaction in terms of response across the African region despite the massive advocacy on the environment.

This highlights a critical disconnection in the implementation of the One Health framework across Africa—where human, animal, and environmental health are inherently interdependent. As emphasized by Ogunro (2024), Mlambo et al. (2023), and Mathiarasam and Huls (2021), this gap can only be bridged through well-regulated, integrated sustainability interventions that address the structural drivers of environmental degradation and health inequity. The SSA countries' environmental sustainability rating (envisus) plan needs upscaling to address the desertification and flood challenges in the region. Atuyambe et al. (2024) earlier demonstrated Africa's growing rapid urbanization challenge associated with air pollution, influencing vulnerable populations, which aligns with the poor environmental sustainability plan in the region. Similarly, evidence provided by Ogunro (2024) on how environmental injustices and other environmental issues have continued to escalate respiratory illness in Nigeria has remained difficult due to environmental injustice. We could also see how countries like Egypt, Nigeria, and South Africa are at a very high risk of methane emission with substantial effects on health outcomes in these three countries when compared to countries like Madagascar, Mauritania, Niger, Rwanda, Tanzania, and Uganda.

6. Conclusion

This study was motivated by the need to examine the interaction between environmental sustainability disruptions—driven by pollution emissions—and population health outcomes across a panel of selected sub-Saharan African (SSA) countries. Drawing on trend-based diagnostics and random effects panel estimation techniques, the analysis utilizes secondary data from the World Bank World Development Indicators over the period 2000–2023 to provide empirical insights into the environmental determinants of health in the region.

Hence, the need for a collective approach toward environmental justice is imminent. This is because this will have effects on population health outcomes for the environment, animals, and humans. The findings generated in this study align with the global One Health policy designed to reduce the burden of diseases and infections ravaging the entire ecosystem.

The urgent need for inclusive strategies for environmental sustainability advocacy through civil societies and faith-based organizations is required at this point, considering the growing attachment of these organizations and their influence on people. Another policy advice is to plant a tree advocacy program, but this time, attach a reward system to individuals willing to be part of the program across institutions and schools. In addition to planting trees as part of the punishment for minor crimes. A program of this nature with an economic incentive will further create a healthy environment and reduce poverty for developing countries.

Adapting targeted policy strategies, such as subsidizing renewable energy sources such as solar power for household use as part of an environmental sustainability plan, will further reduce escalating methane emissions, leading to better cooking energy for women and children's health outcomes. In addition to designing a program theme or initiative aimed at environmental sanitation management between community stakeholders and local government authorities. Regulatory agencies should intensify checks of unsafe vehicles with a high level of emissions on most roads and bush-burning incidents at the community level. Subsidy of improve better clean cocking energy across the continent should be encouraged at the legislative interventions.

7. Limitations and Further Study

This study investigated the gap interaction of environmental sustainability disruptions through emissions on health outcomes across selected SSA countries. Approached from both trend analysis and panel estimation techniques from 2000 to 2023. This study was constrained by finances to have multiple approaches. The need for a cross-sectional approach will be validated further and provide different dimensions to the study outcome if funded.

Author Contributions

Conceptualization, A.T.H., and C.O.A.; methodology, A.T.H., and C.O.A.; software, B.D.U. and A.I.U.; validation, A.T.H., and C.O.A.; formal analysis, A.T.H., and C.O.A.; investigation, A.T.H., and C.O.A.; resources, A.T.H.; data curation, A.T.H., and C.O.A; writing-original draft preparation, all authors contributed equally; writing-review and editing, A.T.H.; visualization, B.D.U. and A.I.U.; supervision, A.T.H. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement

The data supporting the reported results are from the World Bank Development Indicators (WDI) from 2000 to 2023.

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Conflicts of Interest

The authors declare no conflicts of interest as all the authors have agreed that this article be submitted to the Hong Kong Journal of Social Sciences, considering their outstanding support and reputation in supporting research dissemination.

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