

Oteng-Abayie, Eric Fosu; Duodu, Emmanuel; Oduro, Seth; Baidoo, Samuel Tawiah

Article

Greening the future: Unveiling the link between industrial structure upgrading and pollution emission in sub-Saharan Africa

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*Corresponding author: Emmanuel Duodu, Department of Economics, Kwame Nkrumah University of Science and Technology, Kumasi, Ghana; Department of Fundamentals of Economic Analysis, University of Alicante, Sant Vicent del Raspeig, Spain
E-mail: ed59@alu.ua.es; eduodu5@st.knust.edu.gh

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Caroline Elliott, Economics,
University of Warwick Faculty of
Social Sciences, UK

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Greening the future: Unveiling the link between industrial structure upgrading and pollution emission in sub-Saharan Africa

Eric Fosu Oteng-Abayie¹, Emmanuel Duodu^{1,2*}, Seth Oduro¹ and Samuel Tawiah Baidoo¹

Abstract: Industrial structure upgrading (ISU) in sub-Saharan Africa (SSA) has been improving in recent years, making it essential to examine how such upgrading influences pollution emissions in SSA. However, studies concerning the environment in SSA have overlooked this important role. Consequently, achieving the Sustainable Development Goals becomes futile if such critical issues are not given due attention in policy discourse. In light of this, this study examined the effect of ISU on pollution emissions in 28 SSA countries using data from 1980 to 2020 and employed two key measures of ISU as contributions to the literature. Regarding the analysis, the fixed effects, random effects, and feasible generalized least squares estimators and the Dumitrescu and Hurlin (D-H) causality test were employed. The results show that ISU improves the sustainable environment by reducing pollution emissions in SSA by 0.03–0.04%. Furthermore, economic growth (EG) increases pollution emissions by 0.63–0.72%, but after reaching a threshold level of 0.10%, EG reduces pollution emissions by 0.03–0.04%. This confirms the EKC hypothesis in the selected SSAs. The D-H causality analysis also reveals a bidirectional relationship between ISU and pollution emissions. Based on these results, we conclude that upgrading the industrial structure in SSA is crucial for a clean and sustainable environment.

Subjects: Economics and Development; Environment & the Developing World; Environmental Economics; Economics; Industry & Industrial Studies

Keywords: Sustainable Development Goals (SDGs); industrial structure upgrading; pollution emissions; EKC hypothesis; sub-Saharan Africa

PUBLIC INTEREST STATEMENT

The industrial structure upgrading (ISU) in sub-Saharan Africa (SSA) has shown promising improvements in recent years. However, the impact of such upgrading on pollution emissions in SSA has been largely overlooked in environmental studies. This research addresses this critical knowledge gap by investigating the effect of ISU on pollution emissions in 28 SSA countries over 40 years (1980–2020). The findings suggest that ISU significantly improves the sustainable environment by reducing pollution emissions in SSA. Given the critical role of SSA in global sustainable development, the study's conclusions emphasize the urgency and relevance of upgrading the industrial structure in the region. By focusing on ISU and its potential to mitigate pollution emissions, SSA can strive towards achieving the Sustainable Development Goals (SDGs) and ensure a greener environment.



1. Introduction

The issue of climate change continues to dominate policy discourse. Global collective efforts, such as the United Nations Climate Change Conference (UNFCCC), the COP21 agreement (or Paris Agreement), and the SDG Agenda 2030, seek to achieve, among other things, a reduction in temperature (below 2 degrees Celsius), a reduction in greenhouse and carbon emissions. However, these goals have yet to produce the desired results. Hence, the urgency of addressing climate change intensifies, as it poses a grave threat to worldwide sustainable development, especially impacting the poorest and most vulnerable economies. Although sub-Saharan Africa (SSA) contributes a relatively small share of global greenhouse gas and carbon emissions, it remains susceptible to climate change. As a result, any attempt to curtail carbon emissions and its associated negative consequences is essential to achieving Sustainable Development Goals (SDGs).

The 2021 Conference of the Parties (COP26) was a pivotal platform to reinforce the global commitment to climate change actions, including the COP21's adaptation, mitigation, and funding aspects. Concerns have been raised about improving environmental quality in the recent decade. For instance, COP26 emphasizes collaborative efforts to curb methane emissions, transition financial sectors toward net-zero targets by 2050, halt deforestation, expedite coal phase-outs, cease external fossil fuel funding, and encourage the shift from internal combustion engines (Adebayo et al., 2023). Globally, environmental pollution caused by human activities has been increasing due to industrialization and rapid economic growth (Baloch et al., 2019). CO₂ emissions drive climate change, constituting a major global ecological concern given its detrimental effect (Intergovernmental Panel on Climate Change [IPCC], 2021). Countries agreed for the first time at the Paris Agreement to cooperatively mitigate global warming. African countries, through various agreements, can take advantage of existing adaptation and mitigation opportunities to achieve sustainable industrial development with zero emissions (United Nations Climate Change Conference [UNFCCC], 2020).

The upgrading of industrial structures aimed at expediting economic growth in SSA has been increasing in recent years. However, the conflict between the economy's growth and environmental pollution has become increasingly vigorous. CO₂ emissions have increased significantly from newly industrialized countries in SSA compared to industrialized countries (Ahmad & Zhao, 2018). This raises the question of the potential impact of industrial structure upgrading on pollution emissions in SSA due to the increasing CO₂ emissions in the region. Research on industrial structure upgrading (ISU) and carbon emissions has gained popularity due to the impact of industrial sectors (service, manufacturing, and industry) on the environment. According to Dong et al. (2021), industrial structure upgrading refers to a nation's ability to transition its economic sectors from low-value-added labour-intensive forms to high-value-added technology-intensive forms.

Although SSA contributes less than 3% to global greenhouse gas (GHG) emissions, upgrading industrial structures in the region poses threats to its economic and environmental viability, particularly when fuel combustion technologies are employed. Ongoing economic and institutional reforms aimed at boosting growth in SSA can potentially increase GHG emissions in the future, especially if the focus is on sectoral growth at the expense of higher emissions. Rapid industrial upgrading through industrialization in SSA could result in increased activities such as burning coal, fossil fuels (natural gas, oil, and petroleum), chemical solvents, untreated gas and liquid emissions, and improper disposal of radioactive materials, all of which contribute significantly to pollution emissions in SSA. This rise in CO₂ emissions exacerbates the energy crisis in the region, where SSA is already heavily impacted by global warming. However, upgrading the industrial sector by shifting from biomass inputs to clean alternatives like renewable energy and eco-friendly technologies can significantly reduce CO₂ emissions (Alola & Adebayo, 2023). This highlights the potential of transforming industrial economic structures with ecological considerations to effectively lower emission levels. Therefore, it is essential to conduct research that supports policymakers in designing and implementing strategies to reduce CO₂ emissions for sustainable growth and development.

Given the ongoing ISU in SSA aimed at enhancing the continent's socioeconomic fortunes, it is imperative to assess its potential impact on environmental quality. This assessment is vital to ensure the sustainability of economic growth while concurrently reducing CO₂ emissions. Previous studies (Wu et al., 2021; Yang et al., 2022; Zhang et al., 2014; Zhou et al., 2013) on ISU and CO₂ emissions focused mainly on Asian countries, particularly China, neglecting countries in SSA. While most of these studies examined the relationship in developed countries, they overlooked the impact of ISU in developing nations (Dong et al., 2021; Dou et al., 2021; Zhou et al., 2013). Possibly because ISU in developing countries is not substantial enough to influence carbon emissions. However, SSA has seen an increase in manufacturing activities, with manufacturing value-added rising from 10% in 2015 to 12% in 2020. During the same period, CO₂ emissions increased from 777,968.89 kilotons to 823,424.72 kilotons, representing a 6% increase in CO₂ emissions (WDI, 2021). Therefore, it is crucial to assess whether the growth of industrial structure upgrading in SSA affects the rising trend of CO₂ emissions due to the shift from low-productivity to high-productivity activities (UNCTAD, 2013).

The present study makes contributions to the body of knowledge regarding the relationship between ISU and CO₂ emission. Limited research has investigated the connection between industrial structures and carbon emissions in SSA. But, more importantly, such studies have failed to answer a couple of important questions such as whether SSA countries differ in terms of the impact of industrial structure on CO₂ emissions. Moreover, existing studies also completely ignored the concept of ISU altogether (see for instance, Dong et al., 2021; Dou et al., 2021). Therefore, we expand the existing literature such as that of Dong et al. (2021) and others. First, we incorporate the ratio of service value-added to the industry value-added and the ratio of the service value-added to manufacturing value-added as an indicator of industrial structural upgrading. Most previous studies have used either industrial or manufacturing value-added to GDP as a proxy for industrial structure (Abokyi et al., 2019; Dong et al., 2021; Dou et al., 2021; Zhang et al., 2014). The ratio of the service value-added to industry value-added and the ratio of the service value-added to manufacturing value-added as a proxy is broader than using a single indicator for measuring ISU. This is because most countries in SSA have a larger service sector than the manufacturing sector; therefore, using only industrial or manufacturing value-added as the sole indicator will leave the service sector (such as the transportation services sector) that potentially drives carbon emissions and growth in the SSA economies unconsidered. Hence, these two key measures of ISU offer a comprehensive understanding of how the entire economic structure influences pollution emissions, in contrast to the single indicator used in previous studies. Second, this study uses a panel of 28 SSA countries relative to single-country studies such as Abokyi et al. (2019) which focused on Ghana and Adom et al. (2012) which focused on industrial structures and CO₂ emissions for Ghana, Senegal, and Morocco. The use of panel data is significant because the findings and conclusions can be more broadly generalized. This is because findings from single-country research are only applicable to the countries in question and generalizing the results may not provide the desired policy effects due to differences in geographical and economic factors.

Considering the potential implications of ISU on the environment as espoused, this study focuses on exploring the effects of ISU on CO₂ emissions in SSA using the STIRPAT model. Our contribution lies in broadening the understanding of ISU within the SSA context by incorporating two key ISU measures as mentioned. These measures encompass all economic sectors, notably the services sector—an aspect often overlooked in prior ISU assessments, despite its significant impact on pollution emissions in the region. The study finds that industrial structure upgrading (both of the two measures) has a significant negative effect on pollution emissions. Thus, indicating that upgrading industrial structures via the adoption of green technologies in SSA induces pollution reduction.

In the rest of the paper, we review studies that focused on ISU and carbon emissions. We follow the review with a presentation of the methods and data used for the analysis. After that, the

empirical results are presented and discussed. Here we also presented some robustness analysis. The conclusion and policy suggestions are presented in the last part.

2. Literature review

Continuous climate change, including a significant increase in carbon emissions, has been linked to various factors in the literature. These factors encompass economic growth which has been investigated through the EKC theory, FDI through the pollution haven and halo theories, energy consumption, population, trade openness, and more. For instance, Abid (2016) utilized system GMM and fixed effect (FE) estimation methods on a panel dataset of 25 SSA countries and demonstrated that financial development and trade openness contribute to CO₂ emissions. Wang et al. (2023a) in OECD and G20 countries further supported the claim that trade openness does not reduce CO₂ emissions, but trade diversification reduces CO₂ emissions. In contrast, Wang et al. (2023b) found that natural resources rent through trade promotes environmental quality in developing countries. Acheampong et al. (2019), Ajanaku and Collins (2021) and Wang et al. (2023c) utilizing the EKC theory, established that economic growth in the early stages accelerates carbon emissions but later reduces pollution due to appropriate environmental measures. Duodu et al. (2021) further revealed in their study in SSA that economic growth and FDI promote pollution, but effective environmental policies can mitigate the effect of FDI on carbon emissions.

Moreover, Abokyi et al. (2021) and Duodu et al. (2022) discovered that energy consumption in the manufacturing sector increases CO₂ emissions in Ghana and SSA, respectively, primarily due to the predominant use of non-renewable energy sources. While some scholars have identified potential determinants of pollution emissions, others, particularly in China (e.g., Yang et al., 2022), have demonstrated that industrial structure upgrading can significantly impact carbon emissions. Therefore, analyzing the effect of industrial structure upgrades on carbon emissions is valuable, especially considering recent developments in developing countries like SSA.

Zhou et al. (2013) discussed the process of upgrading the industrial structure, particularly the transition from primary industries to secondary and tertiary industries. They emphasized the significance of the tertiary sector in the national economy, as it influences the adoption of green technology and the reduction of greenhouse gas emissions. The relationship between industrial structure upgrading (ISU) and CO₂ emissions has been investigated in two ways: examining the value-added contribution of industries to GDP and considering the ratio of services sector value-added to industrial or manufacturing sector value-added. Zhou et al. (2013) and Zhang et al. (2014) used these measures and found that ISU leads to a reduction in CO₂ emissions. Wang and Xiang (2014) used a dynamic input-output model and concluded that industrial structure adjustment contributes about 60% to achieving carbon emission reduction targets in China. Similarly, Mi et al. (2015) analyzed the effect of industrial structure on carbon emissions and found that it has the potential to reduce pollution through energy conservation.

Furthermore, Yuan et al. (2016) found that during early development, secondary industry with high energy intensity leads to higher pollution emissions. However, as development progresses, the service industry becomes the primary contributor to CO₂ emissions. Wang et al. (2016) and Tian et al. (2019) also support this finding that ISU affects pollution emissions positively. Also, Zhang et al. (2020) used partial least squares to examine China's greenhouse gas emissions and discovered that secondary industry increases emissions, while primary and tertiary industries reduce them. This suggests that secondary industries in China are the major contributors to greenhouse gas emissions. Dong et al. (2021), Dou et al. (2021), and Wu et al. (2021) in their studies further confirm that industrial structure upgrades mitigate the negative impact of energy-dependent industries on emissions. Moreover, Zhao et al. (2022) used the STIRPAT model to show that ISU reduces CO₂ emissions by lowering energy intensity. Similarly, Yang et al. (2022) also found that ISU decreases carbon emissions by increasing green total factor productivity in China from 2000 to 2017.

In Africa, particularly SSA, there is limited research on ISU and CO2 emissions. Notable studies include Adom et al. (2012) for Ghana, Senegal, and Morocco; Abokyi et al. (2019) for Ghana; and Kwakwa and Adusah-Poku (2020) for South Africa. Adom et al. (2012) focused on the causality between CO2 emissions and industrial structure, revealing bidirectional causality for Ghana and unidirectional causality from industrial structure to carbon emissions for Senegal and Morocco. Abokyi et al. (2019) identified unidirectional causality from industry growth to CO2 emissions. Both Adom et al. (2012) and Abokyi et al. (2019) employed industry value-added to GDP as a proxy for industrial structure. Similarly, Kwakwa and Adusah-Poku (2020) proposed that manufacturing output in South Africa contributes to carbon emissions.

2.1. Literature gap

From the reviewed studies above and in Table A1, the lack of research on ISU and CO2 emissions in Africa, specifically SSA, is apparent. Many of these studies primarily focused on China and Asia, likely due to the significant advancements in their industrial sectors. However, the recent industrial upgrading in the SSA region necessitates an analysis of the impact of ISU on CO2 emissions in SSA. Furthermore, the distinctive economic and geographical conditions across continents and countries emphasize the importance of conducting studies in Africa, especially SSA, to guide CO2 emission policies. Additionally, previous studies both in China and single studies on Ghana, Senegal, Morocco, and South Africa have primarily focused on the GDP of the manufacturing sector when examining ISU, neglecting the significant contribution of the services sector to economies. However, given the fact that the services sector drives most economies in Africa, it is important to capture the sector when considering a measure of ISU.

Consequently, our study concentrates on SSA countries and incorporates two essential measures of ISU related to the service sector: the ratio of service value-added to industry value-added and the ratio of service value-added to manufacturing value-added. These measures are more comprehensive to capture all the economic sectors than the single indicator of ISU. By addressing these gaps in the existing literature, our findings provide insights into factors that support the global goal of reducing CO2 emissions and achieving sustainable development (SDG 7). While some studies offer a different perspective, evidence from China and other countries suggests that ISUs can effectively reduce pollution emissions. Based on this, we propose the hypothesis that industrial structure upgrading in SSA leads to a decrease in pollution emissions. For a summary of the reviewed studies on ISU and CO2 emissions, see Table A1 in the appendix.

3. Analytical methods and data

3.1. Model specification

We employ the STIRPAT (Stochastic Impact Regression on Population, Affluence, and Technology) model to link ISU and pollution emissions in SSA. The Dietz and Rosa (1994) model suggests that pollution emissions are affected by population, affluence, and technology. This model is utilized as a theoretical foundation because it offers insights into potential relationships between socio-economic factors and environmental impacts. Building on Dong et al. (2021), we modified the STIRPAT model to include ISU and additional variables impacting pollution emissions. The augmented STIRPAT model is expressed as follows.

$$PE = f(ISU, T, REC, P, A) \quad (1)$$

where PE , ISU , T , REC , P , and A represent pollution emissions, industrial structure upgrading, technology, renewable energy consumption, population, and affluence. Building on the research by Duodu et al. (2021), we substitute population and affluence with urbanization and economic growth, respectively. Similarly, we followed Duodu et al. (2021) and adopted the perspective that technology is shaped by FDI, thus $T = f(FDI)$. Based on this, we revise equation (1) as follows:

$$PE = f(ISU, FDI, REC, URB, EG) \quad (2)$$

where *PE*, *ISU*, and *REC* are defined in equation (1), and *FDI*, *URB*, and *EG* represent foreign direct investment, urbanization, and economic growth, respectively. Equation (2) incorporates the square term of economic growth (EG^2), which represents GDP per capita. This modification aims to investigate the presence of the Environmental Kuznets Curve (EKC) hypothesis in the context of SSA. Dong et al. (2021) and Ajanaku and Collins (2021) utilized a similar approach to validate the EKC. It is particularly relevant as economic growth (measured by GDP per capita) is rapidly increasing in most SSA countries. The estimable model is presented in equation (3).

$$\ln PE_{i,t} = \beta_0 + \gamma_1 \ln ISU_{i,t} + \gamma_2 FDI_{i,t} + \gamma_3 \ln REC_{i,t} + \gamma_4 \ln URB_{i,t} + \gamma_5 \ln EG_{i,t} + \gamma_6 \ln EG_{i,t}^2 + \delta_i + \varepsilon_{i,t} \quad (3)$$

The constant term and the coefficients to be estimated are denoted by β_0 and γ 's, respectively. δ_i represents country-specific characteristics, and ε is the error term. All variables are previously defined in Equations (1–2). Equation (3) is estimated using two measures of *ISU*: the ratio of services value-added to industry value-added and the ratio of services value-added to manufacturing value-added. This ensures accuracy and robustness when analyzing the effect of *ISU* on pollution emissions in SSA.

Furthermore, the dynamic form of Equation (3) was also estimated using the two measures of *ISU*. This is because previous levels of pollution emissions have the potency to explain the present levels of pollution emissions. Hence, this study estimates both the static and the dynamic form of equation (3), using the static form as a baseline model. The dynamic form of equation (3) is given by equation (4).

$$\ln PE_{i,t} = \beta_0 + \tau \ln PE_{i,t-1} + \gamma_1 \ln ISU_{i,t} + \gamma_2 FDI_{i,t} + \gamma_3 \ln REC_{i,t} + \gamma_4 \ln URB_{i,t} + \gamma_5 \ln EG_{i,t} + \gamma_6 \ln EG_{i,t}^2 + \delta_i + \varepsilon_{i,t} \quad (4)$$

3.2. Variable and data description

To ascertain the empirical effect of *ISU* on pollution emissions in SSA, the study relies on balanced panel data on 28 countries (see Table A2 in the appendix) in the region with adequate data for the period 1980 to 2020. The limited availability of data, particularly on *ISU*, restricts the study to only 28 countries. Data for the variables (pollution emissions, *ISU*, renewable energy consumption, foreign direct investment, urbanization, and economic growth) used in this study was sourced from the World Development Indicators (WDI, 2021). In this study, we measured pollution emissions by CO2 emissions (metric tons per capita), and *ISU* by the ratio of the services value-added to the industry value-added and the ratio of the services value-added to the manufacturing value-added. Foreign Direct Investment (*FDI*) and renewable energy consumption were measured using the net inflows of *FDI* and total renewable energy consumption, respectively. Urbanization and economic growth were measured using urban population and GDP per capita, respectively. The above measurements or proxies for the selected variables, based on the STIRPAT model, are being influenced by previous studies conducted by Yuan et al. (2016), Dong et al. (2021), Duodu et al. (2021), Wang et al. (2022), and Duodu and Mpuure (2023), all of whom employed a similar measurement in their studies. However, our measure for *ISU* diverges from those used in prior research on *ISU*, constituting a key contribution. For detailed information on the variables, see Table A3 in the appendix.

3.3. Estimation methods

For this research, we used three estimators: random-effects (RE), fixed-effects (FE), and feasible generalized least squares (FGLS) to examine the effect of *ISU* on pollution emissions. The Hausman test (Hausman, 1978) was utilized in determining the efficient estimator between FE and RE. The null hypothesis of the Hausman test indicates that RE is efficient and hence the preferred estimator. On the other hand, a rejection of the null hypothesis implies that the FE is the preferred estimator. The FE and RE estimators are chosen over the traditional ordinary

least squares (OLS) method because of its advantages. For example, the FE and RE can account for individual-specific characteristics. Despite their ability to generate efficient estimates, FE and RE estimates are inconsistent and biased in the presence of cross-sectional dependence (Pesaran, 2007; Reed & Ye, 2011). As a result, to guarantee robust estimates, we used the panel FGLS, which concurrently controls or compensates for autocorrelation, heteroskedasticity, and cross-sectional dependency in panel data (Reed & Ye, 2011). Although the panel-corrected standard error estimator may account for cross-sectional dependence, it is inefficient when the time (T) dimension is larger than the cross-sectional (N) units. Hence, the use of FGLS is appropriate in this case ($T \geq N$, $41 > 28$).

Next, we used the D-H (Dumitrescu & Hurlin, 2012) panel causality test to analyze the causal link between ISU and pollution emissions. Khan et al. (2020) stated that the D-H test is suitable for both $T > N$ and $T < N$ scenarios, and it controls for cross-sectional dependence and heterogeneity in slope coefficients. Therefore, the D-H causality is deemed appropriate for assessing the causal association between ISU and pollution emissions.

Furthermore, we conducted preliminary tests on our sample data, including cross-sectional dependence and panel unit root tests. To assess cross-sectional dependence with our study's large T and small N, we used the Breusch and Pagan (1980) LM test. For testing stationarity, we employed the Im et al. (2003) and Pesaran (2007) cross-sectionally augmented IPS (CIPS) tests. It must be emphasized that these checks are conducted to prevent spurious estimates. Rejecting the null hypothesis in the Breusch and Pagan LM test suggests cross-sectional dependency while rejecting the null hypothesis in the IPS and CIPS tests indicates stationary variables (no unit root).

To ascertain the threshold level or value of economic growth, at which the EKC hypothesis exists, we follow Nsanyan Sandow et al. (2021) and estimated the threshold value using equation (5).

$$EG^* = -\frac{2\gamma_6}{\gamma_5} \quad (5)$$

where EG^* represents the threshold value, while γ_5 and γ_6 are the parameters for economic growth (measured by GDP per capita) and its square term in Equation (4), respectively.

4. Analysis of empirical results

4.1. Descriptive statistics

In Table 1 are the descriptive statistics of the variables. Pollution emissions (CO₂) in SSA are revealed to have an average level of −0.86 metric tons with a maximum value of 2.29 metric tons. Although the average emissions level in the SSA region may seem relatively lower, it still has health implications for society. The ISU is observed to have a mean value of 0.65 (ratio of the service value-added to the industry value-added) and 1.54 (ratio of the service value-added to the manufacturing value-added). These mean values signify an improvement in the industrial structure in SSA. Therefore, the examination of how such improvement affects pollution emissions becomes relevant. Table 1 also shows that the average FDI inflows, renewable energy consumption, and urbanization level in SSA are about 2.69, 3.99 and 3.46, respectively. Concerning economic growth, we notice that the average growth rate in SSA is about 7.20. The square term of economic growth is indicated to have a mean of 52.81. Apart from FDI, it is observed that the average dispersion around the respective mean values is relatively small.

4.2. Cross-sectional dependence test results

Table 2 shows the cross-sectional dependence results. All models show cross-country correlation (dependency).

Table 1. Summary of descriptive statistics

Variable	Observations	Mean	Standard dev.	Minimum	Maximum
lnCO2	1148	−0.8638	1.4030	−4.4389	2.2948
lnISU ^a	1148	0.6510	0.5483	−1.1634	2.0061
lnISU ^b	1148	1.5354	0.5814	−0.3114	5.0157
FDI	1148	2.6916	4.8584	−32.9071	57.8376
lnREC	1148	3.9880	0.8189	−0.3439	4.6967
lnURB	1148	3.4577	0.5748	1.4676	4.5008
lnEG	1148	7.2035	0.9605	5.3741	9.6749
lnEG ²	1148	52.8126	14.3272	28.881	93.6045

Notes: CO2, ISU^a, ISU^b, FDI, REC, URB, EG, and EG² are carbon dioxide emissions, industrial structure upgrading (proxied by the ratio of the service value-added to the industry value-added), industrial structure upgrading (proxied by the ratio of the service value-added to the manufacturing value-added), foreign direct investment, renewable energy consumption, urbanization, economic growth, and the square of economic growth, correspondingly. FDI is not in the log due to some negative values.

Table 2. Cross-sectional dependence test

		Breusch—Pagan LM test	P-value
Model 1	Static	2358.048	0.0000
	Dynamic	963.484	0.0000
Model 2	Static	2266.801	0.0000
	Dynamic	963.197	0.0000

Notes: Model 1 is where industrial structure upgrading (ISU^a) is measured by the ratio of the service value-added to the industry value-added. In Model 2, industrial structure upgrading (ISU^b) is measured by the ratio of the service value-added to the manufacturing value-added.

The probability values in all models indicate rejection of the null hypothesis of no cross-sectional correlation. The implication is that economic policy in one country may have an economic effect on other economies. So, we employed a second-generation unit root test (Pesaran, CIPS) and FGLS to account for cross-sectional dependence.

4.3. Panel stationarity test results

Table 3 shows that none of the variables have a unit root. The IPS (Im, Pesaran and Shin) test shows that all variables except renewable energy consumption and economic growth are stationary at the levels. However, the presence of cross-sectional dependence violates the assumption of cross-sectional independence of the first-generation unit root test (IPS), making the IPS stationarity results inaccurate in this context. To ensure the accuracy of the stationarity results, we employed a second-generation unit root test (CIPS), which overcomes the cross-sectional dependence (Pesaran, 2007). From the CIPS test, we notice that only pollution emissions (CO2), industrial structure upgrading (ISU^b), and FDI are stationary at the levels. Nevertheless, after differencing to order one, all the variables are stationary at the first difference. Hence, the variables employed for the study are stationary at the first difference. The validation of stationarity prevents spurious estimates in this study. Therefore, we proceed with the estimation of the FE, RE, and FGLS.

4.4. ISU and pollution emissions (FE and RE analysis)

In Table 4, we provide empirical evidence on how ISU in SSA influences pollution emissions using FE and RE methods of estimation. Models 1 and 2 are the results where ISU is measured by the ratio of the service value-added to the industry value-added and the ratio of the service value-added to the manufacturing value-added, respectively. Before proceeding with the FE and RE

Table 3. Panel unit root test results

Variable	IPS		CIPS	
	Levels	1 st difference	Levels	1 st difference
lnCO2	-1.929***	-4.764***	-2.197**	-5.783***
lnISU ^a	-1.805**	-4.800***	-1.897	-5.545***
lnISU ^b	-1.900**	-4.650***	-2.342***	-5.910***
FDI	-2.606***	-6.068***	-3.766***	-5.908***
lnREC	-1.228	-3.722***	-2.035	-5.128***
lnURB	-2.157***	-2.030***	-1.006	-2.150*
lnEG	-1.570	-3.856***	-1.631	-4.860***
lnEG ²	-1.535	-3.796***	-1.666	-4.875***

Notes: IPS and CIPS indicate the Im-Pesaran-Shin test and, cross-sectionally augmented IPS test, respectively. CIPS critical values at 10%, 5%, and 1% are -2.08, -2.16, and -2.3, respectively. *, **, and *** represent significance level at 10%, 5%, and 1%, respectively.

results, the Hausman test in both models (Table 4) suggests that the FE estimator is efficient and appropriate since the probability values in all estimations reject the null hypothesis of RE being appropriate and efficient. Therefore, the analysis in Table 4 is spotlighted on the FE results.

It is revealed that previous levels of pollution emissions significantly contribute to current levels of pollution emissions in both models (Dynamic results [Benchmark]). Specifically, past levels of emissions induce pollution emissions in SSA to increase by approximately 0.75% and 0.74%, respectively in Models 1 and 2. The indication is that there is no convergence in pollution emissions in SSA and hence, calls for urgent attention. This outcome is in line with Duodu and Mpuure (2023) who find no convergence in CO2 emissions in SSA. Focusing on ISU, which is the variable of concern in this study, we observe that ISU in both models improves environmental quality by reducing pollution emissions. The estimates indicate that a 1% improvement (increase) in ISU in SSA reduces the pollution emissions by about 0.03% and 0.04%, respectively, in Models 1 and 2. This outcome suggests that upgrading the industrial structure requires adopting advanced or improved technologies that ensure green production and green production services, which reduces pollution emissions. This finding could be attributed to the fact that through substantial upgrading, the economic structures like the industries and the rest are less engaged in coal-burning activities, which harms the environment and engage in activities that use more renewable energy technology. This result is also plausible in the sense that although industries are upgrading to ensure sustained economic growth, however, effective environmental regulations in SSA ensure that policies towards industrial structure upgrading consider the quality of the environment and hence, leading to this outcome. Thus, our result implies that ISU coupled with other environmental policies is one of the sure ways to sustainable environmental quality. Our findings align with previous studies (see, Dong et al., 2021; Dou et al., 2021; Wu et al., 2021; Zhou et al., 2013), indicating that upgrading industrial structure reduces pollution emissions. However, these studies overlooked the services sector in measuring industrial structure upgrading.

Furthermore, our findings validate the existence of the EKC hypothesis in SSA. The results suggest that economic growth has a double effect on pollution emissions. It is revealed that economic growth promotes pollution emissions of about 0.63% and 0.72% in Models 1 and 2, respectively. However, economic growth turns out to reduce pollution emissions by about 0.03% and 0.04%, after economic growth has reached a threshold level of 0.097% and 0.099% for Models 1 and 2, respectively.

The result implies that economic growth in SSA has an inverted U-shaped relationship with pollution emissions. Thus, the analysis supports Grossman and Krueger's (1995) EKC hypothesis,

Table 4. Effect of industrial structure upgrading on CO2 (FE and RE)

Model 1

	Static (Baseline)		Dynamic (Benchmark)	
Variable	FE	RE	FE	RE
$\ln CO2_{t-1}$			0.7467*** (0.0189)	0.9228*** (0.0099)
$\ln ISU^a$	-0.0963*** (0.0240)	-0.1052*** (0.0241)	-0.0276* (0.0155)	-0.0227* (0.0125)
FDI	-0.0024 (0.0020)	-0.0026 (0.0020)	-0.0001 (0.0012)	-0.0005 (0.0012)
$\ln REC$	-0.6235*** (0.0469)	-0.5994*** (0.0455)	-0.1581*** (0.0335)	-0.0471*** (0.0121)
$\ln URB$	0.0581 (0.0447)	0.0657 (0.0444)	0.0382 (0.0297)	0.0104 (0.0149)
$\ln EG$	1.7399*** (0.3333)	1.7275*** (0.3287)	0.6258*** (0.2176)	0.3754*** (0.1070)
$\ln EG^2$	-0.0718*** (0.0233)	-0.0683*** (0.0229)	-0.0303** (0.0151)	-0.0204*** (0.0070)
Constant	-7.2478*** (1.0972)	-7.4595*** (1.0900)	-2.6045*** (0.7156)	-1.5152*** (0.3819)
EG*	0.0825	0.0791	0.0968	0.1087
observations	1148	1148	1120	1120
R-square	0.7906	0.7989	0.9778	0.9825
Hausman (p-value)	29.96 (0.0000)		125.19 (0.0000)	

Model 2

Variable	FE	RE	FE	RE
$\ln CO2_{t-1}$			0.7413*** (0.0190)	0.9237*** (0.0099)
$\ln ISU^b$	-0.1204*** (0.0199)	-0.1243*** (0.0199)	-0.0363*** (0.0132)	-0.0163 (0.0108)
FDI	-0.0029 (0.0019)	-0.0032 (0.0019)	-0.0002 (0.0012)	-0.0002 (0.0012)
$\ln REC$	-0.6431*** (0.0464)	-0.6223*** (0.0452)	-0.1670*** (0.0335)	-0.0396*** (0.0108)
$\ln URB$	0.0428 (0.0442)	0.0495 (0.0439)	0.0341 (0.0296)	0.0161 (0.0159)
$\ln EG$	2.0360*** (0.3178)	2.0333*** (0.3143)	0.7180*** (0.2100)	0.3566*** (0.1081)
$\ln EG^2$	-0.0902*** (0.0222)	-0.0879*** (0.0219)	-0.0356** (0.0146)	-0.0189*** (0.0071)
Constant	-8.1579*** (1.0414)	-8.3596*** (1.0374)	-2.9005*** (0.6886)	-1.4968*** (0.3848)
EG*	0.0886	0.0865	0.0992	0.1060
observations	1148	1148	1120	1120
R-square	0.7877	0.7945	0.9771	0.9825
Hausman (p-value)	18.96 (0.0042)		133.12 (0.0000)	

Notes: The dependent variable is CO2 emissions. Model 1 is where industrial structure upgrading (ISU^a) is measured by the ratio of the service value-added to the industry value-added. In Model 2, industrial structure upgrading (ISU^b) is measured by the ratio of the service value-added to the manufacturing value-added. *, **, and *** represent 10%, 5%, and 1% significance level, respectively. Standard errors are in the parentheses. EG* denote the economic growth threshold value.

which states that after a certain threshold of economic development, pollution starts to decline (which in this study is 0.097% and 0.099%). The result suggests that at higher levels of economic growth, society becomes aware of the negative repercussions of environmental pollution and, therefore, develops policies and takes actions that combat pollution emissions. Our finding concerning economic growth also accords with some past studies which found evidence of the EKC hypothesis (see Acheampong et al., 2019; Ajanaku & Collins, 2021; Dong et al., 2021; Wang et al., 2023c).

Regarding renewable energy consumption, the results reveal that the use of renewable energy reduces pollution emissions. That is if renewable energy consumption in SSA increases by 1%, pollution emissions in SSA will be reduced by about 0.16% and 0.17%, respectively, in Models 1 and 2, *ceteris paribus*. This is conceivable since renewable energy sources like solar, hydro, and geothermal do not require fuel combustion, resulting in less gaseous emissions and a cleaner environment. This result is congruent with the findings of Acheampong et al. (2019), Wang et al. (2023c) and Liu et al. (2023), who found that renewable or clean energy reduces pollution in SSA. Furthermore, we find that FDI and urbanization have no effect on pollution emissions in all estimates. These outcomes contradict Duodu et al. (2021), Wu et al. (2021), and Oteng-Abayie et al. (2022a, 2022b), who find FDI and urbanization to have a significant impact on CO₂ emissions. Finally, it is observed that the results from the static estimations in both models are consistent with the dynamic estimations. This is an indication that our results are accurate, efficient, and robust.

4.5. FGLS estimates of the effect of ISU on pollution emissions

Although the presence of cross-sectional interdependence was checked using the CIPS unit root test, it is nevertheless necessary to use the FGLS estimator to control for any cross-sectional dependence to ensure the robustness and validity of the findings. The results are reported in Table 5. Note that we concentrate on the comparatively efficient dynamic estimates rather than the static estimates in the discussion of the results.

The FGLS estimates confirm the findings obtained from the FE estimator that show a decrease in pollution emissions with an increase in ISU and renewable energy consumption. Table 5 shows that a 1% increase in ISU (renewable energy) leads to a reduction in pollution emissions by about 0.02% (0.05%) and 0.01% (0.04%) in Models 1 and 2, respectively. These results align with the studies conducted by Dong et al. (2021), Dou et al. (2021), Wu et al. (2021), and Acheampong et al. (2019), who reported that ISU and renewable energy consumption lowers pollution emissions. Additionally, the results indicate that economic growth initially causes an increase in pollution emissions by 0.35% and 0.34%, but beyond threshold values of 0.110% and 0.108% in Models 1 and 2, respectively, it leads to a decline in pollution emissions by about 0.02% in both models. Notably, the FGLS estimates, like the FE estimates, support the reasonableness of the EKC hypothesis in SSA. Previous research has shown that there is an inverted U-shaped relationship between economic growth and carbon emissions, as demonstrated in studies by Ajanaku and Collins (2021) and Dong et al. (2021).

The results also found that urbanization contributes to an increase in pollution emissions by approximately 0.01% and 0.02% in Models 1 and 2, respectively. Similar findings were reported by Dou et al. (2021), Duodu et al. (2021), Wu et al. (2021) and Wang et al. (2022), arguing that urbanization induces pollution emissions both in China and SSA. Although FDI was found to be insignificant concerning pollution emissions in the FE analysis, static models in FGLS revealed that FDI significantly reduces pollution emissions effect of FDI on pollution in SSA supports the pollution halo hypothesis, which suggests that FDI, through the use of advanced technologies, can help reduce pollution emissions. This result contradicts Duodu and Mpuure (2023) as well as Wang et al. (2023d), revealing that the inflow of FDI leads to higher CO₂ emissions.

Table 5. Effect of industrial structure upgrading on CO₂ (panel FGLS)

Variable	Model 1		Model 2	
	Static (Baseline)	Dynamic (Benchmark)	Static (Baseline)	Dynamic (Benchmark)
$\ln\text{CO}_{2,t-1}$		0.9274*** (0.0032)		0.9276*** (0.0033)
$\ln\text{ISU}^a$	-0.0582*** (0.0104)	-0.0209*** (0.0030)		
$\ln\text{ISU}^b$			-0.0712*** (0.0086)	-0.0129*** (0.0028)
FDI	-0.0018*** (0.0007)	-0.0005 (0.0004)	-0.0021*** (0.0007)	-0.0003 (0.0005)
$\ln\text{REC}$	-0.4206*** (0.0155)	-0.0489*** (0.0037)	-0.4167*** (0.0143)	-0.0419*** (0.0036)
$\ln\text{URB}$	0.4093*** (0.0249)	0.0141*** (0.0038)	0.4197*** (0.0261)	0.0197*** (0.0040)
$\ln\text{EG}$	1.0029*** (0.1463)	0.3535*** (0.0238)	1.1174*** (0.1441)	0.3433*** (0.0238)
$\ln\text{EG}^2$	-0.0121 (0.0096)	-0.0194*** (0.0016)	-0.0190** (0.0095)	-0.0185*** (0.0016)
Constant	-7.1210*** (0.5088)	-1.4109*** (0.0813)	-7.5632*** (0.4979)	-1.4265*** (0.0798)
EG^*	0.0241	0.1098	0.0340	0.1078
observations	1148	1120	1148	1120
Wald test p-value	0.0000	0.0000	0.0000	0.0000

Notes: The dependent variable is CO₂ emissions. Model 1 is where industrial structure upgrading (ISU^a) is measured by the ratio of the service value-added to the industry value-added. In Model 2, industrial structure upgrading (ISU^b) is measured by the ratio of the service value-added to the manufacturing value-added. **, and *** represent 5%, and 1% significance levels, respectively. Standard errors (in parentheses) are corrected for autocorrelation, heteroskedasticity and cross-sectional dependence. EG* denote the economic growth threshold value.

4.6. D-H panel causality test results

Because causal relationship has significant policy implications for economies, the study utilized the Dumitrescu and Hurlin (2012) panel causality test. The findings are reported in Table 6.

It is revealed that there exists bidirectional causality between industrial structure upgrading, economic growth, FDI, urbanization, and pollution emissions, as the probability values of these variables reject the null hypothesis. However, the results reveal a unidirectional causal movement between renewable energy consumption and pollution emissions, specifically running from pollution emissions to renewable energy consumption. The result suggests that higher pollution emissions endanger citizens' health (Baloch & Wang, 2019), as a result, they adopt the use of renewable energy that limits pollution emissions. The bidirectional causality between the above variables suggests that to achieve a clean environment, these variables should not be overlooked. For instance, the causal movement between ISU and pollution emissions suggests that ISU come with green technologies that reduce pollution. On the other hand, higher pollution emissions also cause firms to upgrade from traditional technologies to advanced technologies which have less or no effect on pollutants. Dong et al. (2021) and Adom et al. (2012) reported similar results that ISU and pollution emissions have bidirectional causality in China and Ghana, respectively.

5. Conclusion and policy suggestions

Industrial structure upgrading has been argued to enhance environmental quality by reducing pollution emissions. However, this relationship has not been examined to a greater extent in SSA. Therefore, this study examined the effect of industrial structure upgrading on pollution emissions in 28 SSA countries from 1980 to 2020. The study used random-effects (RE), fixed-effects (FE),

Table 6. D-H panel causality results

Null hypothesis	D-H W-bar	D-H Z-bar	P-value
$ISU^a \neq CO_2$	2.0142	3.7949	.0001
$CO_2 \neq ISU^a$	2.3496	5.0499	.0000
$ISU^b \neq CO_2$	2.1377	4.2570	.0000
$CO_2 \neq ISU^b$	3.6063	9.7517	.0000
$FDI \neq CO_2$	2.1298	4.2274	.0000
$CO_2 \neq FDI$	2.8679	6.9892	.0000
$REC \neq CO_2$	1.1598	0.5979	.5499
$CO_2 \neq REC$	2.3282	4.9697	.0000
$URB \neq CO_2$	4.8317	14.3370	.0000
$CO_2 \neq URB$	14.8588	51.8550	.0000
$EG \neq CO_2$	6.1368	19.2206	.0000
$CO_2 \neq EG$	4.8263	14.3168	.0000

Notes: CO_2 , ISU^a , ISU^b , FDI , REC , URB , and EG are carbon dioxide emissions, industrial structure upgrading (proxied by the ratio of the service value-added to the industry value-added), industrial structure upgrading (proxied by the ratio of the service value-added to the manufacturing value-added), foreign direct investment, renewable energy consumption, urbanization, and economic growth, correspondingly. The null hypothesis $A \neq B$ implies that A does not grange cause B.

feasible generalized least squares (FGLS), and Dumitrescu and Hurlin (D-H) panel causality techniques for the analysis. More importantly, this study contributes to the existing literature in advancing the knowledge on ISU and CO_2 emissions by employing two comprehensive measures of industrial structure upgrading. The results of the Hausman test revealed that the FE estimator is more efficient and preferable to the RE estimator.

Based on the findings, the study concludes the following:

- (i) Industrial structure upgrading improves environmental quality by reducing pollution emissions in SSA by about 0.03-0.04%.
- (ii) The EKC hypothesis is valid in SSA, with an average threshold level of economic growth at 0.098% and 0.109% in the FE and FGLS, respectively. The results show that economic growth after the EKC threshold reduces pollution emissions by 0.03-0.04% (FE) and by 0.02% (FGLS).
- (iii) Renewable energy consumption reduces pollution emissions by 0.16-0.17%. However, urbanization increases pollution emissions by 0.01-0.02%.
- (iv) There exists a bidirectional (moving in two directions) relationship between industrial structure upgrading and pollution emissions.

In all, this study establishes that industrial structure upgrading has a potential role to play in improving environmental quality in SSA.

5.1. Policy implications

Regarding the policy implications of the effect of the industrial structure upgrading on pollution emissions, this study suggests that production in the economic structures (services, manufacturing, and industrial sectors) in SSA should be upgraded from environmentally polluting production processes to modern green processes that increase output and minimize pollution emissions. However, it must be acknowledged that the lack of enough incentives for industries to invest in

upgrading their structures to reduce emissions voluntarily becomes a critical issue in SSA. Again, the lack of stringent regulations and enforcement mechanisms to ensure appropriate upgrading of the industries remains questionable in SSA.

To overcome these concerns and improve upon ISU in SSA, this study recommends that governments and the private sector in SSA invest in upgrading domestic industrial structures. One way to ensure that is to introduce incentive mechanisms for upgrading industrial structures. Policymakers or governments should provide tax incentives, grants, or subsidies to encourage industries to invest in green or cleaner technologies and practices for production. Doing so will upgrade the industrial structures and reduce pollution in the long term. Furthermore, we recommend SSA strengthen the regulatory framework to effectively limit pollution emissions from industries. This can be done by implementing stricter emission standards and penalties for non-compliant industries that fail to adopt greener practices. This will ensure that industrial structures in the economy adopt environmentally related technologies and hence lower emissions. Overall, by ensuring the above suggestions, pollution emissions from economic structures will be reduced, leading to improved air and water quality, and benefiting the citizenry's health and ecosystems. This will further put SSA in line with achieving SDG 13.

5.2. Limitations and future work

Although the current study has explored the effect of industrial structure upgrading on pollution emissions in SSA, there is a caveat in generalizing the findings in other African countries, as the data are closely related to SSA. Again, the estimators utilized in this study cannot account for potential endogeneity that might arise from the models. This limitation could consequently impact the study's findings in the presence of endogeneity. In this regard, this study suggests that future studies should capitalize on the present study to incorporate other African countries and, to a greater extent, offer comparative studies across other African countries to ensure the generalization of the present findings. In addition, future studies could consider utilizing estimators that address potential endogeneity to corroborate the present findings.

List of acronyms

CO ₂	Carbon dioxide
COP	Conference of the Parties
D-H	Dumitrescu and Hurlin
EKC	Environmental Kuznets Curve
FE	Fixed Effects
FGLS	Feasible Generalized Least Squares
FDI	Foreign Direct Investment
GHG	Global Greenhouse Gas
GDP	Gross Domestic Product
ISU	Industrial structure upgrading
IPCC	Intergovernmental Panel on Climate Change
RE	Random Effects
SSA	Sub-Saharan Africa
SDG	Sustainable Development Goals
STIRPAT	Stochastic Impact Regression on Population, Affluence, and Technology
UNFCCC	United Nations Climate Change Conference
UNCTAD	United Nations Conference on Trade and Development
WDI	World Development Indicators

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Author details

Eric Fosu Oteng-Abayie¹

ORCID ID: <http://orcid.org/0000-0002-4598-2066>

Emmanuel Duodu^{1,2}

E-mail: ed59@alu.ua.es

ORCID ID: <http://orcid.org/0000-0003-4988-2043>

Seth Oduro¹

Samuel Tawiah Baidoo¹

ORCID ID: <http://orcid.org/0000-0001-5941-6308>

¹ Department of Economics, Kwame Nkrumah University of Science and Technology, Kumasi, Ghana.

² Department of Fundamentals of Economic Analysis, University of Alicante, Sant Vicent del Raspeig, Spain.

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Data for this analysis is available from the corresponding author upon request.

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Appendices

Table A1. Summary of ISU and CO2 research literature

Author(s) (Year)	Country (Duration)	Title	Methods	Key Findings	ISU Measurement
Adom et al. (2012)	Ghana, Senegal, and Morocco (1971–2007)	Carbon dioxide emissions, economic growth, industrial structure, and technical efficiency.	ARDL and Toda and Yomamoto Granger causality test	Existence of bidirectional causality between ISU and CO2 emissions in Ghana and unidirectional causality extending from ISU to CO2 emissions in Senegal and Morocco.	Industry value added as % of GDP
Abokyi et al. (2019)	Ghana (1971– 2014)	Industrial growth and emissions of CO2 in Ghana: The role of financial development and fossil fuel consumption.	ARDL and Granger causality test	Unidirectional causality from ISU to CO2 emission.	Industry value added as % of GDP
Kwakwa and Adusah-Poku (2020)	South-Africa (1975–2014)	The carbon dioxide emission effects of domestic credit and manufacturing indicators in South Africa	ARDL and FMOLS	Manufacturing output increases CO2 emissions	Manufacturing valued added
Zhou et al. (2013)	29 China provinces (1995–2009)	Industrial structural transformation and carbon dioxide emissions.	System-GMM	ISU reduces CO2 emissions	Ratio of services industry value added to secondary industry value added
Zhang et al. (2014)	China (1978– 2011)	The impact of economic growth, industrial structure and urbanization on carbon emission	ARDL and Granger causality test	ISU reduces CO2 emissions	The ratio of tertiary industry value-added to GDP
Mi et al. (2015)	Beijing-China	Potential impacts of industrial structure on energy consumption and CO2 emission.	Input-Output model	ISU reduces CO2 emissions	Constructive index of industries

(Continued)

Table A1. (Continued)

Author(s) (Year)	Country (Duration)	Title	Methods	Key Findings	ISU Measurement
Yuan et al. (2016)	Cross-countries (1998–2011)	The impact of the industrial structure on regional carbon emission	FE and RE	Secondary industry induces higher CO2 emissions but after some time, the service industry becomes the highest contributor of CO2 emissions	Secondary and service industry share
Wang et al. (2016)	30 China provinces (1995–2011)	Empirical analysis on the factors influencing national and regional carbon intensity	FE and RE	ISU affects CO2 emissions positively	The secondary industry added value to the overall GDP
Tian et al. (2019)	Southwest China (2002–2012)	Realizing low-carbon development in a developing and industrializing region: Impacts of industrial structure change on CO2 emissions	Input-output model and structural decomposition analysis	Changes in ISP have significant differences in CO2 emissions	Constructive index of primary, secondary and tertiary industries value added
Zhang et al. (2020)	China (2000–2017)	Relationship between China's greenhouse gas emissions and industrial structure and economic growth from the perspective of energy consumption	PLS	Secondary industry induces higher emissions whereas primary and tertiary industries reduce emissions.	Added value of industry and construction
Dong et al. (2021)	RCEP and Non-RCEP Countries (1990–2019)	How Does Industrial Structure Upgrading Affect the Global Greenhouse Effect?	FE and RE	ISU reduces CO2 emissions	The ratio of the added value of tertiary industry to secondary industry
Dou et al. (2021)	RCEP and Non-RCEP Countries (1990–2019)	Re-Estimating the Impact of Natural Gas on Global Carbon Emissions: The Role of Technological Innovation	FE and RE	ISU reduces CO2 emissions	The ratio of the added value of tertiary industry to secondary industry

(Continued)

Author(s) (Year)	Country (Duration)	Title	Methods	Key Findings	ISU Measurement
Wu et al. (2021)	30 provinces in China (2003–2017)	Energy endowment, industrial structure upgrading, and CO2 emissions in China: Revisiting resource curse in the context of carbon emissions	SDM	ISU reduces the negative impact of energy-dependent industries, and that lowers CO2 level	The ratio of labour productivity between the tertiary industry and secondary industry
Zhao et al. (2022)	China (2000–2018)	Scenario simulations for the peak of provincial household CO2 emissions in China based on the STIRPAT model	STIRPAT model	ISU via reduction in energy intensity reduces CO2 emissions	Constructive index
Yang et al. (2022)	China (2000–2017)	Industrial Structure Upgrading, Green Total Factor Productivity and Carbon Emissions	POLS, RE, FE, and SDM	ISU reduces CO2 emissions by increasing green total factor productivity	Ratio of primary industry, secondary industry and tertiary industry value added to the total value added.

Notes: ISU, ARDL, FMOLS, GMM, FE, RE, POLS, SDM, PLS, and RCEP denote industrial structure upgrading, autoregressive-distributed lag model, fully modified ordinary least squares, generalized methods of moment, fixed-effect, random effect, pooled-ordinary least squares, spatial Durbin model, partial least squares, and Regional Comprehensive Economic Partnership, respectively.

Table A2. List of countries

Benin	Congo, Republic	Mauritania	Sierra Leone
Botswana	Cote d'Ivoire	Mauritius	South Africa
Burkina Faso	Eswatini	Namibia	Sudan
Burundi	Gabon	Niger	Togo
Cabo Verde	The Gambia	Nigeria	Uganda
Cameroon	Ghana	Rwanda	Zambia
Chad	Lesotho	Seychelles	Zimbabwe

Table A3. Description of variables

Variable	Symbol	Measurement/Proxy	Source
Pollution emissions	PE	Carbon dioxide (CO ₂) emissions (metric tons per capita)	WDI (2021)
Industrial structure upgrading	ISU	The ratio of the service value-added to the industry value-added and the ratio of the service value-added to the manufacturing value-added	WDI (2021)
Foreign direct investment	FDI	Net inflows of Foreign direct investment (% of GDP)	WDI (2021)
Renewable energy consumption	REC	Renewable energy consumption (% of total final energy consumption)	WDI (2021)
Urbanization	URB	Urban population	WDI (2021)
Economic growth	EG	GDP per capita (constant 2015 US\$)	WDI (2021)

Notes: WDI denotes World Development Indicators.