Frontiers in Environmental Science

TYPE Original Research
PUBLISHED 11 March 2024
DOI 10.3389/fenvs.2024.1305852

OPEN ACCESS

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RECEIVED 02 October 2023
ACCEPTED 15 January 2024
PUBLISHED 11 March 2024

CITATION
Yu Y, Zhao J, Musah M, Owusu-Akomeah M, Nkyi JA, Li J, Appiagyei Ampong GO, Kumah EA, Cao S, Xu Y, Shi Y, Wang L, Hui C and Li K (2024), Does industrialization promote the emission mitigation agenda of East Africa? a pathway toward environmental sustainability. *Front. Environ. Sci.* 12:1305852. doi: 10.3389/fenvs.2024.1305852

Does industrialization promote the emission mitigation agenda of East Africa? a pathway toward environmental sustainability

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Africa's economy continues to be characterized by increasing environmental pollution caused by anthropogenic activities. Despite the implications of environmental pollution in the continent, little attention has been paid to it, although almost all its countries are signatories to the Paris Agreement. One macroeconomic variable that has proven to be a major driver of environmental pollution in the region is industrialization. However, despite the numerous explorations on the connection between industrialization and environmental degradation, limited studies have examined the linkage amidst the series in East Africa. This study was, therefore, conducted to help fill that gap. In accomplishing this goal, econometric techniques that control cross-sectional correlations, heterogeneity, and endogeneity, among others, were employed for the analysis. From the results, the panel under consideration was heterogeneous and cross sectionally correlated. In addition, the studied series were first differenced stationary and co-integrated in the long run. The elasticities of the regressors were explored via the cross sectionally augmented autoregressive distributed lag (CS-ARDL) estimator, the cross sectionally augmented distributed lag (CS-DL) estimator, and the augmented mean group (AMG) estimator. According to the results, industrialization led to a reduction in the

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Abbreviation: IND, industrialization; FD, financial development; FDI, foreign direct investment; URB, urbanization; EC, energy consumption; RE, renewable energy; CO_2, carbon emissions; GHG, greenhouse gas; SDGs, sustainable development goals; BRI, Belt and Road initiative; USA, United States of America; OVB, omitted variable bias; CLRM, classical linear regression model; EA, East Africa/East African; CS-ARDL, cross sectionally augmented autoregressive distributed lag; CS-DL, cross sectionally augmented distributed lag; AMG, augmented mean group; VIF, variance inflation factor; WDI, world development indicator; CADF, cross sectionally augmented Dickey–Fuller; CIPS, cross-sectional Im, Pesaran, and Shin; DOLS, dynamic ordinary least squares; FMOLS, fully modified ordinary least squares; ARDL, autoregressive distributed lag; DSUR, dynamic seemingly unrelated regression; APEC, Asia-Pacific Economic Cooperation; IPCC, Intergovernmental Panel on Climate Change; ECT, error correction term; RMSE, root mean square error.

environmental quality in the region through high CO_2 emissions. In addition, financial development, foreign direct investments, urbanization, and energy consumption were not environmentally friendly in the bloc. On the causal linkages amid the series, bidirectional causalities between industrialization and CO_2 emissions, energy consumption and CO_2 emissions, and foreign direct investments and CO_2 emissions were detected. Finally, one-way causal movements from financial development and urbanization to CO_2 emissions were unraveled. These findings are useful in helping stimulate the emission mitigation agenda of the region. Based on the findings, the study recommended, among others, that national policies that can promote energy conservation at the industrial level and can convert the industrial structure of the region to a low carbon-intensive one should be formulated.

KEYWORDS

industrialization, financial development, foreign direct investments, urbanization, energy consumption, environmental quality, East Africa

1 Introduction

For decades now, global warming, widely linked to greenhouse gas emissions, has been a major issue for nations and their citizens (Majeed and Tauqir, 2020). Such an unprecedented increase in global temperature and its negative implications for human health and the environment has resulted in the formation of many international agreements (Amin et al., 2022). For instance, the Kyoto Protocol in 1997 and the Paris Agreement in 2015 were established to help abate the rate of global warming through emission mitigations (Amin et al., 2022). According to the European Commission (2017), CO_2 emissions represented a greater portion of greenhouse gas emissions in the globe, accounting for approximately 73% of emissions from fossil fuel consumption. The IPCC (2007) also reported an increase in CO_2 emissions from 21 gigatons (Gt) in 1970 to 38 Gt in 2004. The emission of CO_2 (measured in metric tons) further rose from 4.19 in 1990 to 4.98 in 2014 (World Bank, 2022) due to various anthropogenic activities, of which industrialization is no exception. O'Sullivan and Steven (2003) explained industrialization as the process of converting to a socioeconomic order where the industry is dominant. According to the authors, industrialization entails a significant reorganization of an economy for manufacturing purposes. Industrialization boosts productivity; stimulates economic development; and encourages entrepreneurship, mobility, personal liberty, and good standards of living (Mahmood et al., 2020; Majeed and Tauqir, 2020). Significant changes to infrastructure, like the construction of roads and railways, also accompany industrialization. However, industrialization has long been associated with highly polluting industries that are heavily dependent on fossil fuels (Pomeranz, 2001; Claire et al., 2011). It is reported that industrial energy consumption represents 51% of the world's total energy (Sieminski and Kazemzadeh, 2013), with a large portion being energies from emission-intensive sources that promote environmental pollution in various geographical settings. For nations to, therefore, attain sustainable development goals (SDGs), their industrial practices should be linked to modern cleaner technologies.

The connection between industrialization and environmental quality has been studied expansively. The findings are, however, contradictory. For example, Mahmooda et al. (2020) explored Saudi Arabia, Ullah et al. (2020) researched on Pakistan, Ayitehgiza. (2020) explored Ethiopia, Rauf et al. (2020) investigated 65 Belt and Road Initiative countries, and Samreen and Majeed (2020) studied 89 countries, among others, and they all discovered industrialization as harmful to the environmental quality. However, Chowdhury et al. (2020) analyzed 92 economies, Hong et al. (2019) studied South Korea, Li et al. (2019) investigated China, and Congregado et al. (2016) researched on the United States, among others, and they all confirmed industrialization as friendly to the environmental quality. The above contrasting result might be due to the differences in the study period, the nature of data used, the estimation techniques employed, and the adoption of indicators with heterogeneous attributes across countries, among others. The discoveries of the aforestated explorations form the basis of our study's hypothesis that since industrialization can improve or worsen the ecological quality, it could have an ambiguous relationship with the environmental quality in East Africa.

Despite the countless explorations on the determinants of environmental quality, little consideration has been paid to the linkage between industrialization and environmental quality in East Africa. Most prior explorations on the environmental effects of industrialization focused on sub-Saharan Africa to the detriment of East Africa (for instance, Adjei Kwakwa (2023); Akinsola et al. (2022); Mentel et al. (2022); and Nkemgha et al. (2023)). However, given the surging rate of pollution in the region, coupled with the bloc's net-zero emission targets, examining the connection between industrialization and CO_2 emissions to help raise policy options to improve the environmental quality in the region was deemed appropriate. Therefore, the study specifically seeks to explore the effects of industrialization on environmental quality in East Africa. Based on this objective, the study sought to answer the research question: what is the effect of industrialization on the environmental quality in East Africa?

The rising rate of CO_2 emissions in East Africa motivated our conduct of this study. With regards to overall emissions and regional evolutionary trends, East African emissions have been growing at an annual average rate of 6.03%, tripling nearly from 17.6 million metric tons in 2000 to 47.6 million metric tons in 2017. The trend exhibits a two-staged exponential growth pattern, with 2010 as the turning point (Sun et al., 2022). In addition, the region's fast economic development, with an average yearly rate of 6.45%, is strongly aligned with patterns pertaining to emissions. Since 2010, the surging rate of emissions has quickened and gradually outpaced the rate of economic development. This suggests that future economic viability in the region will be accompanied by higher emissions if significant action is not taken on energy mix and energy efficiency (Sun et al., 2022). In terms of country specifics, Kenya is the nation with the most emissions, whereas Ethiopia and Tanzania have the quickest rates of emission growth. Uganda's emissions fluctuate a lot; between 2013 and 2015, there was a significant increase in emissions because of substantial oil imports for the nation's transportation industry. More than 80% of East Africa's emissions come from Kenya, Tanzania, Ethiopia, and Uganda (Sun et al., 2022). The worsening signals of emissions call for more explorations to offer concrete measures to help reduce the menace in the region. Hence, studying the environmental impacts of industrialization in the presence of financial development, urbanization, foreign direct investments, and energy consumption in East Africa was very fitting.

Our exploration contributes to the extant literature in diverse ways. First, this is a pioneering study to examine the association between industrialization and CO_2 emissions in East Africa while controlling for financial development, foreign direct investment, urbanization, and energy consumption at the same time. Most prior explorations on the determinants of environmental pollution in the region failed to adopt this innovative approach. Second, the study engaged the CS-ARDL, AMG, and CS-DL econometric methods to estimate the elastic effects of the predictors on the response variable. These techniques were adopted because they account for cross-sectional dependence in panel units. Most prior investigations on the region adopted conventional econometric methods that assume cross-sectional independence. Third, our study contributes by developing a robust econometric framework to examine the determinants of environmental pollution in East Africa. This framework can be fully used or augmented by future researchers delving into the predictors of ecological quality. Thus, our econometric framework serves as a guide for future studies on the determinants of environmental quality in economies. Fourth, the study delivers new implications and innovative findings. This helped in making trustworthy and credible suggestions to help promote the sustainable development goals (SDGs) of the region. By adopting and applying the methods of prior researchers, the study finally contributes by enriching the depth of the existing pool of knowledge.

This study is significant because it contributes to understanding the interplay between industrialization and environmental quality in East Africa. Specifically, the study brings to light the effect of industrialization on environmental pollution in the region and offers policy recommendations to help improve environmental safety in economies. Moreover, the study draws implications in building new knowledge for policymakers and managers of economies. For instance, the findings of the study will aid policymakers in developing strategies that could help mitigate the use of polluting energies while encouraging the implementation of green technologies in the nation's industrial practices. This exploration is also important as it assists the nations in developing energy-efficient strategies that are consistent with their macroeconomic goals. Finally, the study improves on the industrialization–CO_2 emissions literature. This serves as a resource document for potential researchers who might undertake similar studies in the future.

The originality of this exploration cannot be underscored. Our research is original because it is from our own perspective, although we drew arguments from other sources to support our work. Our study is also original because it brings out new information as compared to prior explorations in East Africa. Our exploration is unique because the procedures are well-described, and the findings are correctly reported and discussed. The remaining aspects of the study are organized as follows: Section 2 contains the study's literature review, while Section 3 presents the methodology of the exploration. Section 4 presents the results of the exploration, while the fifth part outlines the discussions of the results. The last part of the report presents the study's conclusions and recommendations.

2 Literature review

2.1 Theoretical framework

The pollution haven hypothesis (PHH) is engaged to support the association between industrialization and environmental quality in this study. The PHH posits that the effectiveness of a nation's environmental laws, regulations, and enforcement may have an impact on its industrialization. According to this theory, foreign investors from developed economies seek to build their industries by exploiting underdeveloped nations with lax environmental regulations. The majority of industries from developed nations that seek to maximize returns and minimize operating costs have identified developed nations as the secure environment to launch their operations. Implicitly, as the industries expand with little consideration for the environment, pollutant emissions may eventually lead the native people to danger.

2.2 Industrialization and environmental quality nexus

Kemp (1993) and Kiely (1998) view industrialization as the process of transforming an economy from that focused on agriculture to that based on the production of goods. Under industrialization, individual manual labor is normally replaced by mechanized mass manufacturing, and craftsmen are replaced by assembly lines. According to the ecological modernization theory, industrialization is non-linearly affiliated with environmental quality (Majeed and Mazhar, 2019). Thus, there is less industrial development in the early stages of modernization, which adds to environmental degradation. However, the rate of pollution tends to minimize in the longer term, owing to greater public awareness about environmental quality and the introduction of eco-friendly technologies (Majeed and Mazhar, 2019).

The nexus between industrialization and CO_2 emissions has been extensively explored. The discoveries are, however, divergent. For instance, Claire and Widyawati (2023) studied the industrialization and environmental quality connection in nine ASEAN economies over the period 1990 to 2019. According to

TABLE 1 Data description and measurement units.

Variable	Measurement unit	Source
Carbon emissions (CO_2)	Metric tons *per capita*	WDI (2022)
Industrialization (IND)	Industrial value added (constant 2010 US$)	WDI (2022)
Urbanization (URB)	Urban population (% of total population)	WDI (2022)
Energy consumption (EC)	Kg of oil equivalent *per capita*	WDI (2022)
Foreign direct investments (FDI)	Net inflows (% of GDP)	WDI (2022)
Financial development (FD)	Domestic credit to the private sector by banks (% of GDP)	WDI (2022)

Sample countries: Ethiopia, Madagascar, Mauritius, Comoros, Seychelles, Uganda, Rwanda, Burundi, Kenya, Tanzania, Mozambique, Malawi, Zambia, and Zimbabwe.

the results, industrialization worsened environmental quality in the long run. However, the interaction between industrialization and renewable energy improved the nations' environmental quality. This finding supports that of Majeed and Tauqir (2020) for 156 economies but conflicts with that of Chowdhury et al. (2020) for 92 economies. The conflicting results might be due to variations in the sample size, location, research methods, and variables or conditions, among others, suggesting that the interpretation of the findings warrants some care. Patel and Mehta (2023) investigated the impact of India's industrial development on CO_2 emissions over the period from 1971 to 2019. Based on the estimates, industrialization harmed environmental quality by spurring more CO_2 emissions. This discovery collaborates with that of Sarkodie et al. (2020) but varies from that of Congregado et al. (2016). The conflicting outcomes might be a result of the differences in geographical locations and the choice of econometric techniques and variables. Hence, the interpretation of the findings warrants some caution.

Mehmood et al. (2024) analyzed the role of green industrial transformation in CO_2 emission mitigation in Pakistan over the period from 1975 to 2020. According to the results, industrial transformation enhanced the environmental quality by mitigating the emission of carbon. This finding aligns with the exploration of Zhou et al. (2013) but contrasts with those of Al-Mulali and Ozturk (2015); Hong et al. (2019); Li et al. (2019); Samreen and Majeed. (2020); and Safi et al. (2021). These contradictory findings mean that the debate on the linkage between industrialization and CO_2 emissions is relentless and demands further interrogations. Zhou and Li. (2020) investigated the nonlinear association between industrial restructuring and CO_2 emissions in 32 economies. Through the panel threshold approach, industrial restructuring had an inverted u-shaped affiliation with CO_2 emissions. The study is essential; however, care should be taken when interpreting the results because the study was limited to only the panel threshold approach. If other econometric techniques were to be considered, the outcome might be different. Mahmooda et al. (2020) investigated the industrialization–CO_2 emissions connection in Saudi Arabia and discovered that industrialization was dangerous to the country's environmental quality. This outcome aligns with those of Ayitehgiza (2020), Liu and Bae (2018), Pata (2018), Rauf et al. (2020), Rehman et al. (2021), Sharmin and Tareque (2018), Wang et al. (2020), Xu and Lin (2016), and Yang et al. (2021) but conflicts with that of Congregado et al. (2016). The varying outcomes might be due to differences in the sample size, location, research methods, and variables or conditions, among others. This suggests that the industrialization–environmental quality debate is far from over and warrants further investigations like ours.

Appiah et al. (2021) investigated 25 sub-Saharan African economies from 1990 to 2016. According to the findings, industrialization had a trivially positive influence on CO_2 emissions. This finding contrasts with those of Raheem and Ogebe (2017), Liu and Bae (2018), Dong et al. (2019), Hong et al. (2019), Li et al. (2019), Rauf et al. (2020), and Ullah et al. (2020). The conflicting outcomes might be due to differences in sample and methodological selection, geographical locations, and the study period. Hence, the results cannot be generalized for all economies in the globe. Care must be taken that the exploration is very relevant; however, it was restricted to only developed economies. This implies that one cannot generalize the results for all the economies in the world.

2.3 Literature gaps

Studies on the determinants of environmental quality in Africa have been expansively explored, but little has been done in East Africa as a region. For instance, Kwakwa. (2023) examined the predictors of CO_2 emissions in 32 African countries and discovered that the expansion in the agricultural sector, industrial sector, and service sector exerted upward pressure on CO_2 emissions, while renewable energy reduced the emissions of carbon. Furthermore, renewable energy minimized the detrimental effects of the agricultural and industrial sectors on CO_2 emissions. In addition, the study of Abid et al. (2023) confirmed economic growth, energy consumption, and trade openness as harmful to the environmental quality in West Africa, but corruption exhibited an inhibiting effect in the long run. In the study by Gyamerah and Gil-Alana (2023), electricity consumption and economic growth positively explained CO_2 emissions in Central and Western Africa; however, the variables did not have any causal association with emissions in the regions. Although the above studies were on the determinants of environmental quality in Africa, they did not specifically examine the effect of industrialization on CO_2 emissions in East Africa, controlling for financial development, foreign direct investments, urbanization, and energy consumption. This study was, therefore, conducted to help fill that gap.

Finally, most prior explorations from the review of the relevant literature adopted conventional econometric techniques like ARDL, GMM, and OLS, among others, to investigate the association between industrialization and environmental quality. Although these approaches yield robust outcomes, they are flanked by several limitations. For instance, the above techniques are not robust to cross-sectional dependence in panel units. However, given that nations in East Africa are economically related, there is a high possibility of cross-sectional correlations in the investigated panel. These dependencies, if ignored, could result in biased estimates and conclusions. This study, therefore, bridges that void by adopting second-generation econometric techniques like CS-ARDL, CS-DL, AMG, CIPS, and CADF techniques, among others, that are robust to residual cross-sectional dependence in our analysis. The application of these techniques in our study can help other researchers in conducting similar explorations in other parts of Africa and the rest of the world.

3 Materials and methods

3.1 Data source and descriptive statistics

An unbalanced panel data on 14 nations in East Africa (EA) covering the period 1990–2019 was used for the analysis. The sampled countries are outlined in Table 1. The other countries comprising Djibouti, Eritrea, Somalia, and South Sudan were not considered for the analysis because the countries lacked data for some of the studied variables. For instance, Djibouti did not have data on industrialization for the entire studied period. In addition, the country only had data on energy consumption for the years 1990, 2004, 2005, 2006, and 2007. Additionally, Eritrea did not have data on CO_2 emissions, foreign direct investment, energy consumption, financial development, and urbanization for most of the studied period. The country also could not account for data on industrialization for the entire period under consideration. For Somalia, data for energy consumption, industrialization, and financial development were missing for the entire research duration; however, data on foreign direct investment were available for only 1990. Finally, South Sudan only had data on urbanization for the entire period. However, for CO_2 emissions, financial development, foreign direct investment, energy consumption, and industrialization, data were missing for almost the whole study duration.

With regards to the investigated nations, data on CO_2 emissions for almost all the countries were available for up to 2019. In addition, data on the majority of the regressors were not available for most periods below 1990. Therefore, using 1990 as the starting period and 2019 as the end period, the authors viewed 1990–2019 as the most appropriate period because the selected nations had data available for the entire period. Industrialization, financial development, foreign direct investment, energy consumption, and urbanization are adopted to predict CO_2 emissions in East Africa because they have been widely proven to be key determinants of environmental quality. Specifically, Claire and Widyawati (2023) and Patel and Mehta (2023) support our choice of industrialization as a predictor of environmental quality, while Ren et al. (2023) and Tao et al. (2023) collaborate with our adoption of financial development as a determinant of environmental quality. In addition, Chiu and Zhang (2023) and Wang et al. (2023) agree with our choice of foreign direct investment as a predictor of environmental quality, while Khan and Khan (2023) and Luqman et al. (2023) align with our choice of urbanization as a determinant of environmental quality. Finally, González-Álvarez and Montañés (2023) and Li et al. (2023) support our adoption of energy consumption as a factor that explains environmental quality in economies. All the analyzed variables were selected by taking into consideration the sustainable development goals (SDGs) of the United Nations, specifically SDG 13, SDG 7, SDG 9, SDG 12, SDG 14, and SDG 15, among others. Further details on the series are presented in Table 1.

3.2 Model specification

This exploration analyzed the nexus amidst industrialization and CO_2 emissions in East Africa whilst controlling for financial development, foreign direct investments, urbanization, and energy consumption. The panel data approach was employed to achieve the above aim. This approach was engaged because it contained more information, more variability, and more efficiency than pure time series estimation approaches (Hsiao, 2007). The technique was also engaged because it provides micro foundations for the analysis of aggregate data (Pesaran, 2004; Hsiao, 2005). To comprehensively analyze the industrialization–CO_2 emissions linkage in East Africa, the ensuing panel data model was proposed:

$$CO_{2it} = \alpha_i + \beta_1 IND_{it} + \beta_2 FD_{it} + \beta_3 FDI_{it} + \beta_4 URB_{it} + \beta_5 EC_{it} + \mu_{it}. \tag{1}$$

In Equation (1), CO_{2it} is the response variable of country ***i*** in time ***t*,** with $IND_{it}, FD_{it}, FDI_{it}, URB_{it}$, and EC_{it} as the explanatory variables, resulting in α_i, β_1, β_2, β_3, β_4, and β_5 estimated parameters and disturbance term μ_{it}, which is independent and identically distributed. It should be noted that URB_{it} and EC_{it} were incorporated into the model to help resolve the omitted variable bias issues. Following Chen et al. (2022); Li et al. (2022); and Musah (2022), Equation (1) was transformed into a log-near form to help minimize data fluctuations and heteroscedasticity issues. The resulting specification, therefore, became

$$\begin{aligned} lnCO_{2it} = \alpha_i + \beta_1 ln\, IND_{it} + \beta_2 lnFD_{it} + \beta_3 lnFDI_{it} + \beta_4 lnURB_{it} \\ + \beta_5 lnEC_{it} + \mu_{it}, \end{aligned} \tag{2}$$

where $lnCO_2, lnIND, lnFD, lnFDI, lnURB$, and $lnEC$ are the log conversions of the response and input variables, respectively. From Eq. 2, expectedly ,the rise in industrial activities as a result of economic advancements and rapid urbanization contributes to the use of more energy from nonrenewable sources, leading to the emission of CO_2 (Nasreen et al., 2018). Based on this, we project industrialization to have a positive effect on CO_2 emissions $\left(\beta_1 = \frac{\partial lnCO_{2it}}{\partial lnIND_{it}} > 0\right)$. Contrarily, if the energy consumed at the industrial level in East Africa comes from renewable sources like water, sun, and wind, then the rate of CO_2 emissions will reduce. Similarly, if there is a shift in industrialization from energy-intensive industries to knowledge-intensive industries, like the creative arts industry, then the process of industrialization will not necessarily surge the consumption of energy. By doing so, the rate of CO_2 emissions will minimize in the sub-region. Likewise, if the industrial sector is less contributing to the economic growth of East Africa, then the rate of CO_2 emissions will be minimized in the sub-region. We, therefore, anticipate the marginal effect of industrialization on the emissions of CO_2 to be negative if any of the above circumstances is observed $\left(\beta_1 = \frac{\partial lnCO_{2it}}{\partial lnIND_{it}} < 0\right)$.

In addition, financial development could surge environmental pollution through the provision of funds at a lower cost to industries for them to expand their production facilities, leading to more energy consumption and, consequently, more CO_2 emissions. Financial development further provides consumption finance to individuals that could influence them to go for energy-consuming items like automobiles and other household appliances, resulting in CO_2 emissions into the environment (Dogan and Seker, 2016; Nwani and Omoke, 2020). Based on the above arguments, the researchers expect the marginal impact of financial development on CO_2 emissions to be positive $\left(\beta_2 = \frac{\partial lnCO_{2it}}{\partial lnFD_{it}} > 0\right)$. Contrarily, financial development could help abate CO_2 emissions through investments in renewable energy infrastructures and by assisting industries financially to adopt eco-friendly technological innovations (Islam et al., 2013). In addition, establishments that grow via the help of financial development are guided on how to efficiently use their resources to achieve better outputs without harming the environment (Tamazian et al., 2009). Under these circumstances, we anticipate the marginal effect of financial development on the emission of CO_2 to be negative $\left(\beta_2 = \frac{\partial lnCO_{2it}}{\partial lnFD_{it}} < 0\right)$. Additionally, we expect the impact of foreign direct investment on CO_2 emissions to be positive $\left(\beta_3 = \frac{\partial lnCO_{2it}}{\partial lnFDI_{it}} > 0\right)$ if the influx of foreign direct investment into East Africa is linked to dirty technologies that promote the emissions of CO_2 in the sub-region (Zhu et al., 2017; Sarkodie and Strezov, 2019). Otherwise, the marginal effect of foreign direct investment on CO_2 emissions is to be negative $\left(\beta_3 = \frac{\partial lnCO_{2it}}{\partial lnFDI_{it}} < 0\right)$ if foreign direct investment is affiliated with green technologies that could mitigate the emission of CO_2 in the countries (Haug and Ucal, 2019; Dhrifi et al., 2020).

Furthermore, the shift of labor force from the rural agrarian sector to urban industrial sector has been viewed as the main reason for accelerated urbanization in many economies. However, because energy is a common good, urban concentration may drive the consumption of energy both at the industrial and the household level, causing high CO_2 emissions (Bulut, 2017; Bakirtas and Akpolat, 2018). Based on the above, we expect the marginal effect of urbanization on CO_2 emissions to be positive $\left(\beta_4 = \frac{\partial lnCO_{2it}}{\partial lnURB_{it}} > 0\right)$. Otherwise, if urbanization is connected to energy-efficient technologies and the consumption of clean energies that help in abating CO_2 emissions, then the marginal influence of urbanization on CO_2 emissions is anticipated to be negative $\left(\beta_4 = \frac{\partial lnCO_{2it}}{\partial lnURB_{it}} < 0\right)$. Finally, we project energy consumption to positively influence CO_2 emissions $\left(\beta_5 = \frac{\partial lnCO_{2it}}{\partial lnEC_{it}} > 0\right)$ if energy consumed in the cause of industrialization and other economic activities are from non-renewable sources that lead to high CO_2 emissions (Rahman et al., 2019; Zafar et al., 2019). Otherwise, the marginal effect of energy consumption on CO_2 emission is expected to be negative $\left(\beta_5 = \frac{\partial lnCO_{2it}}{\partial lnEC_{it}} < 0\right)$ if the energy utilized in the industrial processes and other economic advancement activities in East Africa are environmentally friendly (Solarin et al., 2017; Sinha and Shahbaz, 2018).

3.3 Analytical procedure

At the first step of the analysis, we follow the approach of Ozarslan Dogan and Afsar (2023) by engaging the Pesaran (2004) test to examine cross-sectional dependence (CD) or otherwise in the panel. This test was conducted because the negligence of CD in panel units could result in biased estimates and conclusions (Chen et al., 2022). The CD test predicts the null hypothesis of no CD in panel units against the alternative hypothesis of CD in the panel under investigation. In the second stage, the Hashem Pesaran and Yamagata (2008) homogeneity test was adopted to examine the heterogeneity or homogeneity in the slope coefficients in line with the study by Safi et al. (2021). This test was performed because the macroeconomic indicators of the region vary across the countries. These variations might cause heterogeneity in the slope parameters, which needs to be factored into our analysis because ignoring it might lead to erroneous results and inferences. The test by Hashem Pesaran and Yamagata (2008) predicts the null hypothesis of homogeneity in slope coefficients against the alternative hypothesis of heterogeneity in slope parameters. In the third phase of the analysis, the integration order of the variables was scrutinized via the CADF and CIPS unit root tests in line with the study by Espoir et al. (2023). These tests were engaged because they account for CD in panel units. The tests predict the null hypothesis of no residual CD against the alternative hypothesis of residual CD.

At the fourth stage, the co-integration features of the series were assessed. Co-integration analysis was conducted because it is inappropriate to estimate the elasticities of the predictors if the investigated series does not possess a co-integration association. Hence, the Westerlund and Edgerton (2007) test was engaged to examine the co-integration characteristics of the variables in line with the study by Nica et al. (2023). This test was engaged because it is robust to CD and heterogeneity in panel units. To check the robustness of the above test, we follow the approach of Kirikkaleli and Kalmaz (2020) by adopting the co-integration test proposed by Bayer and Hanck (2013) to also assess the co-integration features of the series. From Eqs 3, 4. This test is vigorous to problems encountered by other co-integration tests. Bayer and Hanck (2013) adopted Fisher's formula to derive theirs, and it is reported by Bekun et al. (2019) as follows:

$$EG - JOH = -2\left[ln(PEG) + ln(PJOH)\right], \tag{3}$$

$$\begin{aligned} EG - JOH - BO - BDM = -2\big[&ln(PEG) + ln(PJOH) \\ &+ ln(PBO) + ln(PBDM)\big], \end{aligned} \tag{4}$$

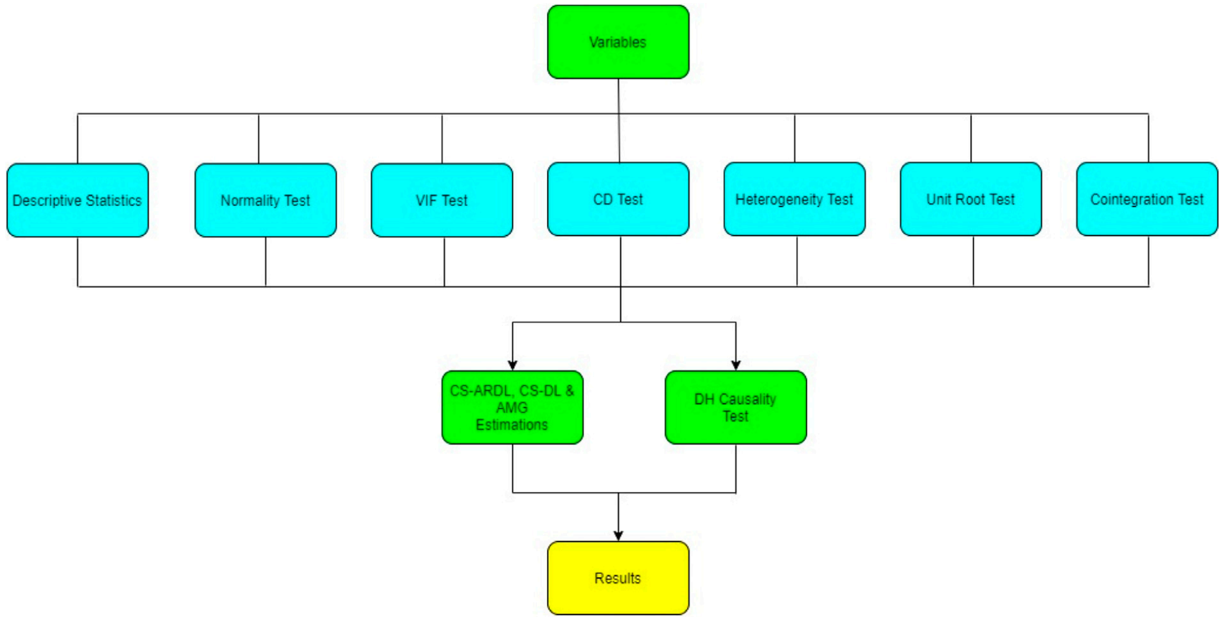

FIGURE 1
Conceptual framework of the study. (Source: authors' creation).

where the Engle and Granger (1987) test is denoted by PEG, the Johansen (1991) test is denoted by PJOH, the Boswijk (1995) test is denoted by PBO, and the Banerjee et al. (1998) test is denoted by PBDM.

In line with Hussain et al. (2022), we first engaged the CS-ARDL technique of Chudik et al. (2016) to estimate the elasticities of the predictors. This estimator was engaged because it caters for residual CD, heterogeneity, and endogeneity in the models. According to Chudik et al. (2016), a general ARDL (P_y, P_x) specification that caters for CD in panel units is expressed as follows:

$$y_{it} = \alpha_i + \sum_{j=1}^{p_y}\lambda_{ij}y_{it-j} + \sum_{j=0}^{p_x}\beta'_{ij}x_{it-j} + \sum_{j=0}^{p}\Theta'_{ij}\bar{\vartheta}_{t-j} + \varepsilon_{it}, \tag{5}$$

where $\bar{\vartheta}_{t-j}$ denotes the cross-sectional averages expressed as $(\bar{y}_{t-j}, \bar{x}_{t-j})$. Based on Equation (5), the estimated ARDL model of this study became

$$\begin{aligned} lnCO2_{it} = \alpha_i &+ \sum_{j=1}^{p_y}\lambda_{ij}lnCO2_{it-j} + \sum_{j=0}^{p_x}\beta_{1j}\,ln\,IND_{it-j} + \sum_{j=0}^{p_x}\beta_{2j}lnFD_{it-j} \\ &+ \sum_{j=0}^{p_x}\beta_{3j}lnFDI_{it-j} + \sum_{j=0}^{p_x}\beta_{4j}lnURB_{it-j} + \sum_{j=0}^{p_x}\beta_{5j}lnEC_{it-j} \\ &+ \sum_{j=0}^{p}\Theta_{1j}\overline{lnCO2}_{t-j} + \sum_{j=0}^{p}\Theta_{2j}\overline{lnIND}_{t-j} + \sum_{j=0}^{p}\Theta_{3j}\overline{lnFD}_{t-j} \\ &+ \sum_{j=0}^{p}\Theta_{4j}\overline{lnFDI}_{t-j} + \sum_{j=0}^{p}\Theta_{5j}\overline{lnURB}_{t-j} + \sum_{j=0}^{p}\Theta_{6j}\overline{lnEC}_{t-j} + \varepsilon_{it}, \end{aligned} \tag{6}$$

where $\overline{lnCO2}$, $ln\,\overline{IND}$, $\overline{lnFD}$, $\overline{lnFDI}$, $\overline{lnURB}$, and $\overline{lnEC}$ are the averages of the cross sections of the regressand and the regressors, respectively; α_i is the intercept; λ_{ij} is the parameter of the lagged output series; $\beta_{1j}, .., \beta_{5j}$ epitomizes the parameters of the regressors; and $\Theta_{1j}, \ldots, \Theta_{6j}$ connotes the lagged series' mean cross-sectional values in Eq 6.

To examine the robustness of the CS-ARDL results, estimates from the AMG and the CS-DL methods were also explored. These techniques were employed because they generate good results when used for heterogeneous and cross sectionally correlated panels, as witnessed in this exploration. In a Monte Carlo simulation, mean group, CS-ARDL, and the CS-DL estimators produced consistent outcomes. However, the results of the CS-ARDL technique outpowered those of the CS-DL and the mean group techniques. Hence, employing the CS-ARDL approach as the principal estimator while using the AMG and the CS-DL techniques as robustness checks was very appropriate.

Following Kazemzadeh et al. (2022) and Zhongming et al. (2019), we used the Dumitrescu and Hurlin (2012) causality test to explore the causal paths amidst the series. This approach was used because it accounts for heterogeneity and CD in panel units. The test is officially expressed as follows:

$$Y_{it} = \gamma_i + \sum_{m=1}^{M}\alpha_i^{(m)}Y_{it-m} + \sum_{m=1}^{M}\delta_i^{(m)}X_{it-m} + \varepsilon_{it}, \tag{7}$$

where Y and X epitomize the output and the input series, respectively; M denotes the lag length; γ_i represents the constant term; $\alpha_i^{(m)}$ is the autoregressive coefficient; and $\delta_i^{(m)}$ denotes the parameters of the covariates. Relying on Equation (7), the ensuing specifications were formulated to explore the causations amidst the series:

TABLE 2 Summary statistics on study variables.

Descriptive statistics

Statistic	$lnCO_2$	lnIND	lnFD	lnFDI	lnURB	lnEC
Mean	−1.452	20.466	2.468	0.191	3.168	14.396
Median	−1.862	21.067	2.507	0.573	3.289	4.410
Maximum	2.190	23.360	4.666	4.058	4.045	6.435
Minimum	−3.867	0.000	0.000	−8.927	1.689	0.000
Standard deviation	0.439	7.184	0.899	0.847	0.501	5.368
Skewness	0.730	−5.042	−0.437	−1.556	−0.510	−0.893
Kurtosis	2.496	32.772	4.209	7.242	2.748	4.395

Correlational matrix and multi-collinearity test

variable	$lnCO_2$	lnIND	lnFD	lnFDI	lnURB	lnEC	VIF	Tolerance
$lnCO_2$	1.000						-	-
lnIND	0.512***	1.000					1.03	0.971
	(0.002)							
lnFD	0.435***	−0.006	1.000				1.20	0.833
	(0.004)	(0.457)						
lnFDI	−0.279***	0.146**	0.078	1.000			1.31	0.763
	(0.006)	(0.045)	(0.175)					
lnURB	0.753***	−0.015	0.314***	0.452***	1.000		1.48	0.676
	(0.003)	(0.767)	(0.001)	(0.009)				
lnEC	0.012*	0.011	0.011	−0.181***	−0.206***	1.000	1.14	0.877
	(0.056)	(0.876)	(0.985)	(0.001)	(0.005)			

Notes: values in parenthesis ( ) denote probabilities; ***, ** and * *denote significance at the 1%, 5%, and 10% levels, respectively.*

$$lnCO2_{it} = \gamma_1 + \sum_{m=1}^{M} \alpha_1{}^{(m)} lnCO2_{it-m} + \sum_{m=1}^{M} \delta_1{}^{(m)} lnIND_{it-m} + \sum_{m=1}^{M} \delta_2{}^{(m)} lnFD_{it-m} + \sum_{m=1}^{M} \delta_3{}^{(m)} lnFDI_{it-m} + \sum_{m=1}^{M} \delta_4{}^{(m)} lnURB_{it-m} + \sum_{m=1}^{M} \delta_5{}^{(m)} lnEC_{it-m} + \varepsilon_{it}, \tag{8}$$

$$lnIND_{it} = \gamma_2 + \sum_{m=1}^{M} \alpha_2{}^{(m)} lnIND_{it-m} + \sum_{m=1}^{M} \delta_6{}^{(m)} lnFD_{it-m} + \sum_{m=1}^{M} \delta_7{}^{(m)} lnFDI_{it-m} + \sum_{m=1}^{M} \delta_8{}^{(m)} lnURB_{it-m} + \sum_{m=1}^{M} \delta_9{}^{(m)} ln\,EC_{it-m} + \sum_{m=1}^{M} \delta_{10}{}^{(m)} ln\,CO2_{it-m} + \varepsilon_{it}, \tag{9}$$

$$lnFD_{it} = \gamma_3 + \sum_{m=1}^{M} \alpha_3{}^{(m)} lnFD_{it-m} + \sum_{m=1}^{M} \delta_{11}{}^{(m)} lnFDI_{it-m} + \sum_{m=1}^{M} \delta_{12}{}^{(m)} lnURB_{it-m} + \sum_{m=1}^{M} \delta_{13}{}^{(m)} lnEC_{it-m} + \sum_{m=1}^{M} \delta_{14}{}^{(m)} ln\,CO2_{it-m} + \sum_{m=1}^{M} \delta_{15}{}^{(m)} ln\,IND_{it-m} + \varepsilon_{it}, \tag{10}$$

$$lnFDI_{it} = \gamma_4 + \sum_{m=1}^{M} \alpha_4{}^{(m)} lnFDI_{it-m} + \sum_{m=1}^{M} \delta_{16}{}^{(m)} lnURB_{it-m} + \sum_{m=1}^{M} \delta_{17}{}^{(m)} lnEC_{it-m} + \sum_{m=1}^{M} \delta_{18}{}^{(m)} lnCO2_{it-m} + \sum_{m=1}^{M} \delta_{19}{}^{(m)} ln\,IND_{it-m} + \sum_{m=1}^{M} \delta_{20}{}^{(m)} lnFD_{it-m} + \varepsilon_{it}, \tag{11}$$

$$lnURB_{it} = \gamma_5 + \sum_{m=1}^{M} \alpha_5{}^{(m)} lnURB_{it-m} + \sum_{m=1}^{M} \delta_{21}{}^{(m)} lnEC_{it-m} + \sum_{m=1}^{M} \delta_{22}{}^{(m)} ln\,CO2_{it-m} + \sum_{m=1}^{M} \delta_{23}{}^{(m)} ln\,IND_{it-m} + \sum_{m=1}^{M} \delta_{24}{}^{(m)} lnFD_{it-m} + \sum_{m=1}^{M} \delta_{25}{}^{(m)} lnFDI_{it-m} + \varepsilon_{it}, \tag{12}$$

$$lnEC_{it} = \gamma_6 + \sum_{m=1}^{M} \alpha_6{}^{(m)} lnEC_{it-m} \sum_{m=1}^{M} \delta_{26}{}^{(m)} lnCO2_{it-m} + \sum_{m=1}^{M} \delta_{27}{}^{(m)} lnIND_{it-m} + \sum_{m=1}^{M} \delta_{28}{}^{(m)} ln\,FD_{it-m} + \sum_{m=1}^{M} \delta_{29}{}^{(m)} lnFDI_{it-m} + \sum_{m=1}^{M} \delta_{30}{}^{(m)} lnURB_{it-m} + \varepsilon_{it}, \tag{13}$$

TABLE 3 Principal component analysis (PCA).

Principal components (eigenvalues)				
Component	Eigenvalue	Difference	Proportion	Cumulative
Comp1	1.647	0.437	0.329	0.329
Comp2	1.210	0.178	0.242	0.571
Comp3	1.032	0.361	0.206	0.777
Comp4	0.671	0.230	0.134	0.911
Comp5	0.441	-	0.088	1.000

Principal component (eigenvector)			
Variable	Comp1	Comp2	Comp3
lnIND	0.116	−0.079	0.937^{r}
lnFD	0.310	0.715^{q}	−0.057
lnFDI	0.607^{p}	−0.146	0.166
lnURB	0.663^{p}	0.104	−0.186
lnEC	−0.287	0.672^{q}	0.236

Notes: p, q, and r denote significant loadings under comp 1, comp 2, and comp 3, respectively.

TABLE 4 Cross-sectional dependence and heterogeneity tests results.

Cross-sectional dependence test		
Variable	Statistic	*p*-value
$\ln CO_2$	20.65	0.000***
lnIND	21.02	0.000***
lnFD	13.64	0.000***
lnFDI	16.13	0.000***
lnURB	26.07	0.000***
lnEC	51.55	0.000***
Slope heterogeneity test		
Test	Statistic	*p*-value
Delta tilde ($\tilde{\Delta}$)	13.786	0.000***
Adj. delta tilde ($\tilde{\Delta}_{adj}$)	15.745	0.000***

*Note: *** denotes significance at the 1% level.*

where $\gamma_1, \ldots, \gamma_6$ are the intercepts; $\alpha_1, \ldots, \alpha_6$ are the autoregressive coefficients; and $\delta_1, \ldots, \delta_{30}$ denote the coefficients of the predictors from Eqs 8–13. The flowchart of the study is shown in Figure 1

4 Empirical results

4.1 Descriptive and correlational analysis

Summary statistics on the variables are shown in Table 2. As evidenced by the table, there was high heterogeneity in industrialization and energy consumption based on their means and standard deviations. However, the means and standard deviations of CO_2 emissions, financial development, foreign direct investment, and urbanization were low, showing low heterogeneity in the series. In addition, the distribution of CO_2 emissions was skewed positively, while that of the rest was skewed negatively. From the kurtosis estimates, urbanization and CO_2 emissions had platykurtic-shaped distributions, whilst those of industrialization, foreign direct investment, financial development, and energy consumption were leptokurtic in shape. Additionally, the tolerance and variance inflation factor tests found no collinearity amid the predictors. Moreover, all the regressors had significant loadings based on the results of the principal component analysis (PCA) exhibited in Table 3. This means that the variables were capable of predicting environmental quality in the countries. Lastly, among the correlation outcomes highlighted in Table 2, industrialization, financial development, energy consumption, and urbanization had a significantly positive association with CO_2 emissions. However, foreign direct investment was significantly negatively related to the emission of CO_2. This finding implies that as industrialization, financial development, energy consumption, and urbanization increased or decreased, CO_2 emissions also increased or decreased in the same proportion and *vice versa*. However, a rise in foreign direct investment resulted in a fall in CO_2 emissions and *vice versa*. Overall, the outcomes from the correlation matrix signify a potential positive impact of industrialization, financial development, and foreign direct investment on the emissions of CO_2 in East Africa.

4.2 Cross-sectional dependence and heterogeneity analysis

East African countries are connected economically, socially, culturally, and politically. These connections could cause

TABLE 5 Unit root and co-integration test results.

Unit root tests								
Variable	CIPS				CADF			
	Level	Decision	1st Diff	Decision	Level	Decision	1st Diff	Decision
$\ln CO_2$	−3.159	I(0)	−4.778***	I(1)	−3.11 4	I(0)	−4.339***	I(1)
lnIND	−4.667	I(0)	−5.707***	I(1)	−2.856	I(0)	−3.354**	I(1)
lnFD	−3.848	I(0)	−4.223***	I(1)	−4.772	I(0)	−6.765***	I(1)
lnFDI	−5.212	I(0)	−3.776**	I(0)	−2.116	I(0)	−2.996*	I(1)
lnURB	−2.449	I(0)	−2.919**	I(1)	−3.891	I(0)	−4.897***	I(1)
lnEC	−3.996	I(0)	−4.421***	I(1)	−4.446	I(0)	−6.997***	I(1)

Westerlund and Edgerton co-integration test				
Value	statistic	Z-value	p-value	Robust p-value
Gt	−1.097	4.050	0.046**	0.019**
Ga	−0.063	5.682	0.025**	0.008***
Pt	−1.454	4.570	0.077*	0.029**
Pa	−0.335	3.621	0.027**	0.006***

Bayer–Hanck co-integration test Fisher			
statistic	Test value	Critical value (5%)	Co-integration decision
EG-JOH	23.423**	10.576	Yes
EG-JOH-BAN-BOS	44.645**	20.143	Yes

Notes: EG, JOH, BAN, and BOS represent Engle and Granger (1987), Johansen (1991), Banerjee et al. (1998), and Boswijk (1995) co-integration tests; however, ***, **, and * denote significance at the 1%, 5%, and the 10% levels, respectively.

TABLE 6 Cross-sectional ARDL (CS-ARDL) estimation results.

Variable	Coefficient	z	p-value
lnIND	5.237	2.93	0.003***
lnFD	3.322	3.57	0.007***
lnFDI	2.069	4.04	0.006***
lnURB	2.418	3.37	0.032**
lnEC	3.232	4.19	0.008***
ECT	−0.645	−2.07	0.005***
F-statistic	171.34 (0.006)***	CD-statistic	−1.18 (0.869)
R-squared	0.85	RMSE	0.02

*Notes: *** and ** denote significance at the 1% and 5% levels, respectively.*

cross-sectional correlations amongst them, leading to unreliable estimates if they are ignored in panel regression analysis. To do away with the demerits of such negligence, the study first tested for dependencies or otherwise in the panel. The test output, shown in Table 4, validates dependencies, aligning with that of Musah et al. (2020), Agyemang et al. (2021), Phale et al. (2021), Donkor et al. (2022), Musah (2022), and Musah et al. (2023). This implies that a major effect on one nation may spill over to others due to strong ties existing between the nations. After the CD test, it was worthwhile to examine heterogeneity in the slope coefficients since its negligence could yield biased results. Therefore, the Pesaran–Yamagata test shown in Table 4 was performed. Revelations from the test confirmed heterogeneity in the slope coefficients, aligning with those of Schmidt et al. (2015), Musah et al. (2020), and Chen et al. (2022).

4.3 Unit root and co-integration analysis

At the third phase, the tests for stationarity exhibited in Table 5 were performed to examine the variables' integration properties. Based on the estimates in the table, all the variables possessed an I(1) integration order. This finding supports the studies of Sun et al. (2021), Kong et al. (2023), and Wu et al. (2023). The variables' order of integration suggests a potential co-integration amidst them; hence, the co-integration tests depicted in Table 5 were conducted to examine the series' co-integration attributes. From the results, there was a co-integration association amidst the series aligning with the studies by Sun et al. (2019), Musah et al. (2021), and Sun et al. (2022). This shows that estimating the long-term elasticities of the predictors was well in line.

4.4 Regression analysis

4.4.1 Regression results

Having affirmed a co-integration association amidst the series, the elastic effects of the regressors on the regressand were then estimated. Based on the CS-ARDL results shown in Table 6, industrialization promoted CO_2 emissions in East Africa by 5.237%, validating the study's hypothesis. In addition, development in the financial sector escalated CO_2 emissions by 3.322%. In addition, urbanization harmed the environmental quality by spurring CO_2 emissions by 2.418%. Similarly, energy consumption positively explained CO_2 emissions by 3.232%. Moreover, foreign direct investment promoted CO_2 emissions by 2.069%. Finally, the negative and significant coefficient of the ECT, with a value of −0.645, indicates that the annual speed of adjustment from disequilibrium to equilibrium was 64.5%. In addition, the model had a very high predictive power based on the significant F-statistic value. Additionally, the R^2 value of 0.85 signifies that the predictors accounted for 85% of the variations in the response variable, and the RMSE value of 0.02 shows that the model was accurately specified. Finally, the trivial CD test statistic implies that CD issues have been minimized after adopting the CS-ARDL technique.

4.4.2 Discussion of the results

According to the regression estimates, industrialization had a significantly positive effect on CO_2 emissions in East Africa. Ceteris paribus, a percentage rise in industrialization raised CO_2 emissions by 5.237%. This is expected as the region is now dominated by carbon-intensive industries relying on dirty fuels. Moreover, the majority of the East African countries are at lower developmental levels. Progress in industrialization at these levels leads to technological transitions and variations in energy utilization models, resulting in higher energy utilization and, therefore, more CO_2 emissions. To enhance environmental safety, industries in the region should embrace environmentally friendly practices in their undertakings. For instance, if clean energies, green technologies, and energy-efficient practices are incorporated into the industrial activities of the region, environmental quality will be enhanced. This finding corroborates with the studies of Akinsola et al. (2022) and Patel and Mehta (2023) but contrasts with those of Mehmood et al. (2024) and Nkemgha et al. (2023).

In addition, financial development positively predicted CO_2 emissions in East Africa. All factors held constant; a 1% rise in financial development escalated CO_2 emissions by 3.322%. This finding is not disputable because the financial system of the region helped industries access low-cost financial facilities to purchase machinery and equipment to boost their operations. However, these items are reliant on energies from polluting sources, consequently increasing emissions in the region. Moreover, the financial sector of the region boosts the financial status of the households, enabling them to go for energy-consuming products like automobiles, air-conditioners, refrigerators, and washing machines, among others, thereby raising the level of pollution in the region. To promote environmental quality, the financial sector must encourage green finance activities. Financing renewable energy consumption, green technological innovations, energy efficiency, and research and development projects will enhance ecological sustainability in East Africa because such activities are not pollution-intensive. This finding contrasts with the study of Nyeadi (2023) that reported financial development as useful to the environment of middle-income economies in sub-Saharan Africa. The finding also conflicts with the studies of Safi et al. (2021) for 10 polluted economies, Abro et al. (2022) for Saudi Arabia, and Tao et al. (2023) for OECD economies. However, Gyimah et al. (2023) investigation on West Africa and Das et al. (2023) analysis on Bangladesh support this finding as they confirmed financial development as harmful to environmental quality.

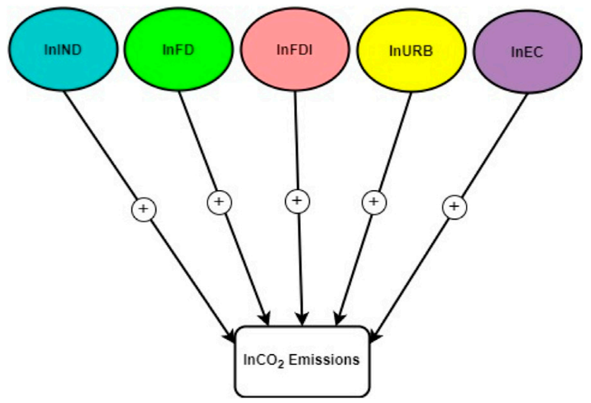

FIGURE 2
CS-ARDL estimation results. Note: (+) denotes positive influence on CO_2 emissions, while (–) represents negative influence on CO_2 emissions.

TABLE 7 Cross-sectional DL (CS-DL) and augmented mean group (AMG) estimation results.

Variable	CS-DL		AMG	
	Coefficient	*p*-value	Coefficient	*p*-value
lnIND	3.467	0.023**	2.208	0.079*
lnFD	2.182	0.043**	1.082	0.081*
lnFDI	1.072	0.018**	0.614	0.045**
lnURB	1.014	0.057*	0.858	0.089*
lnEC	2.168	0.038**	1.282	0.055*
F-statistic	132.99 (0.021)**		Wald chi2 114.12 (0.046)**	
R-squared	0.77		-	-
RMSE	0.04		RMSE	0.06
CD-statistic	−1.209 (0.731)		CD-statistic	−2.74 (0.655)

*Notes: ** and * denote significance at the 5% and 10% levels respectively.*

Moreover, foreign direct investment had a significantly positive effect on CO_2 emissions in West Africa. Ceteris paribus, a 1% rise in foreign direct investment promoted CO_2 emissions by 2.069%, supporting the PHH. This revelation suggests that countries in East Africa had weak environmental regulations, attracting carbon-intensive FDI influxes into the sub-region, causing high

TABLE 8 Pairwise Dumitrescu–Hurlin panel causality test results.

Null hypothesis	W-stat	Zbar-stat	Prob
lnIND ⇏ lnCO$_2$	2.949	4.274	0.002***
lnCO$_2$ ⇏ lnIND	3.034	4.469	0.008***
lnFD ⇏ lnCO$_2$	2.304	2.797	0.005***
lnCO$_2$ ⇏ lnFD	1.814	0.674	0.144
lnFDI ⇏ lnCO$_2$	4.851	2.533	0.034**
lnCO$_2$ ⇏ lnFDI	5.303	3.502	0.016**
lnURB ⇏ lnCO$_2$	3.909	6.475	0.001***
lnCO$_2$ ⇏ lnURB	1.417	0.131	0.673
lnEC ⇏ lnCO$_2$	3.178	4.799	0.002***
lnCO$_2$ ⇏ lnEC	4.292	2.262	0.001**
lnFD ⇏ lnIND	1.418	0.767	0.443
lnIND ⇏ lnFD	4.333	7.446	0.001***
lnFDI ⇏ lnIND	1.622	1.234	0.217
lnIND ⇏ lnFDI	4.126	6.971	0.003***
lnURB ⇏ lnIND	4.826	8.583	0.002***
lnIND ⇏ lnURB	22.261	48.519	0.004***
lnEC ⇏ lnIND	5.724	10.631	0.005***
lnIND ⇏ lnEC	5.434	3.212	0.073*
lnFDI ⇏ lnFD	2.712	3.731	0.002***
lnFD ⇏ lnFDI	3.522	5.588	0.046**
lnURB ⇏ lnFD	3.463	5.452	0.005***
lnFD ⇏ lnURB	12.508	26.173	0.033**
lnEC ⇏ lnFD	4.671	8.219	0.002***
lnFD ⇏ lnEC	1.422	0.776	0.438
lnURB ⇏ lnFDI	3.128	4.684	0.003***
lnFDI ⇏ lnURB	3.696	5.985	0.004***
lnEC ⇏ lnFDI	4.659	8.191	0.007***
lnFDI ⇏ lnEC	0.906	−0.406	0.685
lnEC ⇏ lnURB	20.576	44.658	0.009***
lnURB ⇏ lnEC	3.545	5.643	0.002***

*Notes: ⇏ signifies the null hypothesis that one variable does not homogeneously cause another variable; and ***, **, and * denote significance at the 1%, 5%, and 10% levels, respectively.*

CO$_2$ emissions. To minimize this menace, stringent environmental regulations should be formulated to manage foreign investments into the region. Moreover, authorities should ensure that foreign inflows into the region are linked to green energy generation, energy efficiency, technological innovations, and research and development initiatives that are useful to the environment. Amoah et al. (2023) confirmed foreign direct investment as harmful to environmental quality in 30 sub-Saharan African countries, while Beton Kalmaz and Adebayo (2023) affirmed this finding for BRICS economies. However, the studies of Adjei-Mantey and Adams (2023) for 29 sub-Saharan African economies, Wang et al. (2023) for 67 global economies, and Jahanger et al. (2022) for NAFTA countries affirmed foreign direct investment as beneficial to environmental quality.

Additionally, urbanization positively explained CO$_2$ emissions in East Africa. Specifically, a 1% rise in urbanization increased CO$_2$ emissions by 2.418%. This finding suggests that a high urban concentration drove emissions by increasing energy demand in both domestic and industrial sectors in the sub-region. In addition, the rise in urban population increases urban transportation, shooting up the level of energy consumption and thereby escalating emissions (Cheng et al., 2015).

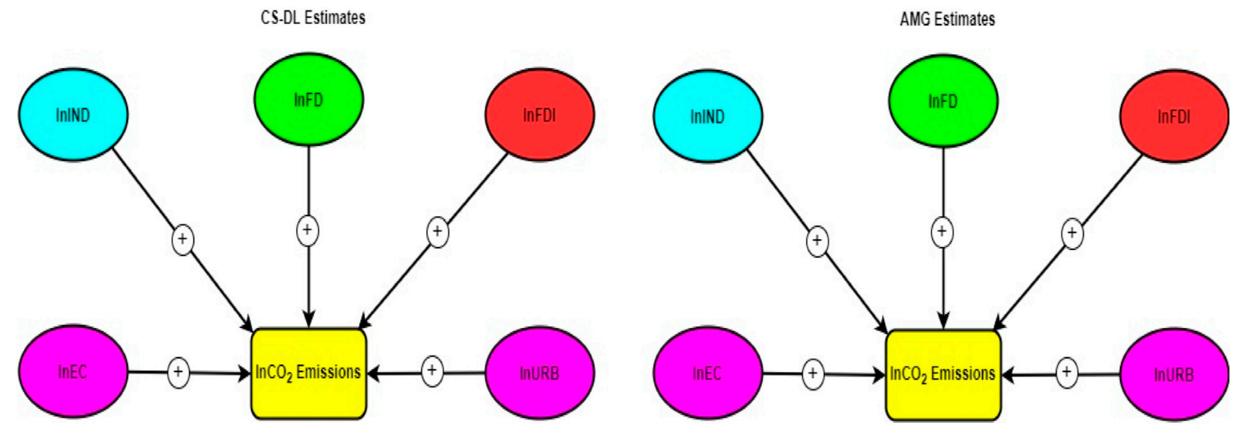

FIGURE 3
CS-DL and AMG estimation results. Note: (+) denotes positive influence on CO_2 emissions, while (–) represents negative influence on CO_2 emissions.

This aligns with the IPCC (2014) report, which indicates that the transportation sector in an economy is anticipated to add 14% to GHG emissions, with the major share coming from urban centers. The finding further suggests that individuals in the urban centers of East Africa adopted sophisticated and modern technologies that are more carbon-intensive due to their rising income levels, thereby offsetting environmental quality. Hussain et al. (2023) supported this finding by confirming urbanization as harmful to environmental quality in 54 African nations, while Opoku Marfo et al. (2023) reported a similar finding for Ghana. However, Khan and Khan (2023) found a nonlinear relationship between urbanization and environmental pollution in Belt and Road Initiative countries, while Tawfeeq (2023) discovered a negative association between urbanization and CO_2 emissions in the United States.

Finally, EC had a significantly positive effect on CO_2 emissions. All factors held constant; a 1% rise in EC promoted CO_2 emissions by 3.232%. This implies that energies used to drive economic activities in the region are dominated by fossil fuels, coal, and natural gas, among others, consequently escalating the rate of emissions in the bloc. Hence, energies from renewable sources should be adopted by countries in East Africa because such energies boost economic activities without negatively impacting the environment. The studies by Udemba and Agha (2020) for Nigeria and Li et al. (2021) for G20 economies support this finding by confirming EC as harmful to environmental quality. However, Rafei et al. (2022) investigation on weak-, medium-, and high-level institutional quality countries, Mentel et al. (2022) investigation on sub-Saharan Africa, and Fuinhas et al. (2017) investigation on Latin American countries, Kazemzadeh et al. (2023) comparative analysis on 94 economies, and Leitão et al. (2022) analysis on Portugal reported contrary outcomes. The elasticities of the CS-ARDL technique are illustrated in Figure 2.

4.4.3 Robustness checks

We conducted robustness checks via the cross sectionally augmented distributed lag (CS-DL) and the augmented mean group (AMG) techniques to confirm whether the results will be consistent across methodologies. From the discoveries shown in Table 7, industrialization worsened environmental quality by promoting more CO_2 emissions. Furthermore, financial development was not friendly to environmental quality as it escalated pollutant emissions in the bloc. In addition, urbanization, foreign direct investment, and energy consumption harmed environmental quality via more CO_2 emissions. Summarily, the coefficients under the CS-ARDL, AMG, and CS-DL techniques varied from those of the CS-ARDL technique in terms of weight. However, the sign or direction of the coefficients under the three methods was the same, validating the robustness of the results. The CS-DL and the AMG estimates are depicted in Figure 2.

4.5 Causality analysis

Finally, the causality tests shown in Table 8 are performed to examine the causal connections amidst the series. The causality results revealed a bidirectional relationship between IND and CO_2 emissions. This signifies that the series were mutually connected in the long term. Thus, any fluctuation in one variable affected the other variable reciprocally. In other words, the two variables had predictive powers of each other. Studies by Al-Mulali and Ozturk (2015) and Liu and Bae (2018) are in support of this finding; however, studies of Afawubo and Ntouko (2016), Silva et al. (2024), and Afawubo and Nguedam (2016) contrast with the above revelation. In addition, a causation effect of financial development on the emission of CO_2 was unraveled. A possible reason for this disclosure is that the stock markets in East African countries act as vital economic instruments that greatly boost the trust of businesses and consumers, thereby stimulating production and consumption activities. These actions contribute to high energy utilization and, subsequently, high emissions of CO_2 in the sub-region. Studies by Cetin et al. (2018) and Shahzad et al. (2017) support the above findings but those of Dogan and Turkekul (2016) and Zaidi et al. (2018) conflict with the study's disclosure (Figure 3.

Further, a reciprocal association between foreign direct investment and CO_2 emissions was discovered. This implies that the series were conjointly related. Thus, a surge in foreign inflows resulted in a rise in the countries' CO_2 emissions and *vice versa*. This implies that reducing the rate of emissions will also lead to a reduction in FDI inflows into the sub-region, supporting the studies by Balsalobre-Lorente et al. (2019) and To et al. (2019).

In addition, a causality effect of urbanization on the emission of CO_2 was discovered. This signifies that a rise in urban concentration negatively affected environmental quality in East Africa by raising the emission of CO_2. The intensity of the effects might, however, vary amidst the nations depending on the rate of energy utilization and economic structure among others. The growth in urban population usually results in increased demand for electricity, food, water, and properties, among others. As a result, available natural resources are strained, and their regenerative ability is reduced, resulting in more environmental degradation. An investigation by Liu and Bae (2018) supports the above revelation; however, those by Afridi et al. (2019) and Khoshnevis and Dariani (2019) are in contrast to the study's discovery. Additionally, EC and CO_2 emissions were strongly interlinked. This insinuates that an increase in energy consumption mutually reinforced environmental pollution in the sub-region and *vice versa*. In other words, the two variables are predictive of each other. Research studies by Saud et al. (2019) and Sun et al. (2022) align with the exploration's discovery; however, those of Cetin et al. (2018) and Shahzad et al. (2017) conflict with the above disclosure.

5 Conclusions and policy recommendations

5.1 Conclusions

Environmental pollution in East Africa has been on an ascending trend. This has called for more studies to be conducted to help raise policy options to reverse the situation. To help in fulfilling this goal, we examined the association between industrialization and environmental quality (measured by CO_2 emissions) in East Africa over the period from 1990 to 2019. The study employed second-generation econometric techniques resilient to cross-sectional correlations, heterogeneity, and endogeneity. From the findings, there were heterogeneity and cross-sectional correlations in the studied panel. In addition, the studied series were integrated in order I(1) and were flanked by a long-term co-integration association. The parameters of industrialization, financial development, foreign direct investment, urbanization, and energy consumption were estimated via the CS-ARDL, AMG, and CS-DL techniques. According to the results, industrialization had a positive effect on CO_2 emissions. This suggests that industrialization harmed environmental quality in East Africa. Moreover, financial development positively predicted CO_2 emissions in the region, implying that development in the financial sector deteriorated ecological sustainability in East Africa. Moreover, foreign direct investment positively explained CO_2 emissions in the region. This means that the inflow of foreign investments worsened environmental safety in East Africa. Finally, urbanization and energy consumption spurred CO_2 emissions in the studied countries. This suggests that the rise in urbanization and energy utilization harmed the environmental quality in the region. On the causalities between the variables, bi-directional causalities between industrialization and CO_2 emissions, financial development and CO_2 emissions, and foreign direct investment and CO_2 emissions were disclosed. Finally, unidirectional causality effects of urbanization and energy consumption on CO_2 emissions were uncovered.

5.2 Policy implications

According to the results, industrialization escalates CO_2 emissions in East Africa. This means that industrial activities undertaken in the region harm environmental sustainability. Therefore, serious industrial restructuring should be considered if the region is to attain energy conservation (SDG 7), sustainable development (SDG 8), and emission mitigation (SDG 13) targets. This supports the postulation of Zhou and Li (2020), stating that the implementation of industrial restructuring policies is beneficial for the economic advancement and emission minimization goals of different economies. Additionally, national policies promoting energy conservation at the industrial level and transitioning the industrial structure of East Africa from carbon-intensive to low carbon-intensive should be formulated. In other words, green and sustainable industrial policies should be embraced by all nations in the bloc (Majeed and Tauqir, 2020). To curb the adverse effects of industrialization, the level of green energy should be raised in the countries. This goal could be attained by channeling more investments in infrastructural developments required for renewable energy production.

In addition, financial development promotes CO_2 emissions in East Africa. This suggests that advancement in the financial sector worsens environmental quality in the bloc. Hence, financial institutions in the region should channel their investments into activities that are friendly to the environment. For instance, financing renewable energy generation and consumption, energy efficiency, technological innovations, and ecologically harmless research and development projects can help improve the environmental quality in East Africa. In addition, financial regulatory bodies should identify means of directing financial growth into environmentally sustainable frameworks. This supports the opinion of Gokmenoglu and Sadeghieh (2019).

Likewise, foreign direct investment promoted CO_2 emissions in East Africa. This implies that the inflows of foreign investments harmed environmental safety in the region. Therefore, governments in East Africa should encourage ecologically harmless foreign direct investments into the bloc. In addition, the influxes of foreign investments should be used to promote clean energy generation, green technological innovations, energy efficiency, and research and development initiatives that are useful to the environment. In addition, good governance should be exhibited in East Africa. This will reduce the corruption that arises when authorities trade off environmental quality for carbon-intensive influxes of FDI. Moreover, when good governance is displayed, appropriate legislation that could encourage the consumption of clean energy with minimal environmental complications will be formulated for the populace and the business community in the region. Furthermore, imposing dumping duties on entities in East Africa would deter the importation of dangerous goods that could damage the environment. Through improved human capital and infrastructure growth, nations in the region can also promote environmentally friendly investments.

Similarly, urbanization escalated CO_2 emissions in East Africa. This implies that the migration of people from rural to urban centers damaged environmental quality in the region. Therefore, authorities in East Africa should encourage people to adopt energy-efficient and low-carbon lifestyles in urban areas. Furthermore, nations experiencing rapid urbanization in the region should take proactive measures to develop their public infrastructure in order to capitalize on the urban agglomeration effects. In addition, green and sustainable policies should be implemented by all the nations to help maintain environmental quality in the region. This could be achieved by diverting internal migrants from large cities to small- and medium-sized cities through the provision of planned and controlled resources. Additionally, balanced development in both urban and rural areas could be done in an attempt to further minimize the negative effects of urbanization in the countries (Majeed and Tauqir, 2020).

Finally, energy consumption promoted CO_2 emissions in East Africa. Hence, the energy-saving strategies of the country should concentrate on increasing energy production via technological advancements. Low-carbon energy production should also be captured by the policies. To control the adverse environmental influences of energy, the share of renewable energy needs to be increased by investing in infrastructural developments that are linked to the production of renewable energy in the sub-region. Finally, offering tax rebates, interest rate holidays, and other types of assistance to businesses that embrace green energy in their undertakings could help advance environmental quality in the bloc.

6 Limitations and future research directions

Even though the study achieved its purpose of examining the environmental impacts of industrialization on environmental quality, some limitations were still encountered. First, the researchers intended to use a very long period for the analysis, but due to data constraints, the study was confined to the period from 1990 to 2019. Therefore, in the future, when more data become available, similar studies could be conducted to compare our study's outcomes. The study was also confined to only countries in East Africa. This implies that the results cannot be generalized for all economies in Africa. For comparison purposes, future explorations should be expanded to cover nations in other parts of Africa. Moreover, controlling for other macroeconomic factors like inflation, interest rate, and exchange rate, among others, in future investigations could bring valuable contributions to the field. In addition, accounting for the role of green energy and green innovations in the link between industrialization and environmental quality in East Africa could help drive the emission mitigation agenda of the region. Finally, further studies should consider employing nonlinear panel models to investigate the associations amidst the series. With reference to the above, we raise the following key questions for future research in this study area: 1) what other macroeconomic factors could be used to augment the industrialization–environmental quality connection? 2) Do green energy and green innovations matter in the link between industrialization and environmental quality? 3) What nonlinear panel models could be used to investigate the association between industrialization and environmental quality?

6.1 Definition of terms

CO_2 emissions: According to the Global Climate Change (2024), CO_2 emission is an important heat-trapping gas that comes from the extraction and burning of fossil fuels (such as coal, oil, and natural gas), wildfires, and natural processes like volcanic eruptions. The World Bank (2024a) also views CO_2 emissions as the emissions stemming from the burning of fossil fuels and the manufacture of cement. They include carbon dioxide produced during the consumption of solid, liquid, and gas fuels and gas flaring.

Industrialization: Industrialization is the process of transforming the economy of a nation or region from a focus on agriculture to a reliance on manufacturing (The Investopedia Team, 2023). Mechanized methods of mass production are an essential component of this transition. The positive characteristics of industrialization include economic growth, a more efficient division of labor, and a growth spurt in technological innovation (The Investopedia Team, 2023).

Financial development: According to the World Bank (2024b), financial development occurs when financial instruments, markets, and intermediaries ease the effects of information, enforcement, and transaction costs and, therefore, do a correspondingly better job at providing the key functions of the financial sector in the economy.

Foreign direct investment: Foreign direct investment (FDI) is a category of cross-border investment where an investor resident in one economy establishes a lasting interest in and a significant degree of influence over an enterprise resident in another economy (OECD Library, 2023). FDI is an important channel for the transfer of technology between countries, promotes international trade through access to foreign markets, and can be an important vehicle for economic development (OECD Library, 2023).

Urbanization: According to the Environmental Protection Agency (2024) of the United States, urbanization refers to the concentration of human population into discrete areas. This concentration leads to the transformation of the land for residential, commercial, industrial, and transportation purposes. Urbanization is influenced highly by the notion that towns and cities have better conditions of service compared to rural areas.

Energy Consumption: According to IEA statistics, energy use refers to the use of primary energy before transformation to other end-use fuels, which is equal to indigenous production plus imports and stock changes, minus exports and fuels supplied to ships and aircrafts engaged in international transport. It includes energy from combustible renewables and waste—solid biomass and animal products, gas and liquid from biomass, and industrial and municipal waste (IEA statistics, 2014).

Data availability statement

Publicly available datasets were analyzed in this study. These data can be found at: https://databank.worldbank.org/source/world-development-indicators.

Author contributions

YY: conceptualization, writing–original draft, and writing–review and editing. JZ: conceptualization and writing–review and editing. MO-A: data curation and writing–original draft. JN: formal analysis and writing–original draft. JL: methodology and writing–review and editing. GA: supervision and writing–original draft. EK: methodology and writing–original draft. YX: methodology and writing–original draft. LW: methodology and writing–original draft. CH: data curation and writing–original draft. KL: conceptualization, writing–original draft, and writing–review and editing.

Funding

The author(s) declare that no financial support was received for the research, authorship, and/or publication of this article.

Conflict of interest

Author JL was employed by Jiangsu Broadcasting Cable Information Network Corporation Limited.

Author KL was employed by the Division of State-Owned Enterprise Reform and Innovation.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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