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Nexus between trade and environmental quality in sub-saharan Africa: Evidence from panel GMM

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Environmental sustainability is a burning fact worldwide, especially in developing nations. Equitable economic development, environmental protection, energy efficiency and security have been placed at the apex of economic discussant and policy formulation. This paper establishes the relationship between trade and environmental quality in Sub-Saharan Africa (SSA). Following the Environmental Kuznets Curve (EKC) theory, we investigate the existence of an inverted U-shape correlation between income per capita growth and nitrous oxide (N_2O), agricultural methane (ACH_4), and carbon dioxide (CO_2) emissions to ascertain the presence of EKC. We also analyze how trade variables, income per capita growth, energy intensity, foreign direct investment, human capital, and CO_2 emissions are related. The results show that trade significantly increases N_2O, ACH_4, and CO_2 emissions for the overall sample of SSA and its income groups [Upper-Middle-Income Countries (UMIC), Lower-Middle-Income Countries (LMIC), and Low-Income Countries (LIC)] using a panel GMM. This paper concludes that reducing emissions is feasible in the future as shown by the existence of the EKC, and trade has a consistently negative impact on the environment in SSA countries, regardless of wealth level. On the policy note, the study suggested that domestic trade liberalization and foreign ownership in the economy play a detrimental role, and thus industrialization has to ensure energy efficiency and energy security.

KEYWORDS
environmental quality, trade, energy intensity, foreign direct investment, environmental kuznets curve

1 Introduction

Sub-Saharan Africa's economic and social status is still precarious and open to internal and foreign shocks. Economic diversification and development are hampered because of the low level of investment (Bangwayo-Skeete, 2012). Many nations have just recently emerged from civil wars that severely hampered their development efforts, while new armed conflicts have started elsewhere in the continent (Chakraborty and Basu, 2002). Economic growth has slowed in the area during the last two decades because of these wars and other reasons, such as bad weather and a decline in terms of trade (Syed et al., 2022). Despite recent economic growth improvements, the subcontinent continues to struggle to reduce poverty, with little or no better housing amenities, insufficient formal education and/or low quality of education, poor health leading to short life expectancies, and so on. Trade is one of the methods or strategies that can be used to achieve growth. On the other hand, some scholars believe that trade aids economic growth (Dollar and Kraay, 2003; Ferdaous and Qamruzzaman, 2014; Mia et al., 2014; Qamruzzaman and Ferdaous, 2014; Hye and Lau, 2015; Musila and Yiheyis, 2015; Gnangnon, 2020). But the real question is how much will it cost? Even though SSA needs economic growth, we must not lose sight of the need for long-term growth. Accordingly, growth that considers environmental quality must be a top priority. This highlights the link between trade and the environment in Sub-Saharan Africa.

Researchers are primarily interested in investigating the environmental Kuznets curve (EKC) because they want to learn more about the relationship between income and pollution (see (Stern, 2004; Qamruzzaman, 2022a; Zhao and Qamruzzaman, 2022)). The EKC hypothesis can be traced back to Kuznets (Kuznets, 1955), who proposed that income disparity rises in the early years of economic expansion and falls as the economy grows. Grossman and Krueger (Grossman and Krueger, 1991) were the first to use the EKC hypothesis. They discovered a similar inverse U-shaped relationship between environmental deterioration and GDP per capita. The current research validates the existence of the EKC SSA region, but at various moments in time (in percentages). Because of the economic research on the relationship between CO_2 emissions and trade openness, there are major concerns among policymakers, economists, and the general public. Trade between countries has increased significantly since establishing the "General Agreement on Tariffs and Trade" (GATT), eliminating trade barriers and boosting trade liberalization. Similarly, the creation of the World Trade Organization (WTO) as a replacement for GATT has boosted global trade tremendously. The establishment of the "Commerce Facilitation Agreement" (TFA) (WTO, 2017) is the most recent approach to promoting global trade. It is expected to enhance global trade by one trillion dollars annually, with developing nations reaping the greatest benefits. However, the TFA's main concern is the long-term effects of negative externalities. Carbon emissions in global supply value chains are increasing quicker than some economic measures, such as real income or population growth (Peters et al., 2011). We know from economic theory that increased commerce leads to increased economic growth. Furthermore, increased economic expansion could harm the environment due to emissions into the atmosphere. As a result, affected countries will be expected to use environmentally friendly production processes to improve environmental quality.

Countries benefit economically from trade, using their comparative advantage to create and trade goods and services. The value of global merchandise exports surged more than 260 times from $59 billion in 1948 to $15.5 trillion in 2016, and a country's exports now account for 29 percent of its GDP (WTO, 2017). While globalization has advantages in terms of trade, it also has unintended effects on economies and the environment. Sub-Saharan African countries are vulnerable to climate change's effects, with substantial risks of weather-related natural disasters such as storms, flooding, and droughts. These African countries have inadequate capacity to regulate, mitigate and adapt to these negative impacts. The wide-ranging effects of such incapacity impact trade and economic growth. The dispute over whether the trade is good or detrimental to the environment has sparked a discussion among academics. Environmental and trade economists have yet to agree on whether the trade is beneficial or harmful to the environment. The relationship between the environment and international trade is extremely complicated, with numerous variables that can lead to a favorable or bad outcome. The theoretical literature on the impact of commerce on pollution levels yields conflicting results. When disparities in environmental policy models are used to cause commerce between countries, according to Helbling, Batini (Helbling et al., 2005), there could be an increase in emissions after liberalization. On the other hand, when Models that leverage differences in endowments to promote trade between countries are used, they imply that emissions drop after liberalization (Hamid et al., 2022a).

According to the findings of several academics, trade openness is linked to lower pollution levels Antweiler, Copeland (Antweiler et al., 2001), (Cole and Elliott, 2003; Frankel and Rose, 2005; Sun et al., 2021) used panel cointegration methods to investigate the relationship between trade openness and carbon dioxide emissions (CO_2). Their research revealed that trade openness could have both detrimental and good effects on environmental pollution emissions, but the consequences varied depending on the type of country. Boleti, Garas (Boleti et al., 2021) used annual data from 88 industrialized and developing nations from 2002 to 2012 to investigate the link between economic complexity and environmental performance. Their findings suggested that increasing economic complexity could lead to improved environmental performance and, as a result, that product sophistication did not increase environmental degradation. However, they discovered a positive association between economic complexity and air quality, which means increased exposure to PM2.5 and CO_2 emissions. Pei, Sturm (Pei et al., 2021) built a unique micro dataset for China for 2007, combining two rich firm-level datasets, and discovered that export status and export intensity were associated with decreased sulfur dioxide (SO_2) emissions. In both the total sample of Sub-Saharan Africa and its subgroups, trade considerably increases nitrous oxide (N_20), agricultural methane (ACH_4), and carbon dioxide (CO_2) emissions, according to the current study (UMIC, LMIC, and LIC). Even though trade degrades the environment in the total sample of Sub-Saharan Africa, the impact on the environment, in the long run, is relatively stronger in the LMIC than in the UMIC and LIC for all environmental variables, according to the current study (N_2O, ACH_4, and CO_2). In the short term, the estimates show that trade increases all emissions (N_2O, ACH_4, and CO_2) in the general sample of SSA, UMIC, and LMIC; however, trade increases CO_2 emissions while decreasing N_2O and ACH in the LIC. This may give policymakers sufficient knowledge of the types of trade and environmental rules that should be enacted in various countries. However, as evidenced by the presence of the EKC, this study implies that future reductions of such emissions are possible.

When it comes to studies on trade and environmental quality, there is no one-size-fits-all approach. To assess these correlations, researchers employed a variety of contaminants and methodologies. However, it is important to know that regional variables must be considered regarding global pollutants like CO_2, Nitrous Oxide (N_2O), and Agricultural Methane (Agricultural CH4). To uncover the empirical data on the impact of trade on environmental quality in SSA, it is critical to pose the following questions: (i) Has trade had a bad or good influence on the environment in Sub-Saharan Africa? (ii) Is commerce the primary source of GHG emissions in Sub-Saharan Africa? (iii) How does energy intensity affect emissions in Sub-Saharan Africa? (iv) Are we pursuing the correct type of trade that will result in long-term economic growth? Accordingly, the purpose of this study is to answer these crucial questions.

The current study uses the traditional KAYA identity to examine the impact of trade and energy consumption on CO_2, N_2O, and ACH_4 emissions as proxies for greenhouse gas emissions. The KAYA identity states that a total CO_2 emission can be expressed as the product of four factors: human population, per capita GDP, energy intensity (per unit of GDP), and carbon intensity measured as emissions per unit of energy consumed (Yamaji et al., 1993; Kaya and Yokobori, 1997). It is a more concrete version of the more general I=PAT Equation, which connects variables that affect the degree of human effect on climate change. In this case, the base KAYA or I=PAT model regresses CO_2 emissions on population, energy intensity, and per capita GDP (Apergis and Payne, 2010; Sharif Hossain, 2011; Arouri et al., 2012; Bölük and Mert, 2014; Farhani et al., 2014). Some researchers have recently proposed changing the KAYA or I=PAT paradigm (Iwata et al., 2010; Jayanthakumaran et al., 2012; López-Menéndez et al., 2014; Dogan and Deger, 2016). This study regresses GHG emissions (CO_2, N_2O, and ACH4) on trade, income per capita growth, energy intensity, foreign direct investment, and human capital, which modifies the KAYA model. The inclusion of trade (natural resource earnings) demonstrates that trade can explain some fluctuations in emissions (CO_2, N_2O, and ACH_4) while avoiding the problem of variable omission bias as well. An increase in commerce (as a proxy for natural resource earnings) may increase natural resource exports which may, in turn, enhance economic activity and necessitate additional energy supply. The inclusion of trade to explain the variations in GHG emissions is significant because global trade rises while GHG emissions fall, especially in advanced countries (Managi et al., 2009).

The current focus in the environment-resource-growth literature is on resource dependency or abundance, not only in economic growth but also in terms of greenhouse gas emissions and climate change. In brief, the current study adds to the existing body of knowledge in the environment-resource-growth literature in the following ways:

First, most recent studies have analyzed the effects of trade (natural resources) on greenhouse gas emissions using resource dependence or abundance (GHGs). Brunnschweiler (Brunnschweiler, 2010) questioned Sachs and Warner's 1995) findings by claiming that a commonly used measure of resources, the ratio of resource exports to GDP, is endogenous. As a result, dividing exports by the size of the economy implies that the ratio is not independent of a country's economic policies and institutions, which affect both GDP level and growth. In light of the preceding evidence, we chose the "Natural Resources Revenues" proxy to avoid issues with measuring trade openness, particularly in the SSA region, where exchange rates are frequently volatile and can alter the assessment of imports and exports GDP.

Second, previous empirical research on the consequences of commerce on the environment has been conducted. However, to our knowledge, the present literature solely focuses on the panel studies conducted at the regional level of Sub-Saharan Africa. Because these pollutants are global, our research looked at the effects of trade (using a proxy of natural resource revenues) on CO_2, Nitrous Oxide (N_2O), and Agricultural methane (agricultural CH_4) emissions for both Sub-Saharan Africa and its subgroups based on their income levels to examine both the short-term and long-run relationships, using the dynamic panel and vector error correction models. To the best of our knowledge, no study has looked into the relationship between trade and N_2O and agricultural CH_4 using a panel of Sub-Saharan African countries with different economic levels. Although a few country-specific studies have attempted to investigate the relationship between trade and emissions in general, none of these studies has looked at the impact of trade on specific emissions like N_2O and agricultural CH_4 using data from a panel of Sub-Saharan African countries. This analysis is more fascinating by including Sub-Saharan Africa and categorizing countries based on income levels. The division of SSA into income groups also reveals which countries pollute the most; it also reveals that each group of countries requires different policies and a variety of policy techniques to improve the environmental quality while clarifying which group of countries should prioritize mitigation policies and which group requires more support in terms of mitigation and adaptation policies (Hamid et al., 2022b).

Third, as other scholars have done, the Environmental Kuznets Curve's turning points are measured in percentages rather than dollars. This is made possible by including an income per capita growth variable in our model, measured in percentages rather than the traditional income per capita. As a result of this strategy, this study determines the various percentage threshold levels of EKC turning points at which the countries' economic growth should begin to reduce, resulting in improved environmental quality. As a result, this study adds to the body of knowledge in the areas of commerce (natural resource earnings) and greenhouse gas emissions in sub-Saharan African countries. To our knowledge, the previous research on this topic focused on monetary turning points rather than percentage turning points. Therefore, the current study brings a unique contribution to the literature in existence by identifying this percentage turning point, at which countries' growth should be focused on the improvement of the air quality. This study validates the occurrence of EKC in SSA and its subgroups band. Thus, the current study adds to the previous literature by demonstrating the presence of multiple EKC percentage turning points for a reduction in greenhouse gas emissions.

Furthermore, the present paper is a comprehensive study of the short-term and long-run effects of trade on CO_2, N_2O, and ACH_4 emissions, as well as the use of natural resource revenues as a proxy for trade rather than the traditional resource abundance/dependence variable, establishing the EKC turning points in percentages rather than the traditional monetary terms and covering the entire SSA and grouping countries into income levels.

The remainder of the paper is laid out as follows: the second section provides an overview of trade and the environment in Sub-Saharan Africa. The Literature Review is included in Section 3. The Methodology is covered in Section 4. Section 5 discusses the presentation and interpretation of the results, while Section 6 gives policy recommendations and conclusions.

1.1 Overview of trade and the environment in sub-saharan Africa

The recent economic expansion in Sub-Saharan Africa is thought to have resulted in "greater exploitation of renewable natural resources beyond their regenerative potential and by increasing GHG emissions." Natural resource-based industries, such as mining, agriculture, forestry, and fisheries, employ 80 percent of the workforce. Similarly, agriculture accounts for over 33% of Africa's GDP. The export and/or use of natural resources such as forestry products, topsoil, and fish stocks have been linked to the African region's recent growth, sometimes at alarming rates.

In SSA, population growth has been tremendous, posing severe environmental and socio-economic issues. This places a lot of pressure on governments to provide services like health and education and citizens' jobs. It will be difficult for governments to raise living standards and reduce unemployment without high economic growth rates. As a result of the rapid population expansion, local natural resources such as water, fuel, and food are under stress. Though demographic development provides an opportunity, it also poses severe obstacles for governments in SSA to provide for their citizens, particularly regarding the environment. In several SSA nations, the negative implications of the recent economic progress outstrip the local government's capacity to deal with such consequences. Waste collection and sanitation systems cannot handle the volumes of waste generated by such economic activities, resulting in significant degradation of the urban and aquatic environments. According to Skellern, Markey (Skellern et al., 2017), though the manufacturing industry boosts economic growth, some countries overlook its development's environmental implications or challenges. There are, for example, insufficient environmental restrictions, and/or they are frequently not applied to the expansion of the manufacturing and extractive industries in SSA, resulting in water, air, and land pollution as well as ecosystem damage. These are the negative effects of globalization, which are hard to deal with, hence the urgency of the present research (Murshed et al., 2022).

Globalization has increased international trade's scale and complexity to unprecedented levels. There has been a movement in the production of goods and services in recent years, first to China, then to other developing countries in the global south (Jiang (Jiang and Green, 2017; Jianguo and Qamruzzaman, 2017; Qamruzzaman, 2022b). Chinese industrial businesses have recently begun to move their operations to SSA countries. However, consequences such as greenhouse gas (GHG) emissions and water use have shifted to less developed countries, particularly SSA (Liu et al., 2017). From 1.26 in 1995 to 1.43 in 2008, the average frequency of carbon embodied in traded items crossing borders rose (Zhang and Cheng, 2009).

Pollution or degradation of the environment is one of the most important concerns that developing countries, particularly in SSA, must address. The majority of SSA countries' economies are growing at a cost. In Nigeria, for example, crude oil is the primary source of foreign cash as national revenue. The erosion and pollution of the environment have become the people's sorrow due to the ongoing drilling in oil-rich areas of the Niger Delta. Gas is continuously burned, degrading the quality of the atmosphere. Oil leaks have made it difficult for inhabitants in these locations to carry out their farming activities; also, the water in the streams is no longer fit for human use.

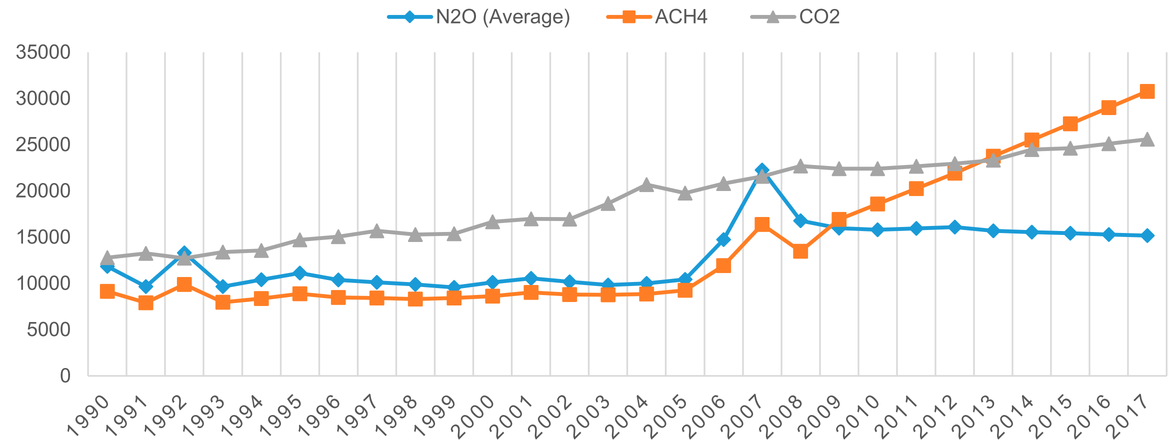

FIGURE 1
Nitrous Oxide (N_2O), Agricultural Methane (ACH_4) and Carbon Dioxide (CO_2) emissions in Sub-Saharan Africa (on average). Source. World Bank data and author calculations.

According to statistics provided between 1973 and 2008, Nigerian gas and crude oil output as a percentage of GDP fluctuated between 21.1 and 37.5 percent (Otekunrin et al., 2021).

According to Yingjun et al. (2021), as a civilization's population grows, people of that society place great demands on finite resources such as land and other natural resources to survive. Most SSA countries began as agricultural economies, but as their economies evolved, they transitioned from rural to industrialized status. These developed societies consume more resources, putting a greater strain on the environment. Economic growth is achieved but at the cost of the environment. Air pollution, natural resource depletion, climate change, noise pollution, deforestation, and other environment-related issues accompany economic progress in many of these SSA countries. The two major issues the African continent faces are the failure to provide safe drinking water to an ever-increasing population and a lack of sanitation.

Figure 1 shows pollution as nitrogen oxide emissions (thousand metric tons of CO_2 equivalent), agricultural methane emissions (thousand metric tons of CO_2 equivalent), and CO_2 emissions (kt). However, in Figure 2, the variable used as a proxy for trade is NRR (measured in billions of dollars). Figure 1 shows that, on average, nitrogen oxide and agricultural methane emissions remained stable until 2005. Between 2005 and 2007, both emissions considerably increased before declining in 2008. After 2008, nitrous oxide emissions continued to reduce but at a slower rate, while the agricultural methane emissions quickly grew until 2017. CO_2 emissions, on the other hand, continued to rise. Figure 2 shows that the earnings obtained by Sub-Saharan African countries followed a similar pattern of nitrogen oxide and agricultural methane emissions on average. Despite some fluctuation, natural resource revenues generally climbed from 1990 to 2008 before declining in 2009. After 2009, the NRR increased until 2011, then declined. The link between trade and pollution could explain the same pattern in the two graphs. It can be seen from the graphs that nitrous oxide and agricultural methane emissions decreased between 2007 and 2009. This could be linked to a drop in commerce around the same period due to a financial crisis when the natural resource exports were severely impacted, and so were the entire economies of Sub-Saharan African countries.

2 Literature review

As more people use more fossil fuels, greater quantities of carbon dioxide (CO_2) are emitted into the atmosphere. These releases have started to alter the composition of the atmosphere significantly. 280 parts per million were the concentration of carbon dioxide in the atmosphere during the start of the industrial revolution. Today, concentrations have reached 360 parts per million (Tucker, 1995). Understanding the link between emissions and economics is a critical part of putting up worldwide restrictions since growing CO_2 concentrations have been identified as a significant contributor to probable global warming. Recently, climate change and global warming have become more detrimental to human well-being. There is speculation that increased economic activity and environmental deterioration are major contributors to environmental degradation (Alvarado and Toledo, 2017). The industrial structure of emerging nations links economic activity and environmental deterioration more damaging in these regions. Environmental degradation is the accumulated effects of economic expansion with the application of conventional energy consumption (Banday and Aneja, 2020), trade expansion (Alola, 2019), financial development (Acheampong

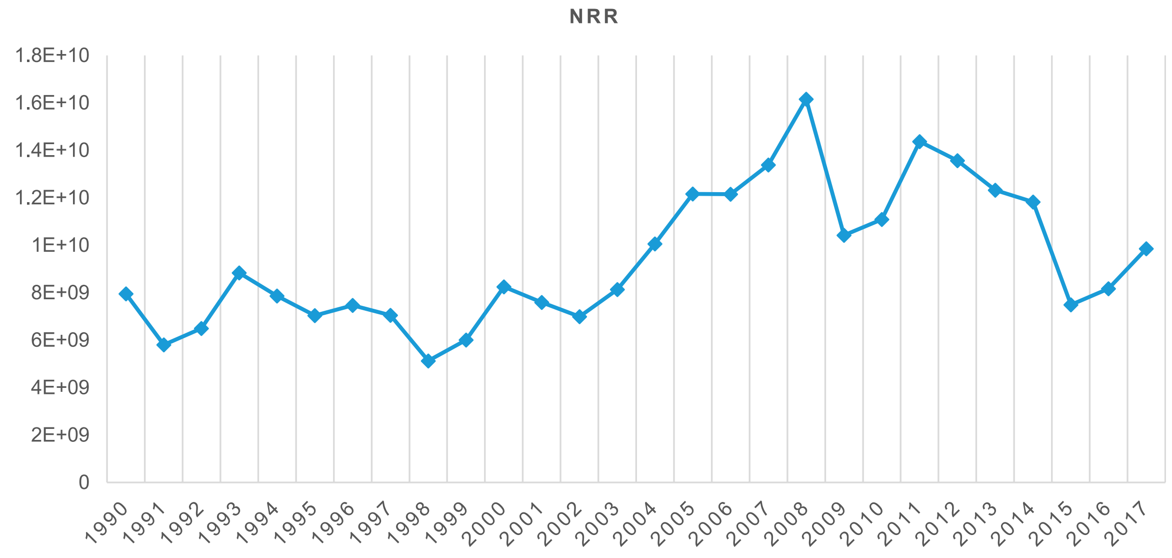

FIGURE 2
Natural Resources Revenues (NRR) in Sub-Saharan Africa (on average). Source. World Bank data and author calculations.

et al., 2020) and global economic and financial integration (Shahbaz et al., 2019). The elimination of national territory is a consequence of the current era of economic globalization, which must first be comprehended from an economic standpoint to be comprehended in its most comprehensive sense. The global economy is governed by unregulated market forces, most of which are multinational corporations located wherever the global market's greatest advantages. In contrast, the globalization process is not limited to the economic component; it also encompasses political, cultural, and environmental components (Eriksen et al., 2014).

Economic globalization not only realigns the global economy but also causes a worldwide redistribution of energy needs, population, and notably, the urban population, which is related to globalization's environmental and social components. The effects of globalization on human dynamics has investigated and established (Balsa-Barreiro et al., 2019). The environmental impact and economic development are both significantly altered by globalization. It has been prominently highlighted, which has prompted nations to cooperate more closely by eliminating cross-border obstacles and connecting global economies through FDI and trade openness (Vongpraseuth and Choi, 2015). Even if globalization benefits economies by fostering expansion, it negatively affects ecosystems (Khan and Ullah, 2019).

The causes of pollution are commonly thought to be the result of economic activity and growth, implying that a rise in output can lead to increased pollution levels in the atmosphere. However, the relationship between environmental deterioration and economic growth is a complex system that may react differently at different times and places. Some believe that economic expansion would eventually harm the environment, while others believe that after a certain point, economic progress can contribute to a cleaner environment (Dinda, 2004). The Environmental Kuznets Curve (EKC) arose from Simon Kuznets' research into the relationship between economic growth and income inequality. It was used to investigate the relationship between per capita income (PCI) and sulfur dioxide (SO_2) concentrations in the atmosphere in 47 cities across 31 countries (Elbadawi and Rocha, 1992). The relationship between PCI and sulfur dioxide content is positive up to a point, after which the trend reverses, forming an inverted U-shape curve.

The EKC's theoretical foundation is based on the repercussions of industrialization; it means a shift from agricultural commodity production in rural areas to industrial output in urban areas. Due to the intensification of industrial production activities, there will be an increase in pollution due to increased industrialization. However, when income levels rise, innovative technology to reduce emissions may become available. It is also thought that once economies develop to a certain point, these countries' economic activities will shift to the creation of services, slowing emissions and eventually reducing them. Furthermore, citizens will begin to campaign for a cleaner environment, which the political elite will take into account; this perhaps is leading to environmentally friendly policies and investments (Bashir et al., 2021). This scenario has been explained by three effects, scale, composition, and technology.

Copeland and Taylor (Copeland and Taylor, 2004) proposed the pollution haven hypothesis (PHH) to explain the impact of trade on the environment. According to the idea, if a country has strong environmental rules, companies in that country may be forced to migrate to a country with lenient environmental regulations and legislation. As a result, we can classify the PHH as a situation in which lax environmental rules provide a comparative advantage to countries and alter international trade patterns. Because of trade liberalization, and because many developed countries have a comparative advantage in producing pollution-intensive commodities, production of these goods could be shifted to developing countries, where environmental laws and regulations are believed to be less strict or poorly implemented. However, this could result in a reduction in one country's emissions while a rise in another, masking the impact of international commerce on emissions. The magnitude, composition, and technology effects completely explain the environmental implications of trade liberalization (Antweiler et al., 2001; Farhani et al., 2014). Because of worldwide trade, global production has been separated into "clean" or "green" and "dirty" productions (Jänicke et al., 1997). This phenomenon only causes local pollution to varying, whereas global pollution levels remain the same or even rise. The displacement hypothesis explains this. The "pollution haven theory" has various production regulations and costs, which can support the displacement hypothesis.

Several studies have developed models based on empirical and theoretical literature to investigate the environmental impact of trade liberalization. The impact of global trade on environmental sustainability plays a significant role in developing trade policies. Shahbaz, Nasreen (Shahbaz et al., 2017a), Shahzadi, Javed (Shahzadi et al., 2014) used the fully modified ordinary least squares (FMOLS) approach to evaluate 105 countries from 1980 to 2014, dividing them into high-(developed), middle-(developing), low-(underdeveloped) income, and global panels. The study's findings for all panels demonstrate an inverted U-shaped relationship between environmental quality and trade. Similarly, Shahbaz, Hye (Shahbaz et al., 2013) find a negative association between pollution and trade openness because free trade generates a lot of research and development (R&D) schemes through foreign direct investment (FDI), resulting in an improvement in environmental quality. Sohag, Begum (Sohag et al., 2015) used mean group (MG) approaches, such as cross-correlated and augmented methods, to investigate the impact of trade, population growth, real GDP growth, and energy consumption on CO_2 emissions in 82 developing countries from 1980 to 2012. The findings suggest that a 1% increase in trade (while keeping the control variables constant) reduces CO_2 emissions by 0.3 percent. Meanwhile, the findings for middle-income, low-income, and the panel for all nations were not definitive. To approximate the entire impact of trade on environmental quality, Managi, Hibiki (Managi et al., 2009) used the instrumental variables modus operandi. The estimates suggest that international trade increases emissions in developing economies while decreasing emissions in developed economies: this increase in emissions was attributed to the scale and some aspects of trade composition effects.

It is also reported that trade openness was investigated and shown to have a detrimental impact on emissions in South Africa. Because their integration into world trade is insufficient, South Africa, Kenya, and Togo have not gained benefits/profits from global trade. Their primary exports are natural resources, whereas their primary imports are manufactured items. Given the continuous swings in commodity prices, they could not purchase new efficient technologies because their priorities were centered on fundamental needs, which would favor the usage of polluting enterprises (Eléazar, 2015).

Because real income, energy consumption, and carbon dioxide (CO_2) emissions are all linked, one school of thought suggests that they should all be considered together (Arouri et al., 2012). For example, according to an EKC study, growing income does not always result in lower CO_2 emissions, and rising wages result in increased pollution of the environment (Salahuddin et al., 2020); Balsalobre-Lorente, Shahbaz (Balsalobre-Lorente et al., 2018). Furthermore, because energy consumption impacts environmental quality, it is prudent to analyze these two variables using a unified procedure to decrease errors. Similarly, because these factors are interconnected, their relationships should be investigated concurrently using a combined procedure, as suggested by Pao and Tsai (Pao and Tsai, 2010) in BRICS nations, Keppler and Mansanet-Bataller (Keppler and Mansanet-Bataller, 2010) in the UK, Ghosh (2010) in India, and Zhang et al. (2009) in China. Despite this, their conclusions differed due to the diverse techniques, data, and countries participating in the study. A large body of past research on the relationship between income and pollution has backed up the reversed U-shaped relationship, often known as the EKC theory. In their papers, Saboori and Sulaiman (Saboori and Sulaiman, 2013),Chien, Hsu (Chien et al., 2022) investigated the EKC hypothesis, yet their findings were mixed. For example, an N-shaped association, a linear relationship, and a U-shaped correlation were discovered. The detection of omitted-variable bias is a major flaw in these earlier investigations. As a result, some recent studies have incorporated numerous elements that have influenced environmental pollution, such as openness to trade, urbanization, energy consumption, and financial development, into the varied research conducted. However, as a result of this multivariate study, different results concerning EKC theory have been developed (Ozturk and Acaravci, 2010; Omri, 2013; Acheampong, 2018; Qamruzzaman, 2022c), employing panel vector Autoregression (PVAR) in conjunction with a system known as the generalized method of moment (GMM) for 116 nations from 1990 to 2014 to investigate the changing relationship between economic growth, energy consumption, and carbon dioxide emissions. The outcomes of their study reveal that real GDP does not affect the territorial and global use of energy. Finally, except for the MENA nations, contamination of the environment had little effect on energy use in the global panel, with some evidence of the EKC theory in SSA countries. Gorus and Aydin (Gorus and Aydin, 2019) implements multiple Granger causality models to analyze the causality between energy use, real GDP, and pollution in eight MENA oil-rich nations from 1975 to 2014. In comparison to the causal relationships of the time domain, the analysis of the panel frequency domain reveals a cause-and-effect relationship among the fundamental variables in various occurrences. Previous studies did not categorize countries by area or income level, making it difficult to determine how real income and energy use influence environmental degradation in this cluster of countries.

In Sub-Saharan Africa, Congo, for example, has negative values for both the short and long term, indicating that economic expansion leads to reduced emissions (Narayan and Narayan, 2010). From 1975 to 2008, income elasticity in Mauritius, for instance, has been steadily increasing. The EKC pattern could not be verified in this way. Mauritius' energy usage heavily relies on imported fossil fuels, with an estimated 82 percent reliance at the time. Almost all energy use is for the provision of power and/or as a liquid for transportation, accounting for 81 percent of the country's total CO_2 emissions (Matadeen et al., 2011).

In another study, Ethiopian time-series data from 1970 to 2010 were reviewed. The findings reveal that while economic expansion increases energy consumption equally in the medium and long run, CO_2 emissions are decoupled from growth in the long run. Ethiopia achieved this by utilizing hydrodynamic and geothermal energy, which aided in developing a green economy (Musah et al., 2022).

Because different pollutants respond differently to numerous trade factors, and because the effect of trade on the environment is nation-specific, which could depend on the level of income and political institutions of the countries involved, inconclusive empirical research may have occurred as a result of some omitted variables, if any (Yang et al., 2021). As a result, we included Nitrous Oxide (N_2O) and Agricultural Methane (agricultural CH_4) emissions in our model, although many earlier studies have focused solely on the relationship between trade and CO_2 emissions. Furthermore, no research has been conducted on the relationship between Nitrous Oxide (N_2O) emissions, Agricultural Methane (agricultural CH_4) emissions, CO_2 emissions, and trade in Sub-Saharan African countries as a whole or its sub-groups; this inspired the present study (Qamruzzaman, 2021).

3 Methodology

3.1 Specification of the model

We assumed that the main determinants of economic development were trade and energy usage; therefore, we, in turn, defined environmental pollution as an outcome of energy consumption in connection with trade and economic growth. That being the case, we defined our models as follows:

$$N_2O_{it} = f\left(TRD_{it,} Y_{it,} EI_{it,} FDI_{it,} HC_{it}\right) \tag{1a}$$

$$CO_{2it} = f\left(TRD_{it,} Y_{it,} EI_{it,} FDI_{it,} HC_{it}\right) \tag{1b}$$

$$ACH_{4it} = f\left(TRD_{it,} Y_{it,} EI_{it,} FDI_{it,} HC_{it}\right) \tag{1c}$$

We include natural logarithms to our selected variables to reduce the heteroscedasticity problem and be able to observe the growth level of the parameters by their log differences to compute Eqs 1a–c, thus using it to study the correlation between the independent and dependent variables, following the modification of the KAYA or I=PAT model by regressing GHG emissions (CO_2, N_2O, and ACH_4) on trade, income per capita growth, energy intensity, foreign direct investment, and human capital:

$$\begin{aligned}\ln\ (N_2O)_{it} = \alpha 1 + \beta_1\, ln(TRD)_{it,} + \lambda_1\, ln(Y)_{it} + \lambda_2\, ln(EI)_{it} \\ + \lambda_3\, ln(FDI)_{it} + \lambda_4\, ln(HC)_{it} + \eta_{1i} + \varepsilon_{1it}\end{aligned} \tag{2a}$$

$$\begin{aligned}ln(CO2)_{it} = \alpha 2 + \beta_2\, ln(TRD)_{it,} + \lambda_5\, ln(Y)_{it} + \lambda_6\, ln(EI)_{it} \\ + \lambda_7\, ln(FDI)_{it} + \lambda_8\, ln(HC)_{it} + \eta_{2i} + \varepsilon_{2it}\end{aligned} \tag{2b}$$

$$\begin{aligned}ln(ACH_{4it}) = \alpha 3 + \beta_3\, ln(TRD)_{it,} + \lambda_9\, ln(Y)_{it} + \lambda_{10}\, ln(EI)_{it} \\ + \lambda_{11}\, ln(FDI)_{it} + \lambda_{12}\, ln(HC)_{it} + \eta_{3i} + \varepsilon_{3it}\end{aligned} \tag{2c}$$

Where:

$\ln\ (N_2O)_{it}$ = the natural log of Nitrous Oxide emissions in country i and time t

$\ln\ (CO_2)_{it}$ = the natural log of CO_2 emissions in country i and time t

$\ln\ (ACH_4)_{it}$ the natural log of Agricultural Methane Emissions in country i and time t

$\ln\ (TRD)_{it}$ = the natural log of trade in the percentage of GDP

$\ln(Y)_{it}$ = the natural log of Income Per Capita Growth (constant 2010 U.S. dollars) in country i and time t

$\ln\ (EI)_{it}$ = the natural log of Energy Intensity (Energy Supply/GDP- measured at purchasing power parity) in country i and time t

$\ln\ (FDI)_{it}$ = the natural log of Foreign Direct Investment in country i and time t

$\ln\ (HC)_{it}$ = the natural log of Human Capital (measured as the rate of secondary school graduation) in country I and time t

β_i measures the relative effects of trade on environmental quality.

λ_i = set of parameters indicating the relative effects of the control variables.

3.2 Estimation techniques

In line with the works of Ghani, Kerr (Ghani et al., 2011), Vlastou (Vlastou, 2010), and Madsen (Madsen, 2009), the study employs a dynamic panel technique in addressing potential endogeneity problems in the data using the methods of Arellano and Bover (Arellano and Bover, 1995) and Blundell and Bond (Blundell and Bond, 1998). This type of dynamic panel framework is developed by the application of the first difference transformation portrayed by the following Eq. 3:

$$ep_{it} - ep_{i,t-i} = (\alpha - 1)ep_{i,t-1} + \beta' X_{i,t} + \eta_i + \varepsilon_{i,t} \tag{3}$$

Where $ep_{it} - ep_{i,t-i}$ is the growth of environmental pollution, $X_{i,t}$ denotes the set of independent variables, including our measure of natural resources revenues, income per capita growth, energy intensity, foreign direct investment, and human capital; η_i Denotes the unobserved country-specific effect, and $\varepsilon_{i,t}$ denotes the error term. We further expressed Eq. 3 as follows:

$$ep_{i,t} = \alpha' ep_{i,t-1} + \beta' X_{i,t} + \eta_i + \varepsilon_{i,t} \tag{4}$$

Changing Eq. 4 into the first difference gives the Equation seen below:

$$ep_{i,t} - ep_{i,t-1} = \alpha' \left[ep_{i,t-1} - ep_{i,t-2}\right] + \beta' \left[X_{i,t} - X_{i,t-1}\right] + \left[\varepsilon_{i,t} - \varepsilon_{i,t-1}\right] \tag{5}$$

It is seen from Eq. 5 that the lagged difference in environmental pollution is correlated with the error term, which suggests the potential existence of endogeneity of the independent variable X, which prompts the use of instrumental variables. In an attempt to address this problem, the system difference estimator includes the lagged levels of the independent variables as instruments in the supposition that the lagged level of the independent variables is weakly exogenous and that the error term is not serially correlated. In the empirical analysis, a positive and significant coefficient of natural resources revenues, income per capita growth, energy intensity, foreign direct investment, and human capital suggest that the independent variables increase pollution, hence deterioration of the environment in the countries under consideration. On the contrary, a negative and significant coefficient implies a reduction in emissions, thereby improving the environment.

Lastly, following the theory behind the EKC analysis, we investigate the existence of an inverted U-shape correlation between income per capita growth and N_2O, ACH_4, and CO_2 emissions. We included the square of income per capita growth into Eq. 2 to compute Eq. 6, using these equations to ascertain the existence of the EKC hypothesis in our model. Consistent with the work of Shahbaz, Van Hoang (Shahbaz et al., 2017b), Andriamahery and Qamruzzaman (Andriamahery and Qamruzzaman, 2022a), we modeled our EKC theory as follows:

$$\ln\ (N_2O)_{it} = \alpha 1 + \beta_1\, ln(TRD)_{it,} + \lambda_1\, ln(Y)_{it} + \lambda_2\, ln(Y^2)_{it}\ \lambda_3\, ln(EI)_{it} + \lambda_4\, ln(FDI)_{it} + \lambda_5\, ln(HC)_{it} + \eta_{1i} + \varepsilon_{1it} \tag{6a}$$

$$ln(CO2)_{it} = \alpha 2 + \beta_2\, ln(TRD)_{it,} + \lambda_6\, ln(Y)_{it} + \lambda_7\, ln(Y^2)_{it} + \lambda_8\, ln(EI)_{it} + \lambda_9\, ln(FDI)_{it} + \lambda_{10}\, ln(HC)_{it} + \eta_{2i} + \varepsilon_{2it} \tag{6b}$$

$$ln(ACH_{4it}) = \alpha 3 + \beta_3\, ln(TRD)_{it,} + \lambda_{11}\, ln(Y)_{it} + \lambda_{12}\, ln(Y^2)_{it} + \lambda_{13}\, ln(EI)_{it} + \lambda_{14}\, ln(FDI)_{it} + \lambda_{15}\, ln(HC)_{it} + \eta_{3i} + \varepsilon_{3it} \tag{6c}$$

The estimated turning points are determined by Eqs 7a–c

$$x_1^* = \exp\left(-\frac{\lambda_1}{2\lambda_2}\right) \tag{7a}$$

$$x_2^* = \exp\left(-\frac{\lambda_6}{2\lambda_7}\right) \tag{7b}$$

$$x_3^* = \exp\left(-\frac{\lambda_{11}}{2\lambda_{12}}\right) \tag{7c}$$

3.3 Data and its sources

This section looks at the data used for the empirical analysis of the relationship between trade and the environment. We compiled data on N_2O, CO_2 emissions, and Agricultural Methane emissions and used them as dependent variables; whereas trade in the percentage of GDP, income per capita growth, energy intensity, foreign direct investment, and human capital from the World Bank online data bank for 33 Sub-Saharan African countries were used as independent variables. We used the yearly data for the period 1990–2017. We put the data into income groups (upper-middle-income, lower-middle-income, and low-income countries). Concerning the previous statement, the first panel of countries consists of Botswana, Equatorial Guinea, Gabon, Mauritius, Namibia, Seychelles, and South Africa. The second panel consists of Angola, Cameroon, Comoros, Congo Rep, Ivory Coast, Ghana, Kenya, Nigeria, Senegal, and Sudan. The third panel contains Benin, Burkina Faso, Burundi, CAR, Chad, Congo Dem Rep, Ethiopia, Guinea, Madagascar, Malawi, Mozambique, Niger, Rwanda, Sierra Leone, Tanzania, and Uganda. The literature has used different variables to measure pollution, including N_2O, SO_2, CO_2, etc. However, our analysis used N_2O emissions, CO_2 emissions, and Agricultural Methane (agricultural CH4) emissions because of their global effects.

4 Analysis of results

4.1 Presentation of results

In estimating the equations at a certain level, the study applies the Hausman specification test to pick between the random and fixed effects models. We use the total sample, which includes nations in Sub-Saharan Africa. We classify Sub-Saharan African countries into three groupings to capture

TABLE 1 Panel estimation results: LNN_2O as the dependent variable.

Variables	**SSA**			**UMIC**			**LMIC**			**LIC**		
	FE	**RE**	**SYS**	**FE**	**RE**	**SYS**	**FE**	**RE**	**SYS**	**FE**	**RE**	**SYS**
Constant	6.7802 (16.40)***	6.5665 (13.58)***	-----	6.4919 (11.91)***	-8.8075 (-42.03)***	-----	8.0243 (15.40)***	7.8931 (11.41)***	-----	7.1147 (6.84)***	6.7892 (6.26)***	-----
LNN_2O(-1)	-----	-----	0.7706 (74.38)***	-----	-----	0.784,065 (12.45)***	-----	-----	11.3899 (3.71)***	-----	-----	0.8542 (22.84)***
LNTRD	0.06931 (4.49)***	0.0775 (5.08)***	0.0214 (6.04)***	0.0638 (2.56)**	0.3973 (81.18)***	0.0394 (2.23)**	0.0707 (4.03)***	0.0750 (4.30)***	0.1222 (2.19)**	0.1242 (3.00)***	0.1359 (3.32)***	0.0457 (2.96)***
LNY	-0.0603 (-3.48)***	-0.0445 (-0.88	0.0257 (5.72)***	-0.1726 (-2.68)***	0.3407 (16.67)***	-0.1034 (-1.82)*	-0.1701 (-3.043)***	0.1695 (3.03)***	-2.3644 (1.79)*	0.0905 (2.11)**	0.0918 (2.14)**	0.0209 (4.79)***
LNEI	-0.0372 (-0.68)***	-0.0096 (-0.17)	-0.0012 (-0.07)	-0.2823 (-14.11)***	1.2941 (37.84)***	-0.0313 (-0.73)	-0.4822 (-4.62)***	-0.4601 (-4.42)***	-0.0523 (-0.15)	-0.1068 (-2.63)***	-0.0817 (-0.97)	0.0946 (2.12)**
LNFDI	-0.0289 (-0.82)	-0.0328 (-0.93)	-0.0288 (-8.38)***	-0.0217 (-0.71)	-1.0295 (-38.11)***	0.0435 (1.32)	0.0857 (2.08)**	0.0834 (2.03)**	0.2090 (0.79)	-0.1116 (-2.59)***	-0.1120 (-2.61)***	-0.0208 (-10.43)***
LNHC	-0.1079 (-3.73)***	-0.1078 (-3.74)***	-0.0455 (-3.16)***	0.0362 (0.51)	1.7773 (58.12)***	0.0211 (0.63)	-0.0841 (-1.72)*	-0.0848 (-1.73)*	-0.5994 (-1.80)*	-0.1554 (-3.03)***	-0.1490 (-2.92)***	-0.1074 (-1.75)
No. of Obs	892	892	827	168	168	162	280	280	270	448	448	416
R^2	0.9625	0.07	-----	0.9941	0.7057	-----	0.9682	0.2298	-----	0.9210	0.0712	-----
F-Statistics	608.822 (0.000)***	13.950 (0.000)***	-----	2654.663 (0.000)***	77.692 (0.000)***	-----	576.331 (0.000)***	16.354 (0.000)***	-----	249.029 (0.000)	6.777 (0.000)***	-----
Hausman Test	Chi^2 (5) = 20.60 (0.0010)***		-----	Chi^2 (5) = 7701.88 (0.0000)***		-----	Chi^2 (5) = 10.18 (0.0703)*		-----	Chi^2 (5) = 4.72 (0.4506)		-----
AR (2)	-----	-----	0.9987	-----	-----	0.9889	-----	-----	0.9866	-----	-----	0.9966
Sargan Test	-----	-----	χ2 = 31.52 (0.5648)	-----	-----	χ2 = 21.22 (0.6921)	-----	-----	χ2 = 24.66 (0.734)	-----	-----	χ2 = 82.52 (0.772)

Note. The variables are expressed in log form, and t–values are reported in parenthesis (except for the Hausman test and F-statistics where probabilities are reported in parenthesis), ----- implies not applicable, (*) (**) and (***) represent significance at the 10%, 5%, and 1% levels respectively. The variables entering the Dynamic model are in first difference, and their coefficients are interpreted as growth elasticities. Both the fixed and random-effects models are in levels.

disparities in income levels: Upper-Middle-Income Countries (UMIC), Lower-Middle-Income Countries (LMIC), and Low-Income Countries (LIC). As dependent variables, three environmental quality measurements were used. The regression is then conducted for each of the sub-economic groups concerning each measure of environmental quality to see if differences in income levels across sub-regions impact the relative effects of the independent variables on the dependent variables.

Tables 1–3 show the results of the panel dynamic model analysis of the long-term effects of trade, income per capita growth, energy intensity, foreign direct investment, and human capital on the three environmental quality measures (N_2O, ACH_4, and CO_2). Estimates for the Environmental Kuznets Curve (EKC) hypothesis were also made; the results are presented in Tables 4–6. These panel regression findings are calculated for all nations in Sub-Saharan Africa and the three sub-income groups.

Individual unobserved country-specific effects are not correlated with the explanatory variables for SSA, UMIC, and LMIC, meaning that the fixed-effects model is superior to the random-effects model for levels regression in these groups, as demonstrated in the lower areas of Tables 1,2. However, in the LIC, it is proposed that the random-effects model be favored over the fixed-effects model. Furthermore, the Hausman specification test results in the lower section of Table 3 consistently show that the fixed-effects model is preferred over the random-effects model for all groups (SSA, UMIC, LMIC, and LIC), as the tests show that individual unobserved country-specific effects are uncorrelated with the explanatory variables.

The results of the Sargan tests in the lower sections of Tables 1–3 show that the instruments are valid in all dynamic panel

TABLE 2 Panel estimation results: LNACH$_4$ as the dependent variable.

Variables	SSA			UMIC			LMIC			LIC		
	FE	RE	SYS	FE	RE	SYS	FE	RE	SYS	FE	RE	SYS
Constant	6.2148 (12.40)***	5.9628 (10.32)***	-----	6.2929 (13.33)***	-12.695 (-69.99)***	-----	9.2487 (16.73)***	9.0914 (12.58)***	-----	2.2717 (1.80)*	1.9631 (1.53)	-----
LNACH$_4$(-1)	-----	-----	0.7707 (74.38)***	-----	-----	6.1023 (12.94)***	-----	-----	13.9089 (3.68)***	-----	-----	0.8016 (8.29)***
LNTRD	0.0947 (5.07)***	0.1045 (5.66)***	0.0214 (6.05)***	-0.0451 (-2.54)**	0.5113 (120.67)***	0.0429 (2.42)**	0.0541 (2.9095)***	0.0589 (3.19)***	0.7894 (2.07)**	0.2995 (5.13)***	0.3142 (5.48)***	0.1212 (2.86)***
LNY	-0.1368 (-2.23)**	-0.1386 (-2.25)**	0.0257 (5.72)***	0.3835 (21.43)***	0.4434 (25.07)***	-0.2089 (-3.13)***	-0.1656 (-2.79)***	-0.1646 (-2.77)***	-1.3071 (-3.96)***	-0.0032 (-0.04)	0.3477 (7.12)***	-0.0389 (-4.98)***
LNEI	-0.1694 (-2.53)**	-0.1356 (-2.04)**	-0.0012 (0.07)	-0.0839 (-1.33)	1.3994 (47.27)***	-0.0602 (-0.95)	-1.1373 (-10.26)***	-1.1084 (-10.04)***	-0.9691 (-2.15)**	-0.0903 (-0.83)	-0.0801 (-0.7485)	-0.0939 (-0.46)
LNFDI	0.1230 (2.89)***	0.1182 (2.78)***	-0.0288 (-8.38)***	-0.6404 (-100.82)***	-1.2681 (-54.22)***	-0.0158 (-0.61)	0.1879 (4.30)***	0.1847 (4.23)***	0.5473 (2.02)**	-0.0231 (-0.44)	-0.3143 (-2.87)***	-0.0312 (-4.43)***
LNHC	-0.1385 (-3.94)***	-0.1378 (-3.94)***	-0.0455 (-3.16)***	0.0652 (1.07)	2.0729 (78.31)***	0.0932 (1.48)	0.0840 (1.62)	0.0853 (1.64)	-0.6549 (-1.89)*	0.0776 (1.25)	0.0681 (1.10)	-0.0969 (-2.38)**
No. of Obs	892	892	827	168	168	162	280	280	270	448	448	416
R^2	0.9567	0.1263	-----	0.9972	0.6561	-----	0.9652	0.4102	-----	0.8840	0.1603	-----
F-Statistics	524.982 (0.000)***	25.624 (0.000)***	-----	5654.345 (0.000)***	61.817 (0.000)***	-----	525.190 (0.000)***	38.114 (0.000)***	-----	162.730 (0.000)***	16.876 (0.000)***	-----
Hausman Test	Chi^2 (5) = 19.67 (0.0014)***		-----	Chi^2 (5) = 19341.51 (0.0000)***		-----	Chi^2 (5) = 12.37 (0.0301)**		-----	Chi^2 (5) = 2.83 (0.7267)		-----
AR (2)	-----	-----	0.9987	-----	-----	0.9984	-----	-----	0.9909	-----	-----	0.4166
Sargan Test	-----	-----	$\chi2$ = 55.33 (0.633)	-----	-----	$\chi2$ = 30.07 (0.701)	-----	-----	$\chi2$ = 24.84 (0.774)	-----	-----	$\chi2$ = 23.24 (0.375)

Note. The variables are expressed in log form, and t–values are reported in parenthesis (except for the Hausman test and F-statistics where probabilities are reported in parenthesis), ---- implies not applicable, (*) (**) and (***) represent significance at the 10%, 5%, and 1% levels respectively. The variables entering the Dynamic model are in first difference, and their coefficients are interpreted as growth elasticities. Both the fixed and random-effects models are in levels.

regressions for the dynamic model. Finally, the tests for second-order serial correlation in the residuals reveal no severe problem with serial correlation in the dynamic panel's regressions.

4.2 Discussion of results

Starting with one of the environmental quality indicators (nitrous oxide emissions), we examine the impact of trade (as measured by natural resource revenues), income per capita growth, energy intensity, foreign direct investment, and human capital on N_2O emissions. Table 1 shows that the trade (NRR) coefficient for the fixed-effects model is positive and significant for the SSA, UMIC, and LMIC for the SSA, UMIC, and LMIC. According to the results of the random-effects model, trade has a positive and significant impact on Nitrous Oxide Emissions in the LIC exclusively. This means that an increase in trade in any of these groups leads to an increase in N_2O, lowering the environmental quality. Table 1 also includes the results of the panel dynamic model study of the long-term consequences. The empirical findings reveal that trading raises N_2O emissions in all populations (SSA countries, UMIC, LMIC, and LIC). This means that a 10% increase in trade in SSA, UMIC, LMIC, and LIC increases N_2O emissions by 0.2, 0.4, 1.2, and 0.5 percent, respectively, when all other explanatory variables are held constant. This effect of trade on the environment could be explained by the fact that nearly 70% of people in Sub-Saharan Africa work in agriculture, which increases the generation of nitrous oxide through soil cultivation, nitrogen fertilizer use, and the management of animal manure. Furthermore, because fossil

TABLE 3 Panel estimation results: $LNCO_2$ as the dependent variable.

Variables	SSA			UMIC			LMIC			LIC		
	FE	RE	SYS	FE	RE	SYS	FE	RE	SYS	FE	RE	SYS
Constant	3.4127 (8.02)***	3.1629 (6.91)***	-----	-3.4775 (-2.09)**	-6.6102 (-10.32) ***	-----	4.0351 (7.43)***	3.4062 (5.97)***	-----	-1.1494 (-1.56)	-1.5133 (-2.05)**	-----
$LNCO_2$(-1)	-----	-----	0.8250 (84.37)***	-----	-----	-1.7424 (-1.21)	-----	-----	-1.6045 (-0.48)	-----	-----	0.8035 (7.21)***
LNTRD	0.2179 (13.74)***	0.2266 (14.58)***	0.0951 (28.44) ***<	0.4377 (6.99)***	0.3988 (26.66)***	0.4585 (8.49)***	0.1287 (7.05)***	0.1518 (8.50)***	0.5473 (2.02)**	0.4207 (12.37)***	0.4328 (13.00)***	0.0613 (6.90)***
LNY	-0.1172 (-2.25)**	-0.1161 (-2.23)**	0.0141 (3.36)***	-0.1326 (-2.04)**	-0.0189 (-0.30)	-0.1642 (-2.99)***	0.1549 (2.66)***	0.1562 (2.6836) ***	2.4000 (1.66)*	0.0693 (1.99)**	-0.0712 (-1.63)	0.1035 (1.38)
LNEI	-0.4854 (-8.55)***	-0.4569 (-8.19)***	-0.0073 (-0.84)	0.4139 (1.87)*	1.3089 (12.53)***	0.2114 (1.09)	-0.2079 (-1.91)*	-0.1042 (-0.97)	-0.3954 (-0.99)	-0.5220 (-8.23) ***<	-0.4836 (-7.78)***	-0.1164 (-1.78)*
LNFDI	-0.0976 (-2.70)***	-0.1027 (-2.84)***	0.0376 (5.79)***	-0.2668 (-2.86)***	-0.6164 (-7.47)***	-0.2964 (-3.77)***	-0.0156 (-0.36)	-0.0304 (-0.71)	0.1168 (0.3919)<	0.0358 (1.18)	0.0370 (1.22)	0.0278 (1.66)*
LNHC	-0.4374 (-14.69) ***	-0.4433 (-14.97) ***	-0.0721 (-7.26)***	-0.9570 (-4.46)***	-1.7219 (-18.43) ***	-0.5577 (-2.91)***	-0.4723 (9.27)***	-0.4641 (-9.16)***	0.3552 (0.94)	-0.2440 (-6.73)***	-0.2472 (-6.87)***	-0.0627 (-2.08)**
No. of Obs	892	892	827	168	168	162	280	280	270	448	448	416
R^2	0.9520	0.5585	-----	0.9317	0.7939	-----	0.9593	0.4538	-----	0.9295	0.7004	-----
F-Statistics	471.052 (0.000)***	224.164 (0.000)***	-----	214.066 (0.000)***	124.857 (0.000)***	-----	447.238 (0.000)***	45.538 (0.000) ***	-----	281.283 (0.000)***	206.675 (0.000)***	-----
Hausman Test	Chi^2 (5) = 22.93 (0.0003)***		-----	Chi^2 (5) = 316.39 (0.0000)***		-----	Chi^2 (5) = 41.95 (0.0000)***		-----	Chi^2 (5) = 12.94 (0.0239)***		-----
AR (2)	-----	-----	0.3705	-----	-----	0.9985	-----	-----	0.9978	-----	-----	0.7923
Sargan Test	-----	-----	$\chi2 = 43.01$ (0.6471)	-----	-----	$\chi2 =$ 48.32 (0.637)	-----	-----	$\chi2 =$ 28.33 (0.548)	-----	-----	$\chi2 =$ 20.46 (0.558)

Note. The variables are expressed in log form, and t–values are reported in parenthesis (except for the Hausman test and F-statistics where probabilities are reported in parenthesis), ----- implies not applicable, (*) (**) and (***) represent significance at the 10%, 5%, and 1% levels respectively. The variables entering the Dynamic model are in first difference, and their coefficients are interpreted as growth elasticities. Both the fixed and random-effects models are in levels.

TABLE 4 Environmental Kuznets Curve (EKC) results.

	Dependent variable: D (LNN_2O)			
Variables	SSA	UMIC	LMIC	LIC
LNTRD	0.0305 (3.62)***	0.4956 (2.88)***	-0.2329 (-1.61)	-0.0608 (-3.52)***
LNY	0.0239 (4.65)***	0.9311 (3.87)***	1.4584 (1.43)	0.0227 (4.41)***
LNY^2	-0.0086 (-4.05)***	-0.1539 (-2.84)***	0.0072 (0.16)	-0.0026 (-0.75)
LNEI	-0.0237 (-1.26)	0.5974 (2.39)**	1.0934 (3.24)***	0.1203 (1.53)
LNFDI	-0.0377 (-6.66)***	-0.4325 (-2.20)**	1.0939 (3.74)***	0.0462 (0.69)
LNHC	0.0315 (1.07)	0.7167 (4.12)***	2.0009 (7.36)***	0.1040 (2.50)**
TURNING POINT	4.01 %	20.59 %	NS	NS

Note. ***, **, * indicate significance at the 1%, 5%, and 10% levels respectively; NS means not significant.

fuel combustion and industrial processes are two of the most significant contributors to anthropogenic emissions, this could indicate that more fossil fuel has been used in the production and sale of natural resources, given the fact that many Sub-Saharan African countries rely on natural resources to boost their economies.

TABLE 5 Environmental Kuznets Curve (EKC) results.

	Dependent variable: D (LNACH$_4$)			
Variables	**SSA**	**UMIC**	**LMIC**	**LIC**
LNTRD	0.0415 (3.56)***	0.0785 (0.64)	-0.1713 (0.47)	0.1505 (2.07)**
LNY	0.0319 (4.81)***	-0.0721 (-0.36)	1.6822 (0.65)	-0.0315 (-2.83)***
LNY^2	-0.0067 (-1.74)*	-0.1030 (-1.97)*	-0.0278 (-0.28)	-0.0076 (-0.64)
LNEI	0.0819 (2.37)**	1.4480 (5.68)***	0.7152 (1.32)	-0.0297 (-0.17)
LNFDI	0.0305 (2.43)**	1.4059 (4.79)***	0.6536 (1.56)	-0.1479 (-0.52)
LNHC	0.0338 (1.08)	-0.3126 (-0.43)	1.5336 (2.42)**	-0.3390 (1.16)
TURNING POINT	10.81 %	0.70 %	NS	NS

Note. ***, **, * indicate significance at the 1%, 5%, and 10% levels respectively; NS means Not Significant.

TABLE 6 Environmental Kuznets Curve (EKC) results.

	Dependent variable: D (LNCO$_2$)			
Variables	**SSA**	**UMIC**	**LMIC**	**LIC**
LNTRD	0.0954 (12.34)***	0.1342 (0.94)	0.4065 (2.98)***	0.0370 (0.82)
LNY	0.0987 (5.59)***	-0.0104 (-0.0324)	1.7537 (2.27)**	0.1051 (1.17)
LNY^2	-0.0101 (-3.77)***	0.0393 (0.39)	-0.0713 (-1.96)*	0.0032 (0.53)
LNEI	0.0389 (5.72)***	0.0674 (0.08)	-0.0697 (-0.16)	-0.0305 (-0.17)
LNFDI	0.0232 (3.05)***	-1.2849 (-2.38)**	0.3129 (0.84)	0.0421 (0.64)
LNHC	0.0922 (10.05)***	1.9730 (1.74)*	1.6673 (4.54)***	0.0683 (1.72)*
TURNING POINT	132.44 %	NS	219,257.04 %	NS

Note. ***, **, * indicate significance at 1%, 5%, and 10% levels respectively; NS means Not Significant.

The mixed results regarding the association between the Income Per Capita Growth (Y) and Nitrous Oxide (N_2O) emissions. The results of the fixed-effects regressions for the entire SSA member nations, UMIC, and LMIC, reveal that income per capita growth hurts N_2O emissions. On the other hand, we published the random-effects model for the LIC. The regression results demonstrate that Income Per Capita Growth and Nitrous Oxide Emissions have a positive association. In the dynamic model, income per capita growth in the UMIC and LMIC has a negative and large impact on N_2O emissions. In relative magnitude, the results reveal that a 10% rise in GDP per capita reduces N_2O emissions in the atmosphere by 1% and 23.6 percent in UMIC and LMIC, thus enhancing environmental quality. The panel data, on the other hand, show that income per capita growth positively and significantly affects N_2O emissions in Sub-Saharan African (SSA) and Low-Income Countries (LIC). This means that a 10% increase in Nitrous Oxide emissions raises the N_2O level in the atmosphere by 0.3 percent and 0.2 percent, respectively, while keeping the other control variables constant.

For the whole sample of Sub-Saharan African (SSA) countries, UMIC, and LMIC, the connection between N_2O emissions and Energy Intensity (EI) is negative and significant in the fixed-effects model. In Low-Income Countries, however, it is not significant for the random-effects model (LIC). The coefficient of energy intensity is only positive and significant for the Low-Income Nations (LIC) in the panel dynamic model; it is not significant for the SSA countries, UMIC, and LMIC. This means that a 10% increase in energy intensity (while keeping the other explanatory factors fixed) increases N_2O emissions in the atmosphere by about 1% in LIC.

While using the fixed-effects model, the association between foreign direct investment (FDI) and N_2O is positive and significant for only the LMIC; when using the random-effects model, the relationship is negative and significant for the LIC. Only the total Sub-Saharan African (SSA) countries and LIC have a negative and substantial association in the dynamic model. In terms of N_2O emissions, a 10% increase in FDI reduces them by 0.3 percent and 0.2 percent in SSA and LIC, respectively.

For the whole sample of Sub-Saharan African (SSA) nations, LMICs, and LICs, the link between Nitrous Oxide (N_2O) emissions and Human Capital (HC) is negative and significant in both fixed and random-effects models. However, it is not important in the Upper-Middle-Income Countries (UMIC). In the dynamic model, the link between N_2O emissions and HC in SSA, LMIC, and LIC is inverse and statistically significant. In the UMIC, it is of minor significance. This suggests that strengthening human capital reduces N_2O emissions in SSA, LMIC, and LIC, but not UMIC. This means that in SSA, LMIC, and LIC, a 10% increase in human capital reduces N_2O emissions by 0.5 percent, approximately 6% and 1%, respectively.

The estimations in Table 2 demonstrate the relative effects of trade, income per capita growth, energy intensity, foreign direct investment, and human capital on ACH_4 emissions, which is another measure of environmental quality. The trade variable (NRR) coefficient for the overall SSA nations, LMICs, and LICs are positive and significant for the fixed/random-effects model, according to Table 2. In the UMIC panel, however, it is negative and substantial. Table 2 also includes the results of the panel dynamic model study of the long-term consequences. The empirical findings reveal that trade increases agricultural methane (ACH_4) emissions in the SSA countries and UMICs, LMICs, and LICs. With the other explanatory factors held constant, a 10% increase in trade in SSA, UMIC, LMIC, and LIC raises ACH_4 emissions by 0.2 percent, 0.4 percent, 7.9 percent, and 1.2 percent, respectively. These findings are in line with the conclusion of Dario, LoPresti (Dario et al., 2014). Increased demand for livestock products could explain the negative impact of commerce on the environment.

The mixed results regarding the association between income per capita growth (Y) and agricultural methane (ACH_4) emissions. The results from the entire SSA member nations and LMIC for the fixed/random-effects model show that the income per capita growth negatively influences ACH_4 emissions, which is significant. The regression results, on the other hand, demonstrate that in the UMIC and LIC, income per capita growth has a positive and substantial effect on ACH_4 emissions. In the dynamic model, income per capita increase in the UMIC, LMIC, and LIC has a negative and significant impact on ACH_4 emissions. In relative magnitude, a 10% rise in income per capita growth reduces ACH_4 emissions in the atmosphere by 2.1 percent, 13.7 percent, and 0.4 percent in the UMIC, LMIC, and LIC, respectively, which is an indication of environmental quality improvement. To reduce ACH_4 pollution, these countries within these income groups need to boost economic growth. The panel data, on the other hand, show that income per capita growth positively and significantly affects ACH_4 emissions across the Sub-Saharan African (SSA) nations. This implies that a 10% increase in per capita income (while leaving all other explanatory variables constant) raises the ACH_4 level in the atmosphere by 0.3 percent.

When looking at the relationship between energy intensity (EI) and agricultural methane (ACH_4) emissions and looking at the regression results in Table 2, it can be seen that the coefficient of the energy intensity (EI) variable is negative for all panels (SSA, UMIC, LMIC, and LIC), but only significant in the SSA and LMIC panels. According to the panel dynamic model, the coefficient of energy intensity is negative in all four panels (SSA, UMIC, LMIC, and LIC), but only in the LMIC panel is it significant. According to the results of the dynamic model, a 10% increase in energy intensity (while leaving the other control variables constant) reduces ACH_4 emissions in the atmosphere by 9.7% in the LMIC at the 5% level. These results could be explained by a situation in which the use of renewable energy, such as solar energy for agricultural activities, is increasing in these countries (LMIC).

The link between foreign direct investment (FDI) and ACH_4 emissions is positive and significant for the total SSA countries and LMIC but negative and significant for the UMIC and LIC in the fixed/random-effects model. The dynamic model shows a negative connection in the total Sub-Saharan African (SSA) countries, UMIC and LIC. However, only the countries of Sub-Saharan Africa (SSA) and the LIC are noteworthy. A 10% increase in FDI in relative emissions reduces ACH_4 emissions by 0.3 percent in SSA and 0.3 percent in LIC, respectively. Nonetheless, it is significant and favorable for the LMIC. In LMIC, a 10% increase in FDI results in a 5.5 percent increase in ACH_4 emissions.

For the whole sample of Sub-Saharan African (SSA) nations, the association between ACH_4 emissions and human capital (HC) is negative and significant using the fixed/random-effects model. However, it is positive but insignificant in the UMIC, LMIC, and Low-Income Countries (LIC). The dynamic model's association between ACH_4 emissions and HC in SSA, LMIC, and LIC is inverse and statistically significant. In the UMIC, it is both positive and insignificant. This suggests that, at the 1%, 10%, and 5% levels of significance, strengthening human capital reduces ACH_4 emissions in SSA, LMIC, and LIC, respectively. This means that in SSA, LMIC, and LIC, a 10% increase in human capital reduces ACH_4 emissions by 0.5 percent, 6.5 percent, and 1 percent, respectively.

CO_2 emissions are also considered a metric of environmental quality. We also examine how to trade (NRR), income per capita growth, energy intensity, foreign direct investment, human capital, and CO_2 emissions are related. According to the regression results in Table 3, the trade variable (NRR) coefficient is positive and significant in all of the panels for the fixed-effects model (SSA, UMIC, LMIC, and LIC). Table 3 also includes the results of the panel dynamic model investigation of the long-term consequences. In all of the panels, the empirical results reveal that trade raises CO_2 emissions significantly. Keeping the control variables constant, we see a 10% increase in trade in SSA, UMIC, and LMIC and an increase in CO_2 emissions by approximately 1%, 4.6 percent, 5.5 percent, and

0.6 percent in LIC, respectively. These figures back up Shahbaz, Topcu (Shahbaz et al., 2021), Zhuo and Qamruzzaman (Zhuo and Qamruzzaman, 2021), Managi, Hibiki (Managi et al., 2009), Xu, Qamruzzaman (Xu et al., 2021). This trade effect on CO_2 emissions could be explained by reliance on coal or fossil-fuel-powered manufacturing methods, household usage of more conventional energy (fossil fuel), and numerous pollutant-producing sectors in these regions.

The mixed results regarding the association between income per capita growth (Y) and CO_2 emissions. The total SSA member nations and UMIC for the fixed-effects model show that rising income per capita hurts CO_2 emissions. And they are important. The regression results, on the other hand, reveal that income per capita growth positively and significantly impacts CO_2 emissions in LMICs and LICs. The income per capita increase has a negative and large impact on CO_2 emissions in the UMIC in the dynamic model. In relative magnitude, the findings reveal that a 10% rise in per capita income reduces CO_2 emissions by 1.6 percent in the atmosphere, improving environmental quality. Countries at these income levels should boost their economic growth to reduce CO_2 emissions and improve environmental quality. This result backs Frankel and Rose's conclusions (2005). The panel results, on the other hand, show that income per capita growth positively and considerably impacts CO_2 emissions in Sub-Saharan African (SSA) and LMIC nations. This means that a 10% increase in income per capita growth (while keeping the control variables constant) raises CO_2 levels in the atmosphere by 0.1 percent in SSA countries and 24% in LMICs. These findings corroborate those of Omri (Omri, 2013), Aka (Aka, 2008), Xia, Qamruzzaman (Xia et al., 2022), JinRu and Qamruzzaman (JinRu and Qamruzzaman, 2022) and Fodha and Zaghdoud (Fodha and Zaghdoud, 2010). The LIC's income per capita growth coefficient is positive but not statistically significant.

Given the relationship between energy intensity (EI) and CO_2 emissions, and based on the regression results in Table 3, the coefficient of the energy intensity (EI) variable is negative and significant in the overall SSA, LMIC, and LIC nations for the fixed-effects model. In the UMIC, on the other hand, it is positive and important. The coefficient of energy intensity is negative and significant only in the LIC panel, according to the panel dynamic model. The dynamic model shows that increasing energy intensity by 10% (while keeping the control variables constant) reduces CO_2 emissions in the atmosphere by 1.2 percent in the LIC at the 10% level.

The link between foreign direct investment (FDI) and CO_2 emissions in the fixed effects model is positive but not significant for the LIC, negative and significant for the total SSA nations and UMIC, and negative but negligible for the LMIC. In the UMIC, the link is negative and significant for the dynamic model. In terms of CO_2 emissions, a 10% increase in FDI reduces CO_2 emissions by about 3% in UMIC. It is, however, positive and significant for the SSA countries and the LIC. This means that a 10% increase in FDI raises CO_2 emissions by 0.4 percent in SSA nations and 0.3 percent in LIC countries. This could be explained by the fact that SSA countries have abundant natural resources, which is seen by natural resources exports as a percentage of GDP. Furthermore, it is widely accepted that most FDI inflows into SSA nations are directed to the natural resources sector, which MNCs dominate. However, these multinational corporations are not likely to employ sophisticated methods in exploiting and mining these resources, resulting in environmental devastation. More studies should be done in this field to better understand the relationship between CO_2 emissions and FDI. In the LMIC, the FDI coefficient is likewise positive but small.

The link between CO_2 emissions and human capital (HC) is consistently negative and significant for all panels in the fixed-effects model (SSA, UMIC, LMIC, and LIC). In the dynamic model, CO_2 emissions and HC in the aggregate SSA countries, UMIC, and LIC have an inverse and statistically significant association. This suggests that strengthening human capital reduces CO_2 emissions by 1%, 1%, and 5% in the SSA countries, UMIC and LIC, respectively. This means that a 10% increase in human capital reduces the CO_2 emissions by 0.7 percent, 5.6 percent, and 0.6 percent in SSA, UMIC, and LIC countries, respectively.

The income per capita growth variable's association with the three environmental quality measurements (N_2O, ACH_4, and CO_2), which has to do with the environmental Kuznets curve, is of higher interest (EKC). Only the most important panels will be covered in this report. For the sample of SSA nations and UMIC, the calculated coefficient on the squared term of income per capita growth (see Table 4) is negative for N_2O. In both panels, they are statistically significant. The calculated coefficient on the squared term of income per capita growth for the total sample of SSA nations and UMIC is negative for agricultural methane (ACH_4) emissions (Table 5). It is statistically insignificant for both panels. The calculated coefficient on the squared term of income per capita growth to CO_2 (Table 6) is negative for the whole sample of SSA and LMIC countries. It is statistically significant for the entire SSA panel and very weakly significant for the LMIC panel. This verifies the EKC theory, but with distinct turning points: constant income per capita increase diminishes these environmental parameters after a specific percentage of growth (reported in percentages at the bottom of Tables 4–6 as "turning points") (N_2O, ACH_4, and CO_2). As other academics have done, the tipping points are measured in percentages rather than dollars. This is conceivable because, instead of the mere income per capita, we add income per capita growth in our model, measured in percentages. The findings of the estimations in Tables 4–6 show that the EKC for the three environmental quality metrics in the overall SSA countries is consistently confirmed. The EKC was only validated for N_2O and ACH_4 emissions in the upper-middle-income nations (UMIC). The EKC was only marginally confirmed in the LMIC for CO_2 emissions and was not confirmed in the LIC panel for any of the three environmental quality parameters. Concerning our EKC data, Omri (Omri, 2013), Qamruzzaman (Qamruzzaman, 2022b) and Li and Qamruzzaman (Li and Qamruzzaman, 2022) came to a similar conclusion. These findings suggest that as countries within these groupings boost their economic growth to a specific percentage of continuous income per capita growth, environmental emissions will rise first, then reduce after the maximum percentage point is reached.

5 Implications and conclusion

5.1 Implications for policy

The outcomes of this study show that trade has similar environmental effects in Sub-Saharan African countries. The panel Dynamic model's results demonstrate that trade raises emissions (N_2O, ACH_4, and CO_2) significantly in the total sample of SSA, UMIC, LMIC, and LIC. In the long run, even though trade affects the environment in the total sample of SSA, its influence on the environment is relatively stronger in the LMIC than in the UMIC and LIC for all environmental variables, according to one of the research's primary findings (N_2O, ACH_4, and CO_2). In the short run, trade raises all emissions (N_2O, ACH_4, and CO_2) in the SSA, UMIC, and LMIC's general sample; trade increases CO_2 but decreases N_2O and ACH_4 emissions in LIC. However, the presence of the EKC indicates a possibility of reducing such emissions in the future, as shown by the study. The findings of this study imply that, for the environmental policies to be effective in achieving the desired results in terms of enhancing environmental quality, SSA nations' trade policies must be considered for environmental reforms. Unpredictability in trade situations among multiple countries, while enacting environmental policy improvements could result in various outcomes, the policies are often kept at their embryonic phases. The gradual implementation of environmental policies is crucially important; it could play an essential role in achieving the desired outcomes. That being the case, policies focused on trade reforms that will improve environmental quality must be implemented as a priority because environmental deterioration is a significant result of anthropogenic actions. Furthermore, initiatives to improve the environment, such as supporting green investment, may lower emissions and improve environmental quality. Previous findings, such as those of Copeland and Taylor (Copeland and Taylor, 2004), Qamruzzaman (Qamruzzaman, 2022b) and Frankel and Rose (Frankel and Rose, 2005), are supported by our findings. Because different income groups have varied inclinations to impact environmental quality through trade, multiple policies and policy strategies are required to improve environmental quality and increase economic growth sustainability. For example, the notion of green investment aims to ensure eco-friendliness, global warming adaptability, and economic diversification. It raises governments' awareness and interest in including green investment in their budgetary planning, taking into account the fiscal and monetary systems, as well as establishing and strengthening effective climate change policies, generating clean/green jobs through reducing or eliminating fiscal taxes. Beneficiaries and stakeholders as a whole must, however, work together for this to happen. The EKC findings show that distinct turning points exist among the groupings and that countries should alter their local environmental laws to achieve universal development goals. As a result, policymakers must adopt major reforms in a step-by-step manner, beginning with trade policies before moving on to environmental measures (Andriamahery and Qamruzzaman, 2022b; Qamruzzaman, 2022b; Xia et al., 2022).

5.2 Conclusions

This research aims to empirically establish the relationship between trade and pollutant emissions (N_2O, ACH4, and CO_2) and other relevant control variables, including income per capita growth, energy intensity, foreign direct investment, and human capital. For robust analysis, data were obtained from a cross-section of Sub-Saharan African countries and sub-divided into income groups (UMIC, LMIC, and LIC). To determine the presence of EKC, this paper looks for an inverted U-shape link between income per capita growth and nitrous oxide (N_2O), agricultural methane (ACH_4), and carbon dioxide (CO_2) emissions. The Hausman specification tests consistently reject the null hypothesis that individual unobserved country-specific effects are not correlated with the explanatory variables for the CO_2 variable, implying that the fixed-effects model is preferred over the random-effects model for all regressions at the level in all panels (SSA, UMIC, LMIC, and LIC). The Hausman specification tests prefer the fixed-effect model for N_2O and ACH_4 variables in the overall SSA countries, UMIC and LMIC; however, the test favors the random effects model in the LIC. In all of the dynamic regressions, the Sargan tests estimates for over-identification constraints reveal that the instruments utilized in correcting for the presence of probable endogeneity are valid.

The findings of this study back up the assumption that commerce has a consistently negative impact on the environment in Sub-Saharan African countries, regardless of wealth level. This study has a clear policy implication: trade policies that support a cleaner environment should be adequately implemented before environmental reforms are implemented to improve the Sub-Saharan region's environment. The findings of this study show that the overall impact of environmental reforms in the SSA area has been ineffective in terms of enhancing the environment. This is hardly surprising, given that many of these countries have enacted weak trade and environmental policies in the region, resulting in environmental damage. As a result, attempts to enhance environmental well-being through environmental policies must be coordinated with trade reforms or rules that promote environmental improvement in the Sub-Saharan African region. Furthermore, we can deduce that the air quality will be lowered due to commerce which, in turn, increases pollution in the atmosphere. International environmental cooperation will almost certainly continue to exist on the list of the regular necessities of the SSA. Under such circumstances, reducing transboundary greenhouse gas emissions and their negative environmental consequences is essential. Cooperation prioritizes technology dissemination and improves environmental quality by enhancing efficiency gains and modernization (Beghin et al., 1995). Various countries have identified the inclusion of environmental measures in trade agreements as one of the most effective ways to promote the global economy while improving environmental quality. As a result, trade agreements should increase governments' abilities to handle environmental concerns. Similarly, reducing trade obstacles related to environmentally friendly items could encourage green technology innovation at a sustainable cost. Renewable energy development must be aided by reducing trade and economic barriers, providing enough subsidies to developers, lowering the risks associated with green investments, and gradually developing and implementing renewable energy markets.

In conclusion, this analysis shows that the effectiveness of environmental reforms is largely dependent on, among other things, the major trade reform policies that promote a cleaner environment. Governments must enact trade policies to increase environmental quality before pursuing environmental changes. This is because poor trade policies are likely to degrade environmental quality. Although this study contributes to a better understanding of this topic, it should be noted that enacting and implementing trade agreements geared toward reducing the environmental pollution in the atmosphere while maintaining real GDP growth should take into account other macroeconomic determinants than the ones used in our study. In addition, a slew of other environmental indicators must be evaluated to thoroughly examine the environment's quality. Other control variables such as innovation, commerce based on consumption and production, urbanization, transportation, and environmental regulation laws could be considered in future expansions of this study in Sub-Saharan African countries.

The present study is not out of certain limitations that can be addressed in future research. First, the study has overlooked the effects of cross-sectional dependency fact in empirical estimation, which may lead to spurious estimation for coefficient assessment. Second, advanced econometrical tools such as CS-ARDL and nonlinear assessment, that is, Panel–NARDL, can be implemented in documenting the explanatory effects of environmental sustainability.

Data availability statement

Publicly available datasets were analyzed in this study. This data can be found here: https://data.worldbank.org https://wdi.worldbank.org/ https://wdi.worldbank.org/ https://data.worldbank.org.

Author contributions

MQ: Introduction, Methodology, Empirical model estimation; AA: Data Accumulation, Literature Survey, First draft preparation, Final Preparation; JD: Methodology, Empirical model estimation.

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Conflict of interest

The 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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